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**Reclamation of aggregate mines in the Manawatu, Rangitikei and  
Horowhenua Districts, New Zealand.**

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## Abstract

Aggregate is the largest extractive industry in New Zealand, in terms of both volume and value of product. In central New Zealand unsustainable extraction of aggregate from rivers has encouraged development of alluvial terrace resources which are often overlain by valuable agricultural soils. Research at commercially reclaimed aggregate mines has shown long-term degradation of the soil resource with productivity of reclaimed land not being maintained at any reported site.

Field trials were designed and implemented on three soils characteristic of major landscape units containing aggregate resources which are mined in the greater Manawatu region. Rangitikei fine sandy loam represents free draining Recent soils; Ashhurst stony silt loam represents excessively draining Yellow-brown soils; and Ohakea silt loam represents imperfectly to poorly drained Yellow-grey soils. In each of the trials a "best-case" reclaimed soil was constructed by stripping and replacing soil horizons in their natural order while minimising compaction and ensuring non-limiting nutrient levels. The productivity and soil physical characteristics of other treatments, including different depths of replaced soil and mixed soil horizons, were compared with this "best-case" treatment. Compaction and drainage treatments were also investigated. Control treatments of soils which were ploughed were also used as a reference.

### *Soil depth and horizon mixing*

- \* Spreading Rangitikei sand over compacted fill material to depths of 0, 0.4, 1.0 and 1.5 m depths resulted in incremental increases in yield of cereal of  $92 \pm 21$ ,  $142 \pm 13$ ,  $169 \pm 14$  and  $184 \pm 7$  kg ha<sup>-1</sup> respectively.
- \* The same treatments had no consistent effect on production of clover and ryegrass for most harvests, probably because pasture roots were able to exploit the fill material as a source of moisture.
- \* Yields of pasture were reduced by removal of 0.5 m of the Ohakea upper B horizon, resulting from decreased aeration. This effect was mainly due to the closeness of the water table, which was exacerbated by the sunken surface of this treatment.
- \* In contrast, pasture yield was unaffected by removal of a 0.2 m deep Ashhurst B horizon, reflecting the lack of impediment to root extension to depth in the Ashhurst soil.
- \* Dilution of Ohakea topsoil by mixing with subsoil material resulted in an increase in soil particle density and bulk density and decrease in percentage of total soil organic carbon so that the mixed soil had properties similar to unmixed subsoil.
- \* Separate stripping and replacement of topsoil significantly increased establishment of pasture in Ohakea soil but not Rangitikei soil.
- \* Dilution of topsoil had no long-term detrimental effects on soil physical properties or pasture production in any of the three soils under the management practices used.

### *Compaction*

- \* A compacted layer at 0.20 m (Ohakea soil  $\rho_b=1.64\pm 0.11$  on construction) either benefitted or did not effect pasture production over 13 of 14 harvests.
- \* The effect of compaction varied with position in the soil profile: pasture production and root length were negatively correlated with bulk density at 0.20 m depth.
- \* greater root mass was produced at 0.30 to 0.35 m depth in low compaction treatments
- \* A compacted layer at 0.20 m (Ashhurst soil  $\rho_b=1.40\pm 0.08$  on construction) had no significant effect on pasture production, although cumulative production over 9 harvests was 18% higher in the high compaction treatment.
- \* Pasture growing in a compacted Rangitikei soil ( $\rho_b= 1.61$ ) produced less than 40% of pasture growing in the same soil with  $\rho_b= 1.21$ , and comprised a higher proportion of weeds.

### *Drainage*

- \* Drainage lowered the volumetric water content of Ohakea soils at four increments to 0.60 m by a mean 3% on five measurement dates.
- \* Pasture production was similar in drained and undrained treatments for 9 of 14 harvests.

The Resource Management Act 1991 requires sustainable use of non-mineral resources. Sustainable use of soil resources requires reclamation of mined land. The highly competitive nature of the aggregate industry means reclamation is unlikely to occur unless it is both required and monitored by District and Regional Councils. A survey of aggregate extraction sites in the greater Manawatu region showed that, prior to the Resource Management Act, no sites were required to be reclaimed to their prior productivity. Results from the trials were used to identify basic strategies for reclamation, to pasture, of three groups of soils most commonly disturbed by extraction of alluvial aggregate. The strategies aim to ensure mining is an interim land use.

Mining of alluvial aggregate should be promoted on soils which are resilient to disturbance; i.e. free-draining Recent and Yellow-brown soils. Where post-mining land use is agricultural or horticultural production, conditions of extraction must include maintenance of pre-mining productivity under a strategy of rolling reclamation. Conditions related to reclamation must be specific and monitored, preferably by the extraction company under supervision of the authorising Council. Linking specific, measureable reclamation criteria to significant bonds would provide a strong incentive to extraction companies to reclaim land adequately.



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## Chapter One Introduction

Production of sand, gravel and crushed rock, (aggregate) is the largest mining industry in New Zealand by both volume and weight of product. The New Zealand aggregate industry comprises many small sites which are scattered throughout the country. At these sites aggregate is mined from river beds, alluvial terraces and hard rock quarries primarily for construction of roads, railways and buildings. Mining of land-based aggregate is increasing as river resources diminish through unsustainable extraction rates and increasing conflict with other groups that value rivers.

A heightened awareness of environmental issues and decreased tolerance of adverse environmental effects by society, has increased the demand for reclamation of mined sites. The passing of the Resource Management Act 1991, which requires sustainable use of non-mineral resources, has a wider definition of environmental impacts and requires community consultation, has legislated this demand. Although Regional and District Councils have responsibility under the Resource Management Act for controlling and monitoring activities, which impact the environment, they may have limited knowledge of land reclamation practices. Additionally, the small size and fiercely competitive nature of the New Zealand aggregate industry has minimised investment in reclamation research by individual companies. As a result little scientific research has been conducted into reclamation after land based aggregate mining in New Zealand. Research so far has focused on measuring soil and crop attributes of commercially reclaimed areas with no investigation into the effect of different soil replacement strategies or soil depths; although some relevant research has been carried out on pastoral reclamation after alluvial gold mining in Westland. Thus there is currently a need in New Zealand for field trials comparing alternative strategies of reclamation.

To date all New Zealand reports and measurements of reclaimed aggregate extraction sites have found lowered site agricultural productivity, with most reporters concluding that damage to soil was serious and long term. This conflicts with United Kingdom, Californian and Canadian experimental and commercial site research which has shown reclaimed land can produce equal or higher yields of agricultural and horticultural crops. To identify why aggregate mine reclamation has generally been unsatisfactory in New Zealand it is necessary to determine the legislative, social and economic factors that affect reclamation practices and the characteristics of aggregate sources and users in New Zealand.

In the past successful reclamation primarily constituted avoiding degradation of nearby waterways, and cosmetic treatments which aimed at blending the site into the landscape. This was usually achieved by screen planting or attempted revegetation. Since the 1970's when agriculturally productive soils were disturbed during aggregate mining some regulatory bodies, notably Waimea County Council and the Ministry of Commerce, required reclaimed land to achieve pasture production equal to or greater than that of the land before mining. This

requirement was rarely met. Successful agricultural reclamation constitutes growing the same crops at the same yields with similar inputs on reclaimed land as on undisturbed land, i.e. the productive potential or capability of the land is not compromised. To incorporate alternative reclamation options such as wetland development, residential or industrial subdivision or recreational land, successful reclamation may also be defined as maintenance of a site's utility or overall economic, social and environmental value.

### **1.1. Objectives**

The general objectives of this project are:

- i. To provide information on aggregate resources and their overlying soils, the aggregate industry and post mining land use options in the greater Manawatu region which incorporates the former Wanganui, Rangitikei, Manawatu, Oroua, Pohangina, Kiwitea, Kairanga and Horowhenua counties.
- ii. To develop reclamation strategies which will enable the return of land mined for aggregate to productive agricultural use.

This information will assist planning decisions in relation to land use for aggregate extraction and reclamation and aid development of reclamation guidelines and monitoring strategies. Figure 1.1 shows how topics considered in the thesis interrelate to affect the standard of reclamation achieved after aggregate extraction.

The specific objectives of this research are:

- i. To determine the effect of soil horizon mixing, soil depth, and soil compaction on pasture growth and soil physical characteristics of three soils most likely to be disturbed by aggregate mining in the greater Manawatu region.
- ii. To determine the effect of drainage when reclaiming a soil with low saturated hydraulic conductivity.
- iii. To assess the effect of soil physical characteristics on success of reclamation and extrapolate this information to identify soils in the greater Manawatu region whose productivity is most easily regained after gross disturbance.
- iv. To formulate procedural guidelines for reclamation of land-based aggregate extraction sites to pastoral agriculture in the greater Manawatu region.

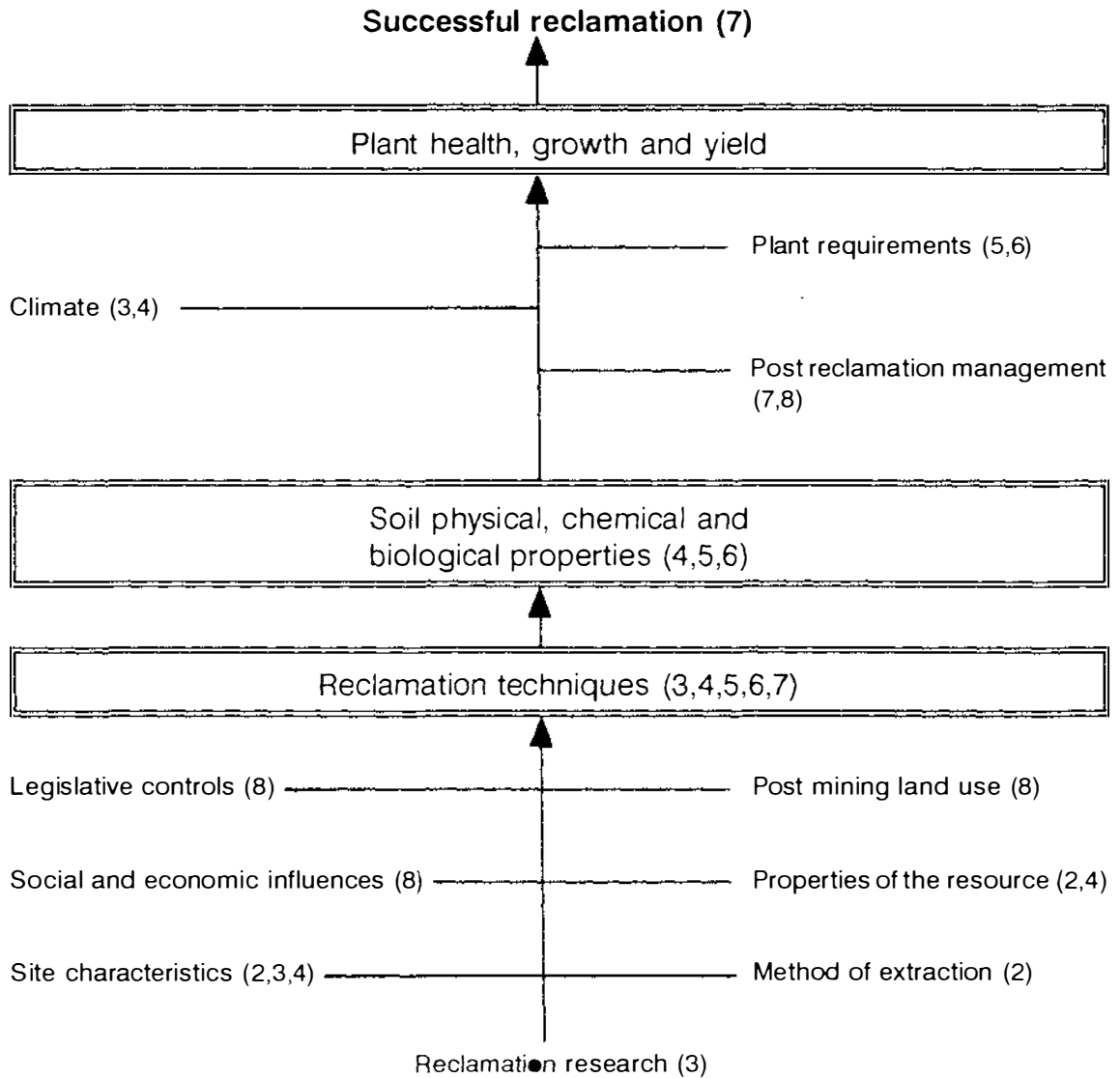


Figure 1.1: Factors influencing the outcome of reclamation of aggregate extraction sites. The numbers in brackets indicate chapters in this thesis in which the subject is discussed.

- v. To determine legislative, social and economic factors that effect reclamation practices.
- vi. To analyze information on post mining land use options and factors influencing reclamation options.
- vii. To describe aggregate sources, use and users in the Central Mining Inspectorate and the potential environmental impacts of aggregate extraction.

## 1.2 Implementation of Objectives

The achievement of these aims has involved two distinct areas of work. Field trials were designed and implemented on three soils characteristic of major landscape units containing aggregate resources in the greater Manawatu region. Rangitikei fine sandy loam represents free draining, Recent soils found extensively along major rivers of the region where the water table is below 1 metre deep. Aggregate in the region is probably most commonly extracted from beneath soils of the Rangitikei series. Ashhurst stony silt loam represents excessively draining Yellow-brown stony soils and Ohakea silt loam represents imperfectly to poorly drained Yellow-grey Earth soils. Both Ashhurst and Ohakea soils form a major aggregate resource along the Rangitikei, Otaki and Manawatu Rivers and are mined in the greater Manawatu region.

The second area of research comprised undertaking a postal survey and analysis of published data. Aggregate producers in the greater Manawatu region were surveyed about the environmental requirements (conditions of extraction) affecting the operation of extraction sites and the choice of post mining land use. The survey in addition to statistical data from the Ministry of Commerce, soil survey information and a literature search on mining, enabled the description of the aggregate resources, the products and the industry in the greater Manawatu region.

## Chapter Two: Aggregates and the Aggregate Industry

### 2.1 Introduction

The aggregate industry provides society with some of its most basic needs as primary products of sand, gravel and boulders and secondary products which include cement, ready mixed concrete and pre-cast concrete. Aggregate is so vital to the general urban economy that it is considered one of the best indices of regional economic activity (Werth, 1980). Aggregate is used extensively as base and surfacing material for roads, railways and airport runways. The rapid internal drainage, or unsaturated hydraulic conductivity, and easily compacted nature of aggregate makes it the preferred material for fills, utility trenches, storm drains and levelling building pads.

Aggregate production is a highly competitive industry (Bennett *et al.*, 1982) characterised by small operators supplying local needs (Department of Statistics, 1990) from rivers, river terraces, the marine foreshore and hard rock quarries. More than 20 million tonnes of aggregate worth c.\$200 million are mined annually (Department of Statistics, 1990). In most of the major cities of the world demand for aggregate is increasing. In the Manawatu a recent expansion of demand is associated with increasing extraction from terrace deposits due to unsustainable rates of aggregate extraction from rivers in the region (Brougham and McLennan, 1985). Expansion is also occurring in a period when the public's awareness and participation in environmental issues is increasing (Tidmarsh, 1991).

This chapter defines aggregate and identifies primary users, common quality specifications and aggregate sources. National and regional supply and demand for aggregate in the past, present and future are presented. Actual and potential on site and off site environmental and social impacts of both in-stream and land based aggregate extraction are outlined.

### 2.2 Definition of aggregate

Aggregate is defined as "*a granular, hard material able to withstand shock or pressure, resistant to weathering and chemically inert*" (after Joll, 1980). In New Zealand aggregate is a collective term used to describe sand, gravel, boulders and mixtures of these (Department of Statistics, 1990). While aggregate has also been defined as materials obtained from naturally occurring stone derivatives (Taranaki Catchment Commission, 1981), shortages of naturally occurring material overseas has led to artificial aggregate production from industrial waste and recycling of aggregates from paving and construction concrete. Aggregates are bulky low cost materials with initial processing and transport comprising a significant amount of final delivered costs (Verney, 1976; Werth, 1980). Aggregate is generally used loose, to provide drainage, or bound to provide bulk strength (Joll, 1980). Sand is produced naturally or as a byproduct of

rock crushing (Joll, 1980) and comprises less than 2 mm diameter grains of lithic and mineral fragments (Taranaki Catchment Commission, 1981).

The terms gravel and shingle are often used synonymously with aggregate although gravel and shingle are generally regarded as being formed from the natural disintegration of rock. Gravel particles can either be irregular, rounded or angular, while shingle is always rounded or water worn (Taranaki Catchment Commission, 1981; Joll, 1980). Other synonyms for aggregate include non metallic minerals, pit metal, sand and crushed rock (Joll, 1980).

## **2.3 Uses and specifications of aggregate**

### **2.3.1 Requirements and characteristics of high quality, multi-purpose aggregate**

Aggregate products are often divided into categories by use and specification (Taranaki Catchment Commission, 1981) as aggregates may have widely differing qualities (Verney, 1976). A higher grade product generally reflects the geology, degree of crushing, fracturing and weathering of the aggregate (Reed and Grant-Taylor, 1966). The most important aggregate requirement is probably hardness (Kear and Hunt, 1969 *cited by* Joll, 1980). All aggregates must be strong enough to withstand specified tensile and compressive loading (Grant-Taylor and Watters, 1976; Verney, 1976; Ward and Grant, 1978). General purpose aggregates should be stable against breakdown, both when in use or when stockpiled, and non plastic, with low shear failure (Grant-Taylor and Watters, 1976; Ward and Grant, 1978; Gribble, 1989; Saunders, 1991). Aggregates should be chemically inert when mixed with other construction materials (Grant-Taylor and Watters, 1976; Ward and Grant, 1978). This is particularly important for aggregate used in concreting (Rowe, 1980). Low porosity and permeability in individual chips (Grant-Taylor and Watters, 1976; Gribble, 1989) and low water absorption (Verney, 1976; Gribble, 1989) increases aggregate resistance to frost and chemical erosion.

In addition Grant-Taylor and Watters (1976) advocated general purpose quality aggregate to be free from joint flaws and micro cracking, not deeply weathered or coated and not polished. The latter two properties may reduce adhesion of bitumen or cement to aggregates (Grant-Taylor and Watters, 1976). Particle shape, form and size greatly affect the performance of bound (Verney, 1976) and unbound construction materials (Woodside and Kelly, 1992). More angular aggregates produce concrete of lower strength because flaky particles have a high surface area to volume ratios and are therefore weaker for any given size. In Wellington rock which produces angular particles also tends to be argillaceous (Rowe, 1980).

The quality of aggregate may be improved by etching with acid to degrade softer minerals in the stone's surface, further processing or calcination. Calcination involves changing the behaviour

of the matrix of an aggregate by heating to fuse specific minerals within an aggregate, thus increasing aggregate loading ability (Woodside and Kelly, 1992).

The most common tests for aggregate quality are the 'Los Angeles Abrasion', 'crushing value or resistance' tests. Both Los Angeles and crushing resistance test results depend mainly on aggregate toughness, hardness, elasticity, strength and particle shape (Rowe, 1980). The Los Angeles Abrasion test consists of grinding an aggregate with steel balls in a rotating drum (Rowe, 1980) and measures the durability of an aggregate against abrasion. A high percentage of abraded aggregate equates to a lower quality aggregate (Rowe, 1980; Taranaki Catchment Commission, 1981). The 'crushing value' test measures aggregate strength by applying a load to crushed aggregate of a defined size with the applied load determined by the aggregate use (Grant-Taylor and Watters, 1976). Fines produced during crushing can significantly influence the quality of aggregate which acquires a fine dust coating that is only partly removed by washing (Rowe, 1980).

Table 2.1 Quality standards for roading aggregate in New Zealand

Quality standard	Comment
Premium grade	for concrete aggregate and sealing chip.
Transit New Zealand grade	TNZ M/4 base course quality.
General grade	second grade base course
Sub-base grade	for lower pavement layers

Note: TNZ grade is equivalent in quality to premium grade.

Four main types of aggregate and four quality standards are recognised by the industry, apart from railway ballast. Aggregate specifications usually include diameter maximum and/or minimum. Aggregate type standards are expressed as *single sized chip* or *sealing chip*, *graded chip* (aggregate diameter lies between two specified limits), *all passing* (aggregate lies below one diameter limit) and *blended mix* where aggregate is mixed with sand. *Sized chip*, *graded chip* and *blended mix* are normally produced from *premium* quality rock. Uncrushed shingle or natural round pebbles are called 'rounds' and differentiated from crushed angular chips. The quality standards listed in Table 2.1 apply to most roading aggregates.

### 2.3.2 Roading aggregate

Most pits and quarries produce aggregate for road construction and maintenance. Roading aggregate is obtained locally, often by private operators on a contract basis to Transit New Zealand, local bodies and roading contractors (Joll, 1980). The Transport Law Reform Act 1989



created Transit New Zealand which was given the function of providing integrated nationwide planning and funding of roading and road safety (Knight, 1992). Some local bodies supply their own needs, for example the Ohakea crusher operating on the Rangitikei river has supplied the former Manawatu County Council with part of its roading aggregate requirements for at least 20 years (Cassidy, 1990).

A road comprises three or more layers, usually a sub-base, basecourse and top course or sealing chip with asphaltic materials. *Fill* or *sub-base* roading aggregate forms the bottom layer of a road, providing a stable foundation (Joll, 1980). Sub-base aggregate is an unsorted mixture of sand and rock, excluding large boulders. Compaction and binding of the sub-base is aided by the sand and fine material (CALNIG, 1986) and is often augmented by lime or cement stabilisation. In New Zealand road foundations are generally thinner than overseas due to a mild climate and low traffic densities (Happy, 1992). The central *base-course* layer helps spread and absorb road loads (Joll, 1980). Base-course roading aggregate includes sand and has a lower maximum aggregate diameter than sub-base (Taranaki Catchment Commission, 1981). *Top-course* or *sealing chip* roading aggregate forms the surface layer of a road. The thickness and quality of material required for each layer depends on the design life of the road, expected traffic loading, and nature of the underlying stratum. Thin surfacing layers usually comprise bitumen sealing, or asphaltic concrete where roads are subject to high traffic volumes (Happy, 1992). These surface layers are made up of high quality, evenly sized aggregate.

Roading aggregate requirements are complex. Road qualities such as skid resistance and crushability are controlled not only by aggregate specifications, but also by the binding agent in the surface course and construction type of the base and sub base (Calnig, 1986). All courses must consist of crushed rock or waterworn material free from non mineral matter which may decompose with time and be able to support a given load without forming fines. Creation of excess fines can cause a road or railway to fail by shearing (Ward and Grant, 1978).

The national standard for basecourse, set by Transit New Zealand, has been TNZ M/4 which follows the NRB M4 and M6 standards, named after the National Roads Board which was replaced by Transit New Zealand (Anon, 1991a; Knight, 1992). In Wanganui and Taranaki, available roading materials comply with a lower M/5 standard, if suitable for the road use, to avoid the cost of aggregate importation (Anon, 1991h). As high quality basecourse becomes less available alternative materials will be used more frequently (McQuire, 1991d). Basecourse specifications have been developed to limit clay content (Grant-Taylor and Watters, 1976) and minimum proportion of crushed aggregate to reduce road plasticity and ensure stability under heavy traffic loadings respectively (CALNIG, 1986).

Materials for the top course of unbound road pavements in New Zealand are subject to the M/4 specification. Sixteen internal criteria are prescribed by Transit New Zealand for testing

topcourse aggregate (Saunders, 1991) including 'percent broken faces', specified strengths, 'sand equivalent', 'plastic index' and 'cleanliness value'. Cleanliness ensures adhesion of bitumen to the sealing chip (Anon, 1991a). Until 1991 enforcement of the grading limits were lax with more than 65% of material failing to conform on at least one criterion, yet accepted and placed in New Zealand roads (Saunders, 1991).

Roading specifications are continually modified. Higher traffic volumes and loadings increase stresses placed on roads affecting topcourse, basecourse and sub base grades (Grant-Taylor and Watters, 1976). Increased cost and decreased availability of high quality aggregate also affect specifications (McGuire, 1991a). In the future roading specifications will probably allow greater scope for innovative road construction that produces a cheaper road of acceptable quality. This may allow lower grades and types of aggregate to be used. Transit NZ continues to review its technical recommendations (McGuire, 1991a). For example, resistance to polishing largely determines the skidding resistance of a bituminous road surface and is particularly important where road slopes and bends are extreme or cars may decelerate suddenly (e.g. at railway crossings). Donbavand (1991b) of Transit New Zealand predicted implementation of specifications for polishing resistance in New Zealand in the future. Saunders (1991) proposes that the sixteen criteria for top course be reduced to six with more sampling. In the future the International Standards Organisation 9000 Series may be adopted by Transit New Zealand for New Zealand's roading industry (McGuire, 1991b).

### 2.3.3 Railway aggregate

New Zealand Railways uses gravel for ballast, yarding and construction (CALNIG, 1986). Railway ballast is a layer of very hard, angular stone on which a railway track rests (Joll, 1980) with size restrictions, enabling it to support high bearing capacities without compaction (Taranaki Catchment Commission, 1981). NZ Railways set their own ballast specifications which are probably higher than for any other stone product. They are mainly based on American Railway Engineering Association recommendations and are similar to those used by the majority of the world's railway systems (CALNIG, 1986). Principal requirements include uniformity of specified size (CALNIG, 1986) to produce voids which enable rapid and free drainage (Joll, 1980) and resistance to abrasion and weathering. Angular aggregates created by crushing produce stones which form a stable structure through interlocking and digging into sleepers (Joll, 1980; CALNIG, 1986). Ballast aggregates must have high strength to resist crushing (Joll, 1980).

### 2.3.4 Construction aggregate

The ready mixed concrete, precast concrete and concrete masonry industries use a range of fine and coarse aggregates to provide bulk and strength to concrete (Nasser, 1987; Happy, 1992). The high internal drainage and stable nature of compacted aggregate makes it suitable for filling

utility trenches and storm drains, levelling building pads and stabilising pipelines and drains, for example the Maui gas pipeline in Taranaki. Aggregate is also used for landscaping and artificial turf construction.

All aggregates used in cement must be strong enough to withstand loads applied to the completed structure (Ward and Grant, 1978) with the strength of individual aggregates equal to or higher than matrix material strength. Aggregates for cement must have clean surfaces to ensure high strength bonding between the cement, sand and aggregate (Ward and Grant, 1978; Taranaki Catchment Commission, 1981). A wide range of products require different grades and qualities of aggregates. The New Zealand Standards Institute coordinates user standards, for other than road and rail, in building codes, local territory activities and government projects. The Institute continually modifies specifications and quality standards (Joll, 1980). Aggregate size specifications vary (Taranaki Catchment Commission, 1981), but gravel diameter is usually smaller than for roading aggregate sealing chip and quality lower (Ward and Grant, 1978). At the New Zealand Railways Otaki Ballast Plant undersized aggregate is traded with an adjacent company which produces aggregate for building construction and roading (Winiata pers. comm., 1988).

Cubic shapes form a stronger bond than flat, flaky chips (Joll, 1980) and the interlocking of angular particles strengthens asphaltic concrete (Nasser, 1987). Rounded aggregates are preferred by some operators as they are less abrasive, reducing concrete pump and pipe wear (Joll, 1980; Taranaki Catchment Commission, 1981; Nasser, 1987). Rounded aggregates also improve the workability of concrete, which is especially important for pumped concrete to allow minimum cement, sand and water contents for economy and strength (Rowe, 1980). The preferred use of one aggregate material over another depends the cost of aggregate as well as use specifications outlined in this section (Nasser, 1987; McGuire, 1991).

### 2.3.5 Other uses of aggregate

Large, more or less rounded, blocks of rock greater than 250 mm diameter are called boulders. They are mainly used in river and harbour protection works both in wire cages as rip rap and loose (Taranaki Catchment Commission, 1981).

Aggregate is used in plastering and other surfacing and decoration uses. Aggregate for these uses is highly processed and conforms to size and shape specifications.

Fill is used in harbour reclamation and major building projects. Fill is generally equivalent to sub-base used in roading and must be low in decomposable or organic materials that may affect future stability of the surface.

## 2.4 Geology of aggregate

Quality aggregates are produced from hard sedimentary rocks, intermediate to basic volcanic rocks, granites, gneisses and schists. Granites, gneisses and schists are limited to the South Island (Reed and Grant-Taylor, 1966). Intermediate to basic volcanic rocks such as scoria and basalt are localised; found only in Otago, Christchurch, parts of the Central North Island, Auckland and parts of Northland. Greywacke is quantitatively the most common hard rock aggregate except where basalts or andesites are available (Happy, 1992). In the United Kingdom large quarries, producing more than 1 million tonnes of aggregate per annum, mine gabbros, granites and limestones, avoiding greywacke and basalt deposits which often display heterogeneous quality and composition (Gribble, 1991). Some sedimentary rocks are avoided due to high water absorption and porosity values which result in low strength aggregates (Gribble, 1989).

In the lower half of the North Island a variety of rock types are used for aggregate production. These include greywacke, argillite sedimentary rocks, Tertiary conglomerates, Tertiary tuffs and coquina limestones located in the Wanganui area (Ker, 1966) Manawatu Gorge and Pohangina areas (Brougham and McLennan, 1985). Crystalline, shelly and relatively soft limestones are used for construction and maintenance of unsealed roads (Happy, 1992) (Figure 2.1). Pleistocene limestone is being mined in the Manawatu Gorge for boulders used in river protection work (King, 1982a). Ripping and blasting greywacke bands in quarries is predominant in the Wellington region (King, 1982b) (Figure 2.1). Andesite lahars and deposits along the Whangaeu river and in Taranaki are also utilised for aggregate. Andesites are used in all grades of aggregate though the presence of glass, clay-like minerals or clays can lower their quality. Volcanic pumice or rhyolite deposits are extracted in the upper reaches of the Rangitikei river and Central Plateau region (Ker, 1966). Pumice is used for horticultural and light weight aggregate use and premium pumice has been used in gypsum wallboard manufacture (Happy, 1992). Volcanically sourced aggregate from Taranaki and the central North Island may be chemically active and readily weathered with very variable hardness, abrasion and crushing resistances (Reed and Grant-Taylor, 1966). Taranaki and Gisborne are the only areas of New Zealand where high grade aggregate materials are unavailable (Happy, 1992; Robertson pers. comm., 1992).

Greywacke and argillite are the main sources of aggregate for concrete production and road making in the West Coast North Island (Ward and Grant, 1978; NWASCA, 1987) and usually occur as alternating bands of rock (Reed and Grant-Taylor, 1966). When fresh, greywacke and argillite have very similar properties, however, greywacke is more stable when exposed to air. A typical greywacke is a hard, medium grained (0.5 to 2 mm diameter), well jointed sandstone which is green/grey to light grey when fresh (Marden, 1984) and more lightly coloured or iron-stained when weathered. Mineralogically greywacke comprises mainly quartz and feldspars with mica and traces of other minerals and rock fragments set in a very fine grained partly

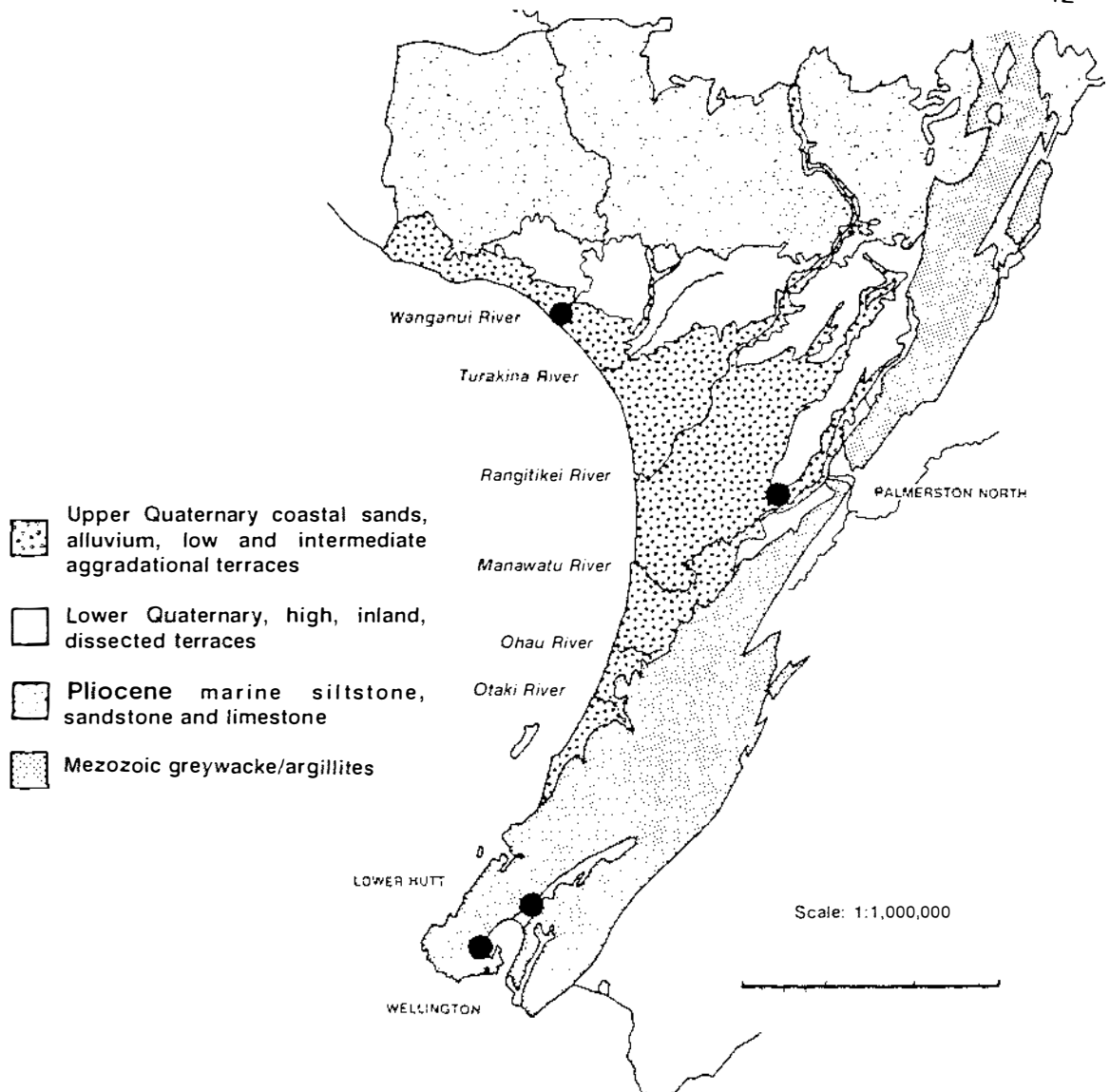


Figure 2.1: Major rock types in the south west of the North Island (adapted from NZ Geological Survey, 1972).

recrystallised matrix.

Argillite is typically black to dark grey when freshly exposed and can be considered as a fine-grained (mean grain size finer than 0.031 mm) equivalent of greywacke (Rowe, 1980). As rock properties, in particular strength, density, hardness and degradation tendencies, are linked directly or indirectly with mean grain size, argillites are generally weaker, softer, less elastic and degrade more rapidly than greywackes (Reed and Grant-Taylor, 1966; Grant-Taylor and Watters, 1976; Rowe, 1980). Argillite generally occurs as discrete beds or thin partings 0.02 to 0.5 m thick between beds of sandstone and siltstone lithologies (Marden, 1984). Argillite has a similar mineralogical composition to greywacke but always contains more clay minerals (Reed and Grant-Taylor, 1966; Williams, 1974 cited by Joll, 1980). Physical properties of an aggregate are reflected in concrete made from it, thus argillitic aggregates have lower strength in concrete than

greywacke aggregates. Although argillitic aggregates are unsuitable in certain environments they still have a place in low strength concrete applications and where they are not exposed to wetting and drying cycles (Rowe, 1980).

Properties of an aggregate deposit, whether river or land based, which determine its commercial potential are the thickness and variability of the overburden and deposit and the physical properties of the deposit, including its particle-size distribution, lithology and durability. Unsatisfactory size gradations or ratios and dirtiness can require costly processing to meet market specifications (Werth, 1980).

## 2.5 Sources of aggregate in the greater Manawatu region

The main axial ranges of the Manawatu region supply eroded detritus to the streams and rivers of the region (Figures 2.1 and 2.2). River gravels in active channels are the traditional source of aggregate for the greater Manawatu region. River gravels located in aggradational and degradational alluvial terraces form a resource which has increased in popularity in recent years (Figure 2.2).

Table 2.2: Lithology and extraction status of rivers from which aggregate is extracted in the greater Manawatu region.

Rivers supplying major quantities of aggregate		
River	Lithology	Status of extraction
Otaki	greywacke	Excessive degradation from 1973 ~. Total ban on extraction recommended in 1983. Ban implemented in 1987 except for river control.
Manawatu	greywacke	Extraction balances or exceeds replacement*+ Extraction limited to 40 000m <sup>3</sup> annum*!
Oroua	greywacke	aggregate shortages and degradation*!
Rangitikei	greywacke	Full potential reached (1980) Finite and diminishing resource*
Whangaehu	andesite	Aggregate generally soft, acidic and low quality.
Wanganui and tributaries	greywacke, andesite, Tertiary	Upper Wanganui most sites closed, tributaries under pressure*
Taranaki rivers	andesite	extraction exceeds supply as sediment is lahar derived*\$ closed to extraction!
Rivers supplying minor quantities of aggregate		
Pohangina	greywacke	extraction close to maximum sustainable as demand balances or exceeds supply ^ *
Mangatainoka	greywacke	extraction limited to that required for river control purposes#+
Ohau	greywacke	shingle shortages but extraction continues*

### KEY TO TABLE

#	Brougham and McLennan, 1983	^	Brougham and O'Conner, 1982
~	Brougham 1976a; Anon, 1985	*	CALNIG, 1986
+	Brougham and McLennan, 1985	\$	Taranaki Catchment Commission, 1981
!	confirmed 1992 by Manawatu-Wanganui Regional Council		

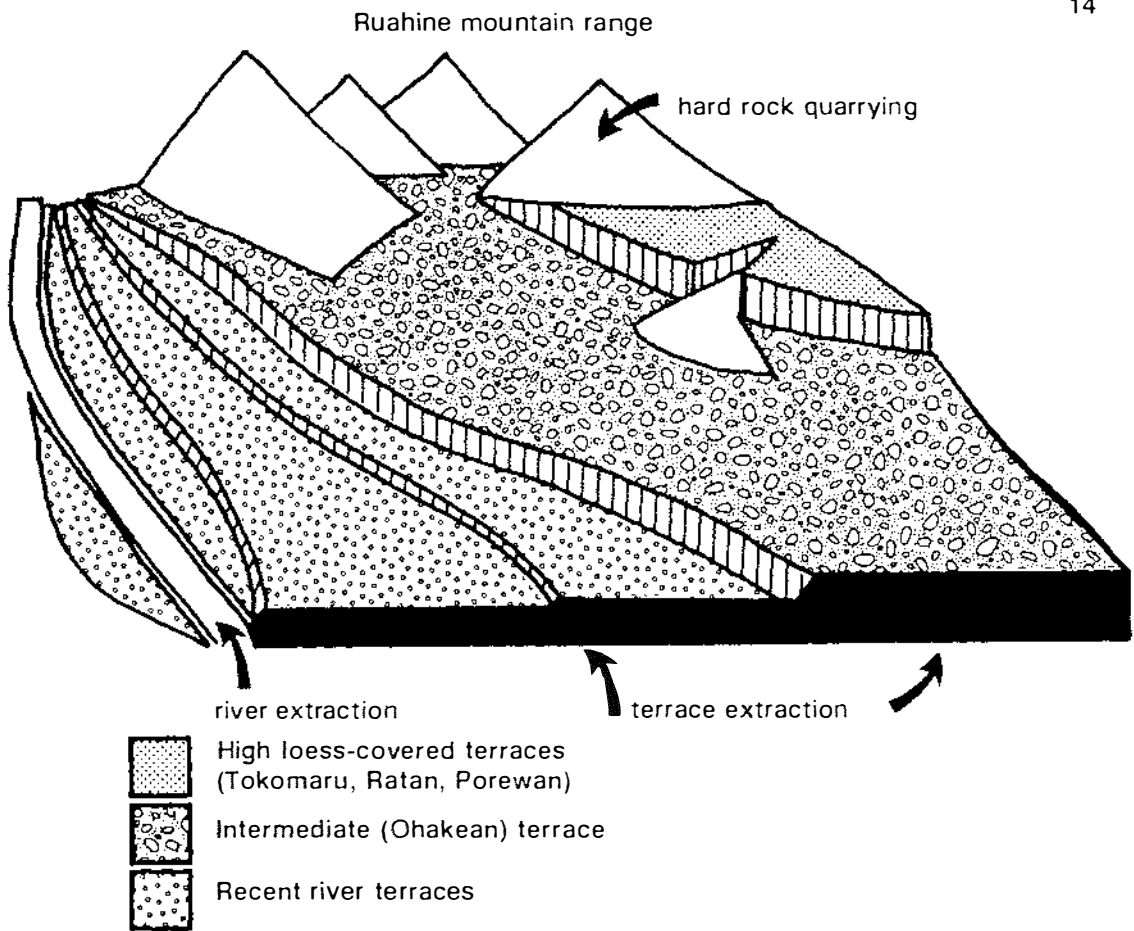


Figure 2.2: Aggregate resources and associated land forms in the greater Manawatu region

2.5.1 Rivers

In the greater Manawatu region south of Whangaehu River, debris avalanches and occasional large scale deep-seated slumps provide bedrock detritus and colluvium to streams originating from the Ruahine and Tararua ranges (Figure 2.1 and Appendix 2.1). During high intensity rainfalls and floods this detritus is transported downstream along with material from old alluvial deposits and scree (Brougham and McLennan, 1985). Marden (1984) proposed that an increase in erosion seen from 1974 in the Southern Ruahines resulted from progressive enlargement of erosion sites and failure of forest to recolonise eroded sites. Marden (1984) submitted that this was due to a progressive deterioration of forest vegetation, possibly associated with sudden changes in precipitation and introduction of browsing mammals such as opossums, deer, pigs, goats and domestic stock.

Streams which drain the eastern side of the Ruahine Range feed the Manawatu River and are characteristically short and steep. Large aggradations of aggregate have created relatively wide, shallow valleys beyond the mountain front (Marden, 1984). Little aggregate extraction occurs in

these streams as demand for aggregate in these sparsely populated areas is low and freshly eroded detritus is unsorted with impurities not removed by weathering and therefore a low quality aggregate resource. Marden (1984) recommended establishment of *gravel reserves*. These are areas where groynes, retard structures and willow plantings divert and slow floodwaters to detain large volumes of aggregate and thus reduce aggradation and associated flooding of productive farmland downstream. Streams which drain the western side of the Ruahine Range to the Pohangina River carry less aggregate and have longer channels which are often deeply incised into narrow, steeply sided valleys so aggradation is not a problem (Marden, 1984). Aggregate extraction from western streams is limited by low demand and difficult access.

Extraction of aggregate is concentrated in the central and lower sections of rivers where high quality sorted aggregate is easily accessible (Appendix 2.3). Aggregate size varies between river bend or straight beach locations (Higgins, 1990) with larger aggregates on river bends. In the lower reaches of large rivers gravel size decreases, limiting the range of aggregate products able to be produced (Joll, 1980). The lower Manawatu River sediments, for example, are mainly sandy and silty. Extraction of aggregate from the Manawatu River, therefore, stops below Opiki (Brougham and McLennan, 1985).

Holocene river gravels are clean, with abrasion and attrition during river transportation removing deleterious softer material (argillite and clays) and naturally fragmenting rock to produce rounded aggregates with consistent strength in their natural state (Reed and Grant-Taylor, 1966; Rowe, 1980; Taranaki Catchment Commission, 1981; NWASCO, 1987). Aggregate in shorter rivers draining areas of variable rock types may be contaminated with soft rocks like young mudstones and sandstones (Happy, 1992). Large and long rivers have harder aggregates in their lower reaches as aggregates are subject to more physical weathering. For example, crushed aggregate from the Manawatu, Ohau and Otaki rivers have lower Los Angeles Abrasion test values than the smaller Tokomaru, Makakahi and Mangairi rivers of the greater Manawatu region (Grant-Taylor and Watters, 1976). Only the large rivers contain aggregate suitable for railway ballast (CALNIG, 1986). Rowe (1980) compared quarried and alluvial road concrete aggregate. Rowe (1980) found that alluvial greywacke performed more consistently than quarried aggregates and had lower Los Angeles Abrasion test results. The researchers concluded that this was because quarried aggregates normally include some argillite which is more easily comminuted, more absorbent and contains more incipient flaws than greywacke. Extraction of in-channel river gravels is preferred by aggregate producers as the cost of extraction is low (Reed and Grant-Taylor, 1966; Joll, 1980) with a minimum crushing and cleaning requirement (Taranaki Catchment Commission, 1981). Recently increased royalty payments for shingle and introduction of restrictions on extraction depths and the volume and sites of aggregate extracted has increased the cost of river shingle (Higgins, 1990). For example, the cost of Otaki river shingle increased from \$2 per cubic metre in 1988 to \$3 in 1989 (Winiata pers. comm., 1988).



Aggregate is extracted from rivers using scrapers, hydraulic excavators and dump trucks or draglines to be processed at mobile or static plants. Mobile plants are more desirable from Regional Councils' point of view, as they can extract from a variety of sites limiting localised over extraction which is associated with static plants (CALNIG, 1986). Mobile plants also give savings to the end user in reduced cartage and avoidance of double handling (Higgins, 1990).

*Natural supply of aggregate sourced from rivers*

River aggregate is a renewable resource, replaced naturally through erosion in catchment areas and subsequent water transport; Manawatu River beaches, for example, are estimated to be replenished every 8 to 10 years (Goodwin pers. comm., 1992). Brougham and McLennan (1985) estimated gravel supply to the mid-Manawatu River at 25,000 to 153,000 m<sup>3</sup> per year, based on research relating bed loads to suspended sediment loads. Sustainable extraction rates are difficult to estimate, however, as aggregate supply varies from year to year. Little is known about the sediment transport rates and rate of sediment supply to rivers with aggregate thought to be supplied to the Otaki river in only catastrophic events (Brougham, 1976a; 1976b) such as cyclones, earthquakes and dramatic climate change. The natural rate at which aggregate is supplied to the Otaki river has been estimated at 0 to 100,000 m<sup>3</sup>/annum between 1978 and 1986, averaging 75,000 m<sup>3</sup>/annum (O'Conner, 1975). Direct observation of bed aggradation and degradation and estimates of material shifted in 'freshes' through river bed transect measurement is used as an indicator of potential reserves (Joll, 1980; Brougham and McLennan, 1985).

Tables 2.2 and 2.3 show that reserves of aggregate in the rivers are diminishing with over extraction occurring in most rivers in the south western North Island (Brougham, 1976b). Many rivers in the lower western North Island are severely depleted or under pressure, including the Manawatu, Oroua, Otaki and upper Wanganui rivers, although in many cases extraction continues (CALNIG, 1986). Brougham and McLennan (1985) recommended reduction in aggregate extraction from all rivers in the Manawatu Catchment Board scheme areas except the South East Ruahine Ranges. Table 2.3 shows 217,000 more m<sup>3</sup> of aggregate was extracted from rivers in the greater Manawatu region than is naturally supplied. The total demand for aggregate in the greater Manawatu region in 1990 was approximately 851,000 m<sup>3</sup>. If river-aggregate extraction rates were reduced to sustainable levels <sup>a maximum of</sup> 621,000 m<sup>3</sup> of aggregate, or 24% more of the total aggregate produced, would have be supplied from land or foreshore deposits in 1990. Catchment Board reports since 1976 have advocated the development of terrace deposits to supplement or replace river shingle resources, specifically on the Otaki, Lower Manawatu, Mangatainoka and Upper Wanganui rivers, the Taranaki ring plain and Northern Wellington areas (Brougham, 1976b; Brougham and McLennan, 1983; Brougham and McLennan, 1985; CALNIG, 1986). Aggregate extraction from aggrading rivers along the south east Ruahine Foothills was considered uneconomic due to long distances from large markets and long distances to processing plants due to the narrow nature of the deposits (CALNIG, 1986).

Table 2.3: Present and sustainable extraction rates of aggregate from rivers in the greater Manawatu region.

River System	Present Extraction Rate m <sup>3</sup> /year	Sustainable Extraction Rate m <sup>3</sup> /year
South East Ruahine streams and gravel reserves	7,000*	40,000*
East Manawatu above Oringi	25,000*	15,000*
Upper Manawatu, Oringi and Lower Mangahao rivers	30,000*	10,000*
Oroua river	25,000*	10,000*
Pohangina river	12,000*	11,000*
Lower Manawatu river	150-200,000*	40,000*#
Otaki river	140-150,000* 200,000 1974-5 ~	Nil* 50-75,000 once recovered+
Ohau river	27,000*	19,000*
Mangatainoka river	31,000* ^	10,000*
TOTAL	447,000 (minimum)	230,000 (maximum)

#### KEY TO TABLE

- \* Brougham and McLennan, 1985; CALNIC, 1986
- # confirmed Manawatu-Wanganui Regional Council pers. comm., 1992
- ^ Brougham and McLennan, 1983, extraction from 1978-82
- ~ Brougham, 1976a
- + O'Conner, 1975

#### 2.5.2 Alluvial terraces

Major land based sites require close, relatively stable markets to compete with more cheaply won river aggregate which may also be of higher quality and more cheaply processed. Operations in alluvial gravel deposits may be longer term and much larger than those in river deposits, since the former usually have much larger reserves. The process of obtaining planning consents may also promote the development of larger operations because of the cost and time required to gain a consent. Extraction usually involves removing overburden material to a depth where aggregate becomes a thick, continuous deposit using motor scrapers, bulldozers or hydraulic excavators and dump trucks (Macleod and Rouse, 1991; Happy, 1992). Hydraulic excavators can excavate 2 to 3 metres below the water table while draglines may be used to excavate deeper aggregate (Taranaki Catchment Commission, 1981). Alluvial terrace aggregate extraction generally affects agricultural land (McRae, 1982a) or frequently flooded 'waste' land.

### *Quality of aggregate sourced from terraces*

Physical and chemical characteristics of gravels are dependant on the age of the deposit (Nasser, 1987). In the greater Manawatu region the Los Angeles Abrasion test on terrace gravels is poorer than on fresh river gravels and shows a direct relationship with terrace age (Grant-Taylor and Watters, 1976). Shingle from river terraces, being older than river aggregate, has been exposed to more weathering (Reed and Grant-Taylor, 1966). Weathering alters gravels, reducing durability while breaking down minerals to clay (Nasser, 1987). In significant quantities clay reduces the cement-aggregate bond effectiveness in concrete and increases the water content required to produce workable concrete, decreasing its strength. Weathering also reduces the coherence of rock particles, making them softer and concrete strength is affected if the aggregate is weaker than the cement (Grant-Taylor and Watters, 1976). The intensity and distribution of iron staining of iron-containing aggregates is an indication of the degree of weathering of the aggregate as weathering usually mobilises iron (Grant-Taylor and Watters, 1976). In the greater Manawatu region young, high quality gravels are found on the floodplains and lower terraces and are suitable for concrete aggregate and topcourse road material. Older greywacke gravels on progressively higher terraces generally have greater iron staining with very old and weathered aggregates limited to local use as roading or subgrade material (Nasser, 1987).

In most areas all terraces are formed of fine grained quartzofeldspathic material, however in some areas of Taranaki and Wanganui the parent material of terraces may vary. For example, in Taranaki high quality, hard aggregates are related to lava flow fragments preserved in lahar deposits originating from Mount Egmont. Similarly, along the Whangehu River some terraces are formed from mudstone alluvium and others are formed from laharcic material sourced from Mount Ruapehu (Palmer pers. comm., 1992).

### *Landscape evolution and physiography in the greater Manawatu region*

The major landforms and soils of the greater Manawatu region are derived from greywackes and the products of their erosion. Greywackes were formed from the accumulation of eroded sediments in a major offshore depositional area (Kemp, 1986). Over time these predominantly sandy and silty sediments were buried deeply to where great pressures and temperatures consolidated them into greywacke (Marden, 1984). About 3 million years ago the greywackes were folded, fractured and lifted into large fault blocks to form the Ruahine and Tararua axial ranges (King, 1982a; 1982b). Abutting and in some places draped across or preserved as inliers within the ranges from south Taranaki to Paekakariki are poorly consolidated marine sediments that formed part of the sea floor up to about 500,000 years Before Present (BP) (Stevens, 1990). These Wanganui basin marine sediments have been largely covered from the east by alluvially-transported materials eroded from the ranges during Pleistocene and Holocene times, and

covered from the west by a belt of dune sands deposited in several phases since the maximum of the last glaciation.



Photograph 2.1: Tokomaru marine terrace (LHS skyline) and Ohakea aggradational terraces (LHS and RHS) flanking the Tiritea River. The Tararua Ranges form the skyline and in the centre Holocene degradational terraces occupy the foreground.

The climate of the Pleistocene period has dominated the shaping of landforms in the greater Manawatu region (Fair, 1968 *cited by* Lieffering, 1990). Throughout the Pleistocene period the world experienced an alternating sequence of glacial (cool) and interglacial (warm) periods which differed in mean annual temperature by 4 to 5 degrees Celsius (McGlone, 1988; Pillans, 1991) with intervening stadial and interstadial periods of lesser intensity. During glaciations cold temperatures depressed the snow and vegetation lines in the Tararua and Ruahine ranges exposing increased areas of soil and rocks to frost action (Molloy, 1988; Stevens, 1990). Throughout the North Island these factors resulted in widespread instability of areas above 500 m altitude during the last glacial maximum.

Rocks shattered by frost action were transported down to rivers. Rivers, unable to transport the massive amount of debris, aggraded to form wide braided river beds and poorly sorted outwash fan deposits (Brougham *et al.*, 1985). These unconsolidated alluvial gravels form the foundations of the terrace remnants that once occupied the entire width of valley floors and are now found along the sides of large rivers throughout the region (Photograph 2.1). Silt sized particles from the broad gravel plains, derived from eroded soil material and rock erosion, were blown by the predominantly north westerly winds and deposited on higher surfaces at the time of sediment aggradation (Cowie, 1964; Stevens, 1990). Cowie (1964) found that loess deposits were thicker and coarser on the downwind, south-east, side of all the major rivers in the Wanganui basin. The higher surfaces

with moderate to deep accumulations of loess are defined as high terraces. This definition excludes the lower intermediate terraces which can have shallow loess deposits up to 1m deep.

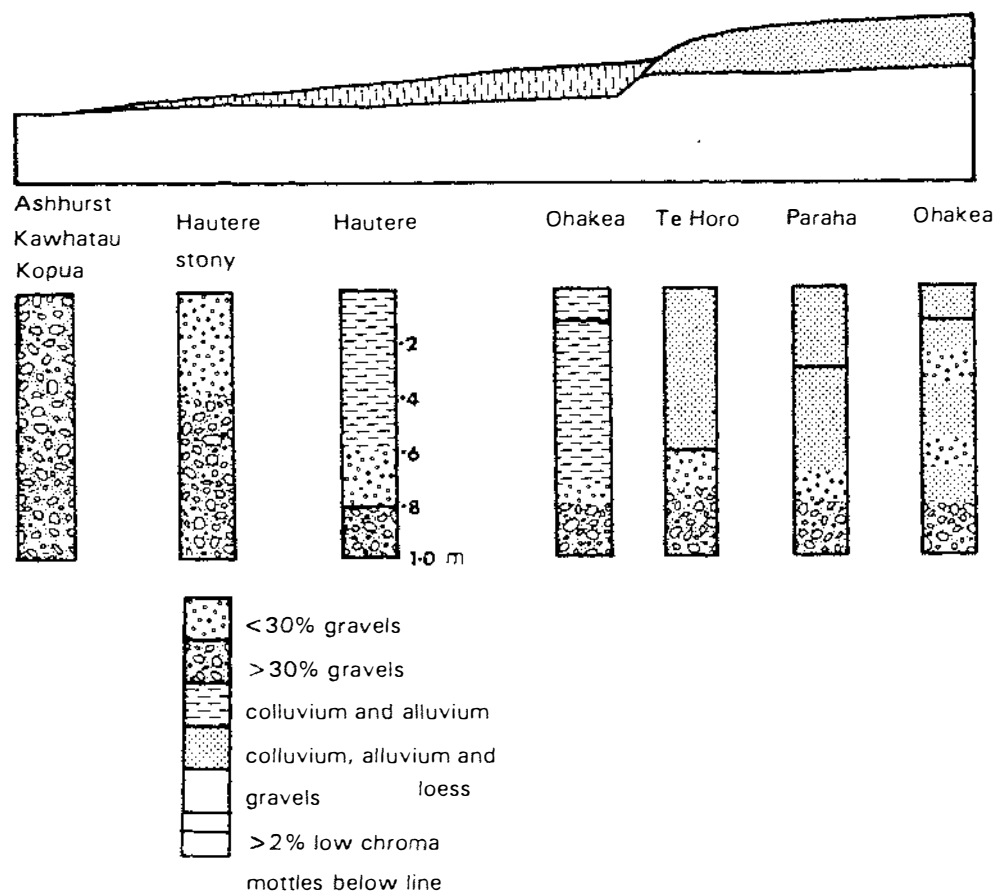


Figure 2.3: Diagrammatic cross section showing soil profiles and the relationship between soils, parent materials and topography on the youngest aggradational (Ohakea) terrace (adapted from Pollok and McLaughlin, 1986).

The Ohakean terrace is the lowest, therefore the youngest, aggradational terrace in the greater Manawatu region. It comprises gravels deposited at the end of the last (Otiran) glaciation 25,000 to 13,000 years BP. Extensive remnants of Ohakean-aged terraces are found around Linton, Palmerston North and Ashhurst towns (formed by the Manawatu River), Ohakea air base (formed by the Rangitikei River) and Hautere plains (formed by the Otaki River). The Ohakean terrace has age equivalents in Wanganui, Hawkes Bay, Wairarapa, Nelson, Marlborough, Canterbury, Westland, Otago and Southland regions of New Zealand.

Greywacke gravels and stones of the Ohakea or intermediate terrace are covered in places with a thin veneer of loess, alluvium or colluvium. Colluvial material, eroded from higher terraces, and

perhaps loess characteristically form a fine textured wedge which is thickest towards the back of the Ohakea terrace and thins out gradually towards the terrace lip. A sequence of soils is defined on the terrace depending on the depth of soil to gravels and development of gley features (Figure 2.3). Poorly drained Ohakea soils and imperfectly drained Paraha soils develop from thick colluvial and fine grained alluvial deposits. Moderately well drained Te Horo and well drained Hautere soils develop in thinner colluvial or fine grained alluvial deposits. Te Horo and Hautere soils grade to free draining Ashhurst, Kawahatau or Kopua soils where loess and colluvium are absent and stones near the soil surface. These stony soils are differentiated according to their degree of soil leaching (Table 2.4), with Ashhurst soils located in drier coastal areas and Kopua soils in higher rainfall inland areas (Rijske, 1977). Alluvial silt and clay are deposited locally by shallow streams across the top of the terrace, complicating this soil pattern.

Table 2.4: The relationship between soil series and mean annual rainfall on Ohakea and high terraces in the Pohangina district (Rijske, 1977).

Mean Annual Rainfall (mm)	Ohakea Terrace soil series	Dominant High Terrace soil series
1020 - 1140	Ashhurst	Marton and Milson
1140 - 1400	Kawahatau	Kiwitea
1270 - 1780	Kopua	Dannevirke

Two older terraces formed from predominantly greywacke alluvial gravels are found in extensive areas of the greater Manawatu region. The Ratan Terrace was formed during a stadial 45,000 to 30,000 years BP and was covered with loess during the Ohakean stadial period. Accumulation of Ohakean loess occurred in many areas of the North Island from 28,000 to 12,000 years BP (Pillans *et al.* in press). The Porewan terrace was formed during the stadial that stretched from 75,000 to 65,000 years BP (Milne, 1973) and is covered with loess from both Ohakean and Ratan stadial aggradational surfaces.

A fourth 130,000 to 120,000 year old terrace cut into marine sediments is mantled by three loess units, in total up to 6 metres deep (Cowie, 1974) which were derived from the Ohakean, Ratan and Porewana stadial periods. This marine bench formed during the Last Interglacial when higher sea levels cut into the land. <sup>Along</sup> with younger terraces this has been preserved by tectonic uplift. In the vicinity of Massey University this marine bench is called the Tokomaru terrace and is characterised by undulating interfluvial and deeply dissected valleys with underlying mudstone and gravel surfaces sometimes exposed (Figure 2.4).

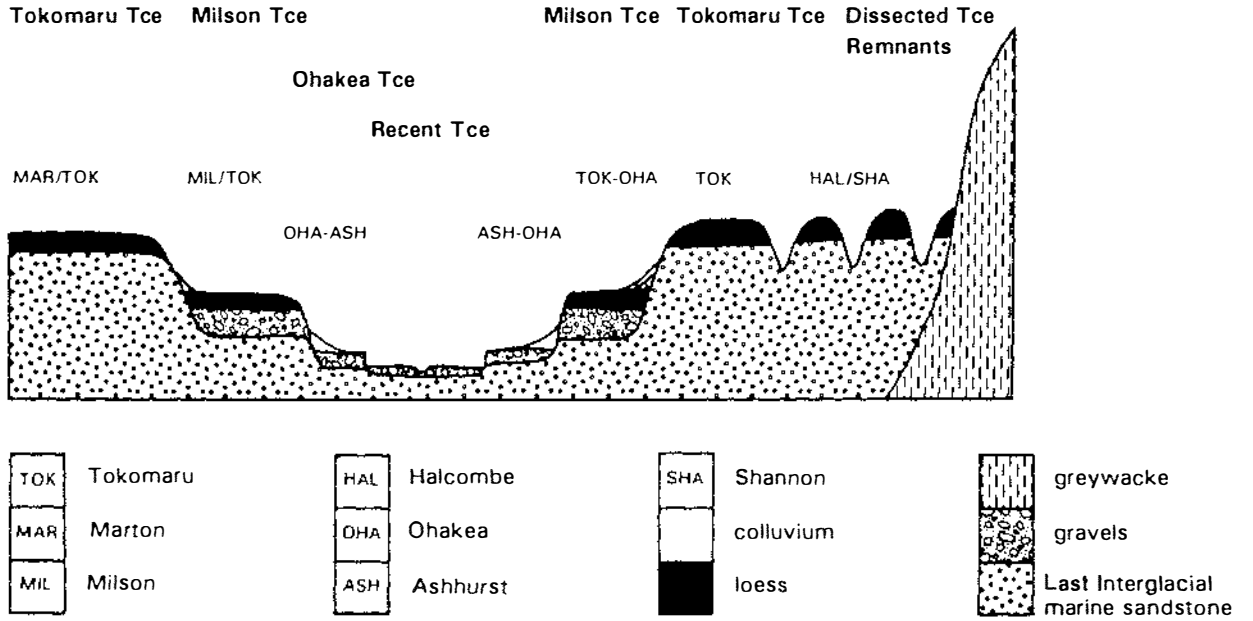


Figure 2.4: Diagrammatic cross section showing the relationship between soil series, topography and parent materials in the greater Manawatu region (Cowie *et al.*, 1967; Rijske, 1977; Cowie, 1978; Molloy, 1988).

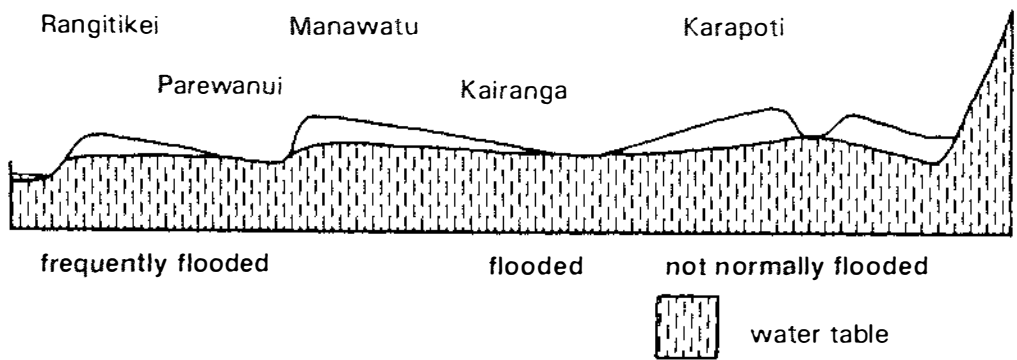


Figure 2.5: Diagrammatic cross section showing the relationship between soil series, topography and depth to water table on Holocene river terraces (Cowie *et al.*, 1967; Rijske, 1977; Cowie, 1978; Molloy, 1988).

All soils on these three high terraces have developed in Ohakean loess, which buried older loess units. Differences between soils on these terraces are primarily related to the fineness of their constituent loess and rainfall regime under which the soils developed. Pronounced summer moisture deficits with annual wetting and drying cycles has resulted in the development of Tokomaru, Milson and Marton soils (see Table 2.4). Tokomaru soils occur in coarse silt and fine sand loessial deposits immediately downwind of major rivers, while Milson and Marton soils developed in thinner, finer loess deposits away from the margins of the major rivers. Tokomaru, Milson and Marton soils display gleying and mottling which are indicative of impeded drainage. Dannevirke and Kiwitea soils generally evolved in inland, higher rainfall areas which did not experience significant summer soil water deficits and may have received additions of tephra. Despite these features the five soils may occur as a complex (Palmer pers. comm., 1992). The Dannevirke and Kiwitea soils resemble the Levin and Shannon soils respectively which are found in the Horowhenua district and also occur as a complex, are well drained to imperfectly drained and developed under low summer water deficits (Molloy, 1988).

During the warmer climates of Interstadial and Interglacial periods the vegetation line in the ranges lifted. This resulted in decreased erosion and sediment loads in the rivers which consequently cut down into the gravel plains (Pollok and McLaughlin, 1986; Molloy, 1988) forming the scarps of the high terraces. Tectonic uplift has helped form and preserve these terraces (Brougham *et al.*, 1985). Present day (Holocene) floodplains are degradational terraces, formed over the last 10,000 years from fluvial reworking of alluvium. Cowie *et al.* (1967) divided Holocene terraces in the greater Manawatu region into distinct zones according to their rate of alluvial accumulation (Figure 2.5). Rapidly accumulating soils which flood regularly are located adjacent to rivers. Slowly accumulating soils comprise a slightly higher terrace further away from rivers while non-accumulating soils which no longer flood form the highest of the recent river terraces. Each terrace comprises a well drained, coarse textured levee closest to the river which grades into lower lying poorly drained gley and peat swamps further away from the river (Figure 2.5). Since completion of the lower Manawatu flood control scheme in 1963 most alluvial flats outside stop banks on the Manawatu and Oroua rivers are considered to be flood free (Cowie and Rijske, 1977) as are parts of the Otaki and Rangitikei rivers.

#### *Suitability of soils for aggregate extraction in the Greater Manawatu region.*

The suitability of an aggregate deposit for extraction is determined by the qualities of the deposit and the overburden depth, all other things being equal. The age and history of terraces in the greater Manawatu region provide a general indication of the geology, depth and extent of aggregates within them and therefore an indication of their suitability for aggregate extraction. Soil types indicate probable overburden depths and properties.



The New Zealand Land Resource Inventory provides information on both soils and rock types. Land Resource Inventory work-sheets group similar landscape units in terms of rock type, soil type, slope, erosion type and degree, vegetation type and major limitation to agricultural production at a scale of 1:63,360 (1 inch to 1 mile) or 1:50,000 for new surveys. Potential aggregate resources may be identified as soil parent material rock types or as shallow phases of soil series where aggregates occur near the land surface. Land Resource Inventory work-sheets may identify stony or shallow soils as having a soil limitation due to a low water holding ability. Extended legends or soil bulletins associated with soil surveys usually describe soil parent materials and soil profiles to depths of 0.5 to 5 metres. Each major gravel containing surface in the Manawatu, Rangitikei and Horowhenua areas is overlain by characteristic soil series. Neither soil surveys nor Resource Inventory work-sheets, however, usually indicate aggregate quality or total depth of aggregate, due to their focus on soil properties.

Table 2.5: Summary of suitability of soil series for extraction of aggregate and main characteristics of the underlying aggregate deposits in the greater Manawatu region.

Group	Terrace	Soil series	Deposit Characteristics
1	Holocene	Rangitikei, Tarata, some Manawatu, Kairanga, Te Arakura and Karapoti	unweathered shingle
2	Pleistocene	Ohakea, Ashhurst, Kawhatau, Hautere, Paraha, Koputaroa, Crofton, Kopua, Raumati.	weakly weathered aggregate, overburden depth <2 m
3	Holocene	Some Manawatu and Karapoti, most Kairanga, Parewanui and Te Arakura	unweathered aggregate, overburden >2 m, water table <1 m.
4	High River	Milson, Marton, Kiwitea, Table Flat	moderately to highly weathered aggregate in continuous deposits, overburden >2 m
5	High River and Marine	Tokomaru, Halcombe, Levin, Shannon Raumai, Oroua, Opawe, Pohangina, Makiekie.	moderately to highly weathered aggregate in discontinuous beds or lenses, overburden >2 m

I have categorised terraces in the greater Manawatu region into 5 groups, depending on their suitability for aggregate extraction (summarised in Table 2.5). Within each terrace type soils have been differentiated according to the suitability of the underlying aggregate deposit for extraction by compiling information from soil surveys in the area (Tables 2.9, 2.7 and 2.8). Important qualities of an aggregate deposit, whether river or land based, include the degree of weathering, percentage of fine material and deposit continuity, thickness and variability. The degree of weathering has been categorised broadly as low for Holocene deposits, i.e. those underlying the low river terraces, medium for aggregates comprising the Ohakean terrace, and high for aggregates on higher, older terraces. Continuous, even aggregate deposits are more valuable than deposits that exist as discontinuous lenses. Depth is the most important character of overburden. This is sometimes expressed as an overburden to resource ratio. Favourable aggregate deposits have been designated as those with less than 2 m of overburden, although resources with deeper overburden become economic where they are sited closer to a market (Gribble, 1989). Similarly a water table depth of less than 1 m has been chosen to distinguish between high and low value resources. Additionally, 1 m was chosen as most soil descriptions indicate if a water table features above 1 m in a soil profile. Suitability groups do not take into account the accessibility of deposits to major transport routes, likelihood of flooding, ease of reclamation or restrictions placed on operations by district or regional councils. Soils overlying sandy deposits, which may also be mined, have not been included. The quality of resource assumes high quality aggregate is preferred over low quality aggregate because it is the most versatile resource. In specific circumstances Group 2 or Group 3 aggregates may be the most desirable resource, for example where fill is required.

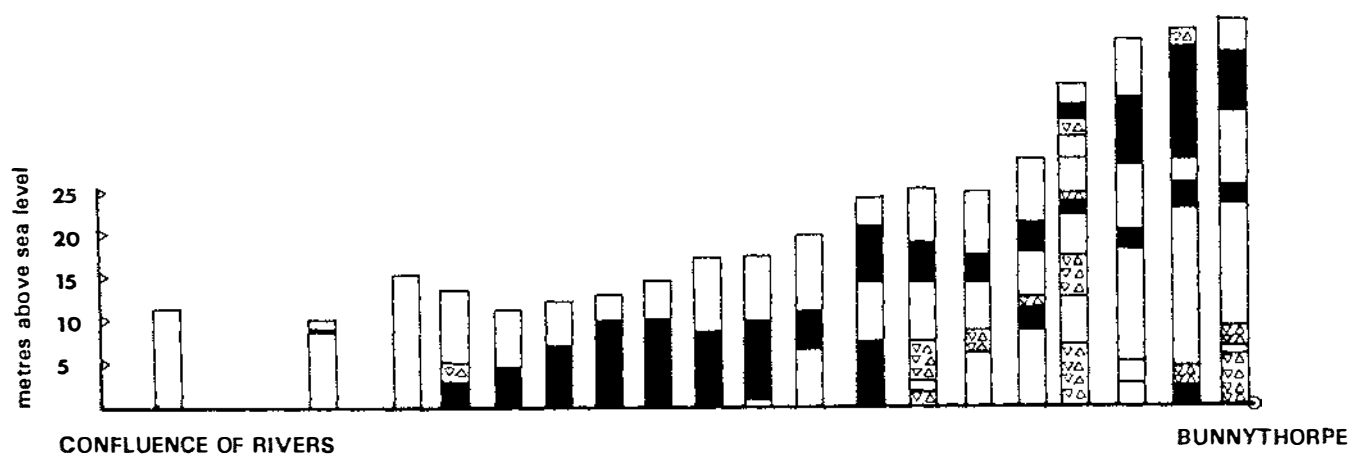


Figure 2.6: Cross section of alluvial deposits from Bunnythorpe to the confluence of the Manawatu and Oroua Rivers, based on bore logs showing gravel ( $\Delta$ ) and sand ( $\blacksquare$ ) deposits (after Lieferring, 1990).

Table 2.7: Suitability of soil types on recent river terraces in the greater Manawatu region for extraction of aggregate. The key to the table is on page 29.

<b>Recent River Terraces</b>		
<b>Soil Type or Series</b>	<b>Suitability Group for Extraction</b>	<b>Depth to Gravels</b>
Rangitikei loamy sand	1 * + ~ ^ #	50-120cm#, 24cm variable+, 40cm*
loamy sand, gravelly phase	1 *	unspecified
sandy loam	1 * \$ ^ # + ~	75cm+, 8cm ~, 76cm# grey sand
fine sandy loam	1 ~ # ^	60cm gravels or fine sands#
fine sandy loam, shallow phase	1 +	less than 45 cm#, less than 30cm+
mottled fine sandy loam	1 ^ #	1.6 m
Parewanui sandy loam, loamy sand	3 ~	
fine sandy loam	3 ~ #	
silt loam	3 ^ # ~	
heavy silt loam	3 # ~	
Manawatu sandy loam	1 * ~ # + ^	60-90cm#, less than 3m variable+
fine sandy loam	3 ! \$ * ~ ^ #	less than 3m
silt loam	3 ~ ^ # +	gravel lenses 115-285cm+, gravels less than 3m+, 60cm (Linton)#,
fine sandy loam and sandy loam, gravelly phase	1 + #	less than 1m +
mottled fine sandy loam	1/3	less than 3m+
mottled silt loam	3 ^ # +	greater than 3m+

Table 2.7 (continued)

Recent River Terraces		
Soil Type or Series	Suitability Class for Extraction	Depth to Gravels
Kairanga fine sandy loam	3 ^ # + ~ !	greater than 6 m+
sandy loam	3 * ^	unspecified
silt loam	3 +	2-8m+
silt loam, gravelly subsurface variant	1 +	1.2-2m +
Karapoti black sandy loam and black silt loam	3 ~ # ^ +	greater than 3m+
silt loam, gravelly subsurface variant	1	1.2 to 2.1 m
brown sandy loam	3 \$ # +	2 to 5 m +
brown sandy loam, gravelly phase	1 # +	less than 30 cm#
Tarata sandy loam	1 \$	24cm\$, greywacke with minor volcanic alluvium
Te Arakura silt loam	3 # + ~ \$	variable depth 1-2m+
sandy loam	1 # + ~	less than 1m, variable+
sandy loam, shallow phase	#	less than 45cm#
fine sandy loam	3 # +	less than 3.75m, variable+

Group One comprises the Holocene terrace levees and adjacent slopes that have slight or no limitations to extraction (Figure 2.4). Soils in this group includes the *Addington* series, found on stony beach ridges near Otaki but mainly comprises the river beaches of all rivers sourced from the Tararua and Ruahine ranges and shallow recent alluvial soils where the water table is deeper than 1 metre (Table 2.7). Shingle deposits underlying recent alluvial soils in the vicinity of Palmerston North comprise unweathered, weakly-packed gravels and stones. In Holocene times many rivers have had a complex history of lateral and vertical movement creating complex deposits (Brougham *et al.*, 1985; Lieffering, 1990) (Figure 2.6). Consequently gravels may lie within a matrix of sand or beds of gravels may contain sand lenses or bands of silt (Cowie, 1974).

Table 2.8: Suitability of soil series on intermediate terraces in the greater Manawatu region for extraction of aggregate. The key is given on page 29.

Intermediate Terrace		
Soil Type or Series	Suitability Group for Extraction	Depth to Gravels
Ohakea series	2 ~*#+\$&	90 to 150cm variable ~, 90-120cm#, 60-90cm#, 33cm ^, 120-180cm*, 100cm+.
Ashhurst series	2 *#\$+	13(65)cm*, 80cm#\$, 120-150cm*, less than 1m+
shallow phase	2 \$#+*	0-23cm\$, 15(60)cm#, (80)cm+, 15cm*,
Kawhatau series	2 \$#	120cm\$, 80cm#
shallow phase	2 *\$	10-20(40)cm*, 0(60)cm\$
Kopua series	2 *	0-90cm*
Hautere series	2	60-90 cm
Paraha series	2	60-90cm
Raumati series	2 *	locally below 60cm*
Koputaroa series	2	50 cm minimum depth, may overlie beach sand
Crofton series	2 \$	70 cm

Depth to unaltered gravels is in brackets and depth to many gravels not bracketed.

Group Two comprises the Ohakean aggradational terrace and its soils which are generally characterised by slight or no limitations to extraction (Figure 2.8). Medium quality, Pleistocene-aged greywacke gravel deposits are characteristically thick, 2 to 15 metres deep and unweathered (Cowie *et al.*, 1967; Cowie, 1974; Lieffering, 1990), although some iron staining occurs in surface gravels of wetter soils. Gravels are either weakly cemented (Cowie, 1974) or packed (Palmer pers. comm., 1992), with lenses of sands. The Putiki, Rotoaira<sup>and</sup> Otamatea soils found along the Rangitikei river have developed from pumiceous alluvium and have limited use as aggregates, so have been excluded from the survey.

Group Three comprises back swamps<sup>s</sup> and lower areas of the Holocene terrace (Table 2.7). Group Three is characterised by high quality, Holocene gravels with moderate limitations to extraction comprising an overburden depth greater than 2 metres and/or a water table less than 1 metre from the soil surface. The nature of Group One and Group Three shingle deposits is similar, although Group Three gravels may occur in thinner beds with more interbedded sand and silt.

Group Four comprises High river terraces and associated soils which usually overly medium to low quality, 30,000 to 75,000 year old (Upper Pleistocene) greywacke gravel deposits of alluvial origin (Table 2.9). Deposits are often extensive and continuous gravels with alluvial sands and silts (Rijske, 1977). Extraction is moderately limited by one or more loess units and some volcanic ash together comprising greater than 2 metres of overburden.

#### KEY TO TABLES 2.7, 2.8 and 2.9

*	Rijkse, 1977.	^	Cowie <i>et al.</i> , 1967.
#	Cowie, 1978.	+	Cowie, 1974.
\$	Campbell, 1979.	~	Cowie and Rijske, 1976; 1977.
!	Cowie and Smith, 1958.	&	Pollok and McLaughlin, 1986.

Table 2.9: Suitability of soil series on high terraces in the greater Manawatu region for extraction of aggregate. The key to the table is on page 29.

High terraces		
Soil Type or Soil Series	Suitability Group for Extraction	Depth to Gravels
Tokomaru series	5 ~ +	sand underlain by gravel at 6m+, local lenses of gravel within surface 4-5.5 m ~
Halcombe series	5 *\$ ~ + &	underlain by bands of iron stained gravels and weakly consolidated sands+, greywacke gravels*, cemented greywacke gravels &
Milson series	4 ~ + #	Iron stained gravels within 270cm#, iron stained weakly cemented gravels with some sands @3m+., 251 cm iron stained stones & gravels with sandy lenses
Marton series	4 \$ ~ + #	firm sands and gravels deeper than 8.5m+, sandstone 300-700cm below surface#, 485 cm iron stained stones and gravels. Nature & depth to gravels fairly constant. marine beach sands and gravels near Wanganui.
Levin series	5	loess over marine sands (with rare gravels)
Shannon series	5 &	loess over marine sands (with rare gravels)
Kiwitea	4 *	greywacke gravels 180-200cm depth*

NOTE: On some soil maps Levin, Shannon and Kopua soils on marine terraces are mapped as Kiwitea soils.

Group Five comprises high river and marine bench terraces and their soils (see Table 2.10). Group Five is characterised by low quality shingle of marine origin occurring as discontinuous gravel lenses or cemented gravel and pumice bands within loose marine sands and sandstone (Rijske, 1977). South of the Rangitikei River these are approximately 130,000 year old. North of the Rangitikei River marine gravels 60,000 to 680,000 years old and are likely to be andesitic and of lower quality. A moderate limitation is an overburden depth of greater than 2 metres. Group Five soils usually occur in flat and rolling phases.

Terrace dissection exposes gravels so rolling phases may form in a mixture of gravels, loess and sandstone. Gravels underlying Group Two, Four and Five soils, found on intermediate and high terraces may display variable weathering, therefore aggregate quality should be determined before extraction.

The above groups are illustrated in Appendices 2.1 and 2.2 which <sup>map</sup> potential aggregate deposits in the Lower Rangitikei, Upper Manawatu and Oroua Rivers, based on soil maps of the areas and information from Tables 2.7, 2.8 and 2.9.

In Taranaki, Horowhenua, and Manawatu terrace extraction has occurred as high quality, low cost river resources have been exhausted or degraded. Pressures from increased population have increased demand for aggregates while also requiring maintenance of river channels and beaches (Rowe, 1980). In Taranaki, Otaki and Manawatu terrace extraction has occurred as high quality, low cost river resources have been exhausted or degraded. Aggregate is currently, or has in the past, been commercially extracted from low and intermediate river terraces of the Otaki, Manawatu and Rangitikei Rivers. Old gravel pits used for road construction dot the length of the Karapoti ridges lying between the Manawatu and Oroua Rivers (Cowie, 1978). Recent Oroua and Manawatu River terraces are being mined, with the greatest number of active sites adjacent to the upper Manawatu river supplying the Palmerston North aggregate market. Railway ballast has been produced from intermediate terraces of the Otaki and Rangitikei rivers. Extraction for non commercial farm requirements occurs on most terraces containing gravels. Marine and alluvial gravels exposed on the sides of rolling high terrace lands and intermediate terrace scarps respectively, are commonly used for maintenance of farm roads.

### 2.5.3 Hard rock quarries

Hard rock quarries are generally found where other sources, such as river and terrace shingle, are unavailable (e.g. Wellington) or the quality of material from alternate sources is substandard (Joll, 1980). Thus quarry-sourced aggregate does not usually compete in the same market as alluvially sourced products (Robertson pers. comm., 1992). Hard rock quarries are restricted to resources where unweathered greywacke, free from large amounts of deleterious secondary minerals such as calcite, zeolite and chlorite, are near to the land surface. Naturally fractured rock is preferred. In Wellington Mesozoic greywacke and argillite bands are quarried (Reed and

Grant-Taylor, 1966; Rowe, 1980; King, 1982) using hydraulic excavators to selectively remove greywacke for processing (Happy, 1992). The Kohinui, Gorge and Tokomaru quarries operated by the Wanganui-Manawatu Regional Council produce large rocks and boulders for river protection works. Other hard rock quarries in the greater Manawatu region generally produce low quality aggregate for fill and road basecourse construction.

Quarried rock has sharp angles which make it less suitable for concrete pumping, unless it is highly processed (NWASCA, 1987) or the proportions of sand and cement in the wet concrete mix are increased (Nasser, 1987) (see Section 2.3.4). Quarried rock in the lower half of the North Island is generally unsuitable for ballast manufacture (CANNING 1986). The sharp angles and paucity of polished faces of quarried gravel, however, does make it suitable for sealing chip and asphaltic concrete (Nasser, 1987) where high quality resources are mined (Reed and Grant-Taylor, 1966).

#### 2.5.4 Foreshore deposits

Foreshore aggregate resources, like river deposits, are readily accessible with low extraction and processing costs and have been a convenient source of aggregate in the past. In 1980 the non renewable resources in shingle fans and raised beach ridges comprised the highest volume of cheap, high quality rock products in the Wellington region (Joll, 1980). One innovative aggregate producer placed freshly won aggregate from a cliff face on a small beach, later retrieving crudely wave-sorted and cleaned aggregate (Joll, 1980; Rowe, 1980).

Beach and dune sands are used widely for drainage and construction site preparation. East Coast North Island sands are used in concrete blends but the fineness, high density and dark colour of West Coast sands precludes them from use for concrete blends (Happy, 1992). West Coast sands have an increasing andesitic component from Wellington to Taranaki while East Coast sands are derived from Tertiary quartzo-feldspathic mudstones and siltstones.

Hard rock coastal quarries operate in Canada, United States and United Kingdom. Large, high quality deposits of aggregate in excess of 150 million tonnes are required to support the infrastructure associated with barge transport in these countries (Gribble, 1989). In Canada two high volume quarries are located on the Atlantic seaboard and a third has been proposed in Nova Scotia which is forecasted to produce up to 5.4 million tonnes each year for construction markets on the East Coast of the United States. In Scotland, Glensandra quarry produces about 5 million tonnes of aggregate each year (Tidmarsh, 1991).



### 2.5.5 Other sources of aggregate

In New Zealand there is no significant production of off-shore or marine gravel deposits (Joll, 1980; Happy, 1992) although large deposits of boulders, cobbles and pebbles were reported by Matthews (1977) during investigation of the Maui gas field offshore from Taranaki (*cited by* Joll, 1980). Harbour sands are suction dredged near Auckland for use in concrete manufacture (Happy, 1992) and silica sands are mined from Northland's Parengarenga Harbour for glass production (Fieldman, 1992).

In the United Kingdom manufactured aggregates are made from industrial wastes such as blast furnace slag, pulverised fuel ash, colliery spoil (Verney, 1976), or residue from burnt domestic waste (Anon, 1992a). In 1990 10% of United Kingdom aggregates were produced from waste and recycled materials such as demolished paving or concrete structures (Anon, 1991f). Aggregate recycling is well utilised in European countries lacking ready aggregate resources and is beginning to be used in United States (Zimmerman, 1991a), Canada (Nasser, 1987) and New Zealand.

Recycled and manufactured aggregates are generally low grade and used as crushed stone substitutes in road construction as low grade fill and subbase material (Anon, 1991g; Zimmerman, 1991a; Anon, 1992a). Recycled asphalt is blended with new asphalt (Zimmerman, 1991a). Recycling allows reduced haulage distances, so is particularly cost effective in large cities with depleted resources or resources that have been built-over making them unaccessible (Nasser, 1987; Zimmerman, 1991a). Studies by the National Cooperative Highway Research Programme indicate recycled aggregates have an increased freeze/thaw resistance compared to virgin stone (Zimmerman, 1991a).

## 2.6 Organisations of aggregate producers

Two formal organisations provide forums for aggregate producers. The Aggregates Association of New Zealand mainly represents companies and focuses on activities of common concern or interest while the Institute of Quarrying primarily focuses on education and training of individuals.

### 2.6.1 Aggregates Association of New Zealand (Inc.)

The Aggregates Association of New Zealand was established in 1969. The organisation is concerned with all aspects of aggregate extraction, processing, transport and use. The Aggregates Association provides member companies and private individuals the means of coordinating their efforts in areas of mutual interests and common concerns. Voluntary membership is open to all aggregate producers other than local authorities or government departments. Eighty full member companies produce about 60% of the aggregate produced in New Zealand (Strong pers. comm., 1991).

Activities of the Association can be grouped into the broad areas of research, education and lobbying with particular areas of responsibility specified in the Association 'Rules'. Research activities include carrying out or assisting statistics collection and market surveys. Past and present research topics include reviewing manufacturing techniques and processes, identifying existing and prospective aggregate user needs.

Education carried out by the Aggregates Association aims to encourage high standards of aggregate quality and use, promote safety and assist members with technical advice. The Association achieves these aims through the production and dissemination of information through the Association annual conference, 'Contractor' Magazine, newsletters, publications and industry training material. A technical committee looks after technical aspects of the industry, especially specifications put out by Transit New Zealand. The Aggregates Association encourages staff training by developing and maintaining relationships with educational authorities, particularly supporting the industry education programme through the Open Polytechnic.

The Aggregates Association acts as an industry lobbyist, advocating industry interests in industrial negotiations, with major aggregate users and before local and central Government on topics including the protection of aggregate resources from sterilisation and environmental requirements of extraction.

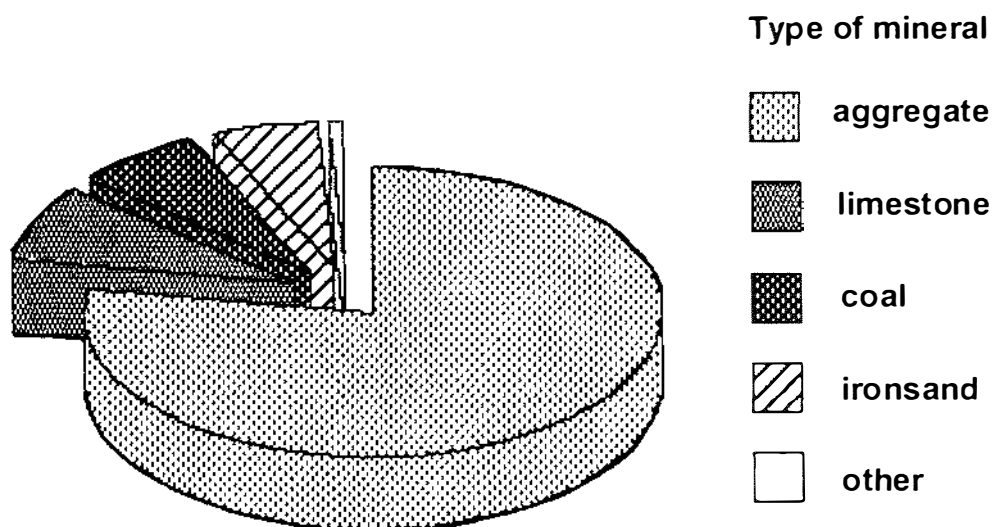
#### 2.6.2 Institute of Quarrying

The Institute of Quarrying is an international body for individuals in the quarrying and related extractive and processing industries. The Institute was founded in 1917 as The Quarry Manager's Association, becoming the Institute of Quarrying in 1927. World membership is approximately 5000 in 70 countries, with about 200 members in New Zealand.

The main aims of the Institute are the promotion of education and training within the industry. This is to encourage improvements in all aspects of quarry operation and business management. This aim is achieved through publication of a monthly *Quarry Management* journal, which covers technical developments and industry news from around the world and various meetings. An annual national conference comprises the major technical session of the year and is supplemented by monthly regional group meetings in the main centres which involve presentations and field trips. Technical qualifications can be gained through Auckland Polytechnic which offers papers in quarrying operations, engineering, safety and legislation, materials processing, management and administration.

## 2.7 Demand for aggregates in New Zealand

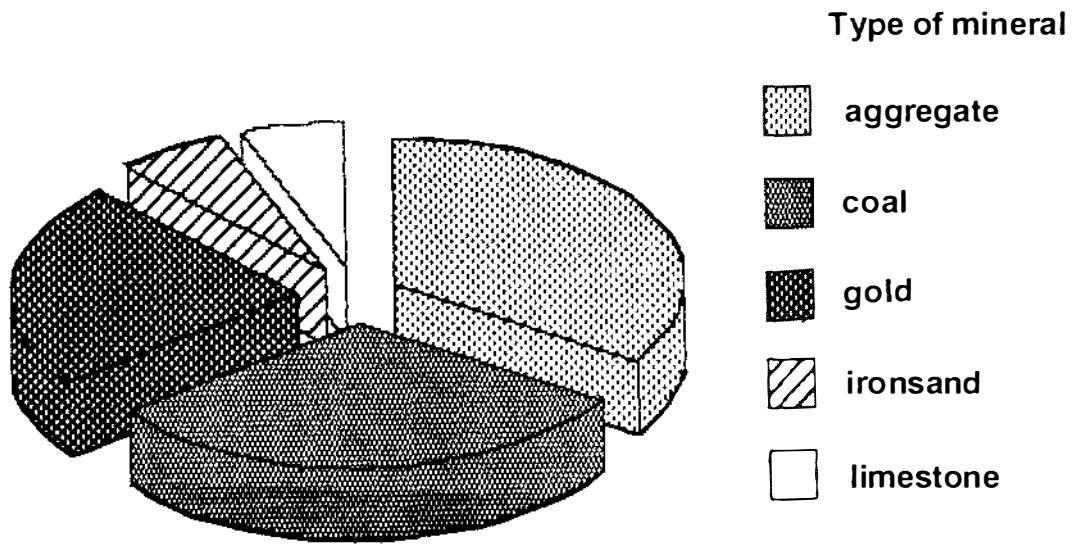
World production of sand, gravel and crushed stone was worth more than US \$25 billion in 1990 with twice as much sand, gravel and crushed stone produced by weight than any other minerals commodity in the world (Anon, 1992b). Sand, rock and gravel are also the dominant mineral extracted in New Zealand (Mackenzie and Cave, 1991)(Graph 2.1). Aggregate and coal have consistently been the two most important mined products in terms of monetary value and tonnes produced in New Zealand with aggregate production varying between 18 and 30 million tonnes over the last 20 years (Graphs 2.2 and 2.3). The importance of aggregate to the economy is greater than indicated in Graphs 2.1 and 2.2. The monetary value of aggregate does not include aggregate extracted privately, for example aggregate used on farms. Roading is the largest use for aggregates in New Zealand (Happy, 1992) with aggregate used in about 93,000 km of developed roads in New Zealand (Knight, 1992).



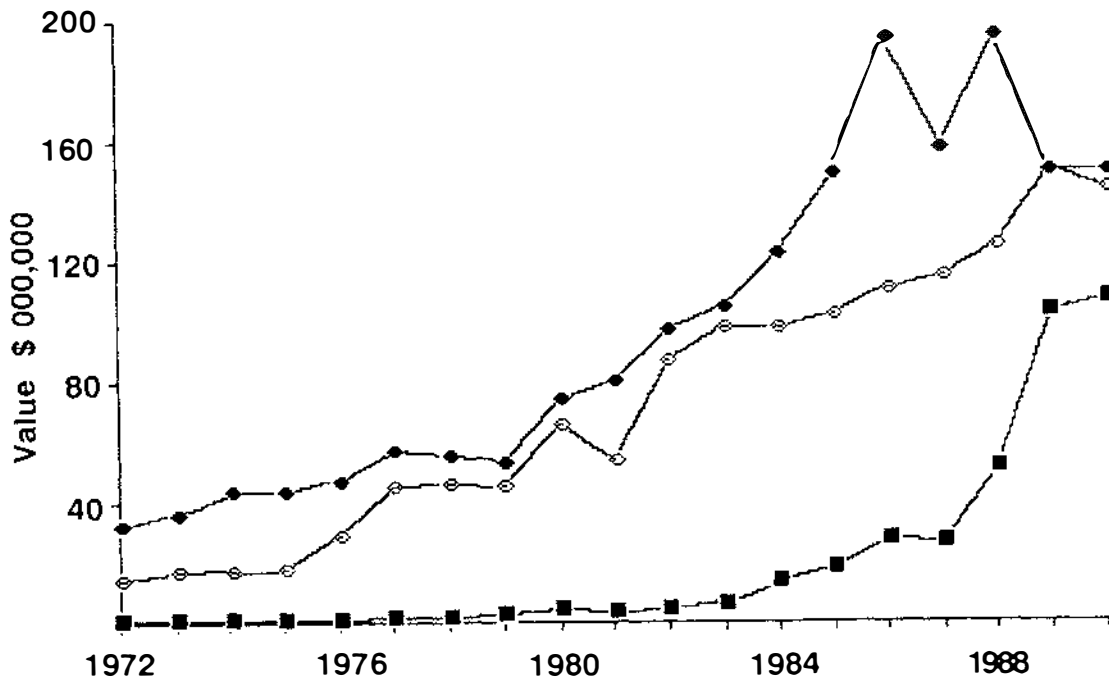
Graph 2.1: Tonnes of aggregate and minerals produced in New Zealand in 1990. NOTE: data for graphs in Section 2.7 is from *Annual returns of production from quarries and mineral production statistics*.

In 1992/93 official gold production will surpass the value of aggregates for the first time in recent history as the large Macraes Flat and Golden Cross gold mines join the Martha Hill gold mine in full production. In 1990 the Martha Hill and Macraes Flat mines produced 60% of total gold production in New Zealand (Mackenzie and Cave, 1991). The actual production of gold is, however, under-declared (Ministry of Energy, 1989).

Unlike coal and gold production, aggregate is produced in every region of New Zealand near most towns and all cities. Most regions are self sufficient in aggregate but Taranaki, Wanganui, Gisbourne and Auckland regions all import high quality aggregate. Additionally, unlike hard rock



Graph 2.2: Value (\$) of aggregate and minerals produced in New Zealand in 1990.



Graph 2.3: Value (\$) of coal (○), gold (■) and aggregate (●) produced in New Zealand from 1981 to 1990.

gold and opencast coal mining operations, aggregate mines are generally small in terms of area disturbed and depth of extraction. The visual and landscape impact of individual sites, however, can be highly significant as the majority of material mined is saleable aggregate or "topsoil" and extraction sites are often adjacent to major roads, urban centres, or rivers.

Much of the data for section 2.7 was derived from the publications: Mines Department, New Zealand, 1973; 1975; 1977; Ministry of Energy, Mines Division, 1979; 1981; 1983; 1985; Ministry of Energy, Resource Management and Mining Group, 1986; 1987; Ministry of Energy, Market Information and Analysis Operations Division, 1988; 1989; Mackenzie *et al.*, 1990; Mackenzie and Cave, 1991.

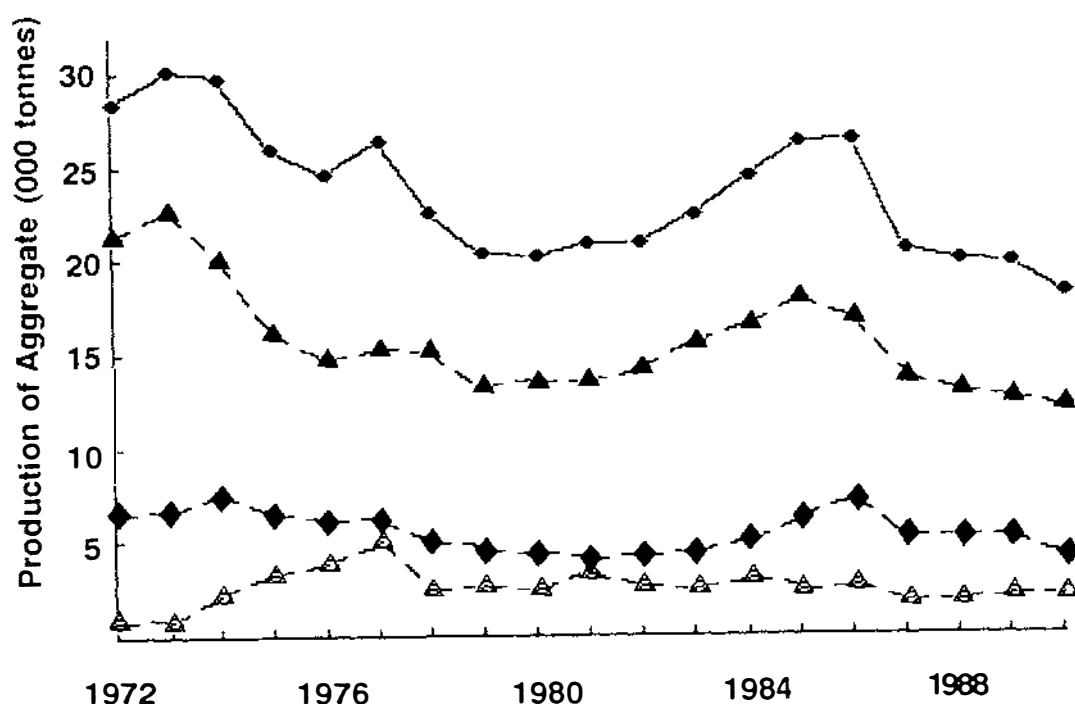
### 2.7.1 Aggregate extraction from 1900 to 1991

Before mechanisation aggregate extraction and processing sites were small and scattered. Sites were located close to individual markets because axle loadings were low and transport, by horse drawn drays, relatively slow. Early forms of recovery involved little more than selecting a site at which the desired coarseness or fineness of shingle was present (Craven, 1969 *cited by* Joll, 1980). Rivers and beaches were preferred aggregate sources as the material was naturally graded. Where economic, pits were dug on land or rock faces broken up.

The widespread use of motor vehicles since c.1920 increased the range and quantity of aggregate able to be supplied by individual producers. Motor vehicles required improved road surfaces, consequently aggregate quality became more important (Joll, 1980). In 1962 a report critical of the quality of aggregate produced by hard rock quarries in the Wellington region resulted in the modification or closure of many quarries (Grant-Taylor and Watters, 1976) and establishment of standards for durability, plasticity and grading of roads. Aggregate processing and quality monitoring methods at pits and quarries were also improved (Grant-Taylor and Watters, 1976).

Aggregate records have been kept since 1920, although categories of aggregate have changed over the years. From 1982 to 1986 basalt for industry was included in aggregate records and before 1974 limestone for roads was not included. Aggregate production mainly comprises aggregate for building, roads and ballast, harbour work, reclamation and filling. Dimension stone, clay for bricks, tiles and pottery, limestone for roads, pumice, sand for industry, silica sand and basalt for industry comprised, on average, 4% and 8% of total aggregate value in the 1970's and 1980's respectively. Brougham and McLennan (1985) compared aggregate production returns by aggregate producers to the Manawatu Catchment Board and Mines Department and concluded that all Manawatu extractors did not submit annual returns to the Mines Department. They also suspected that figures presented as tonnes may actually have related to cubic metres. Joll (1980) also proposed that not all producers in the lower half of the North Island submitted returns and considerable quantities had been extracted without authorisation or for farm feed pads and farm roading (Joll, 1980).

The demand for aggregate in New Zealand has reflected the cyclical nature of the construction industry and the state of the national economy, although the demand for aggregate often lags



Graph 2.4: Aggregate production in New Zealand between 1972 and 1990 for fill and reclamation (  $\Delta$  ), building construction (  $\blacklozenge$  ), road and rail (  $\blacktriangle$  ), and total aggregate produced (  $\bullet$  ).

movements in the general economy, as funding is usually committed for projects a year in advance. Decreased economic activity during the Depression of 1927 to 1935, World War Two and the late 1970's 'Oil Crisis' was associated with lower aggregate demand, while economic booms of the 1950's, early 1960's, 1972 to 1974 and 1984 to 1987 were reflected in greatly increased demand for aggregate over that period (Graph 2.4). United Kingdom aggregate production figures followed the same general pattern, with production peaks from 1970 to 1974 and from 1983 to 1988 (Gibble, 1989). Plentiful national funds and growth in 1972 and 1973 was linked with the highest national aggregate consumption since records began. The end of 1974 saw the initial effect of a massive rise in oil prices with New Zealand's annual oil bill increasing from \$100 million in 1973 to \$350 million in 1974. A general world recession was signalled in 1974 with the full impact of the recession occurring from 1975 (Reserve Bank of New Zealand, 1975). This was reflected in a large drop in aggregate consumption in 1975. World wide inflation, aggravated by further oil price rises, lead to stringent economic policies to control an expanding balance of trade deficit. A hesitant economic recovery in New Zealand in 1976 was followed by slow national economy growth rates from 1978 to 1980 (Reserve Bank of New Zealand, 1980).

The rise in aggregate consumption from 1984 to 1987 (Graph 2.4) was accentuated by New Zealand Rail's electrification and upgrading of the central section of the North Island main trunk line from Palmerston North to Te Rapa. The project involved increasing the width and depth of

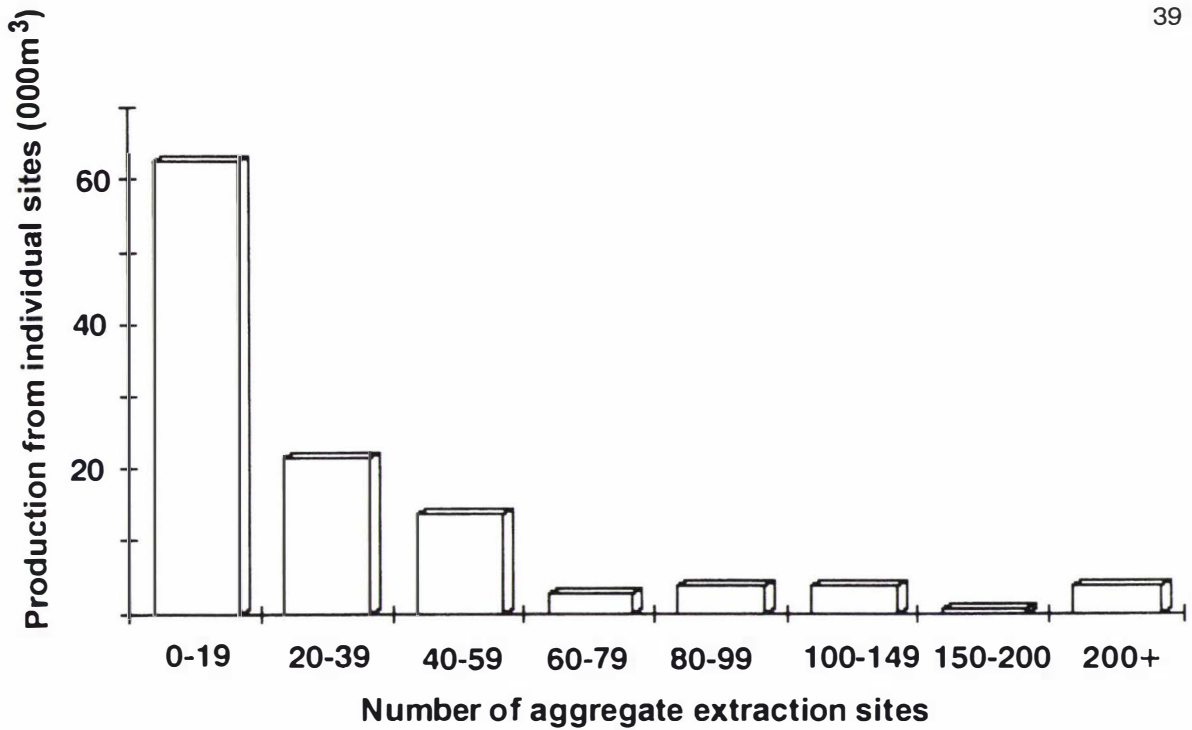
the ballast bed (CALNIG, 1986) and construction of new sections of track to ease gradients and curves. From 1984 to 1987 this project increased the average demand for ballast in the southern half of the North Island by about 50%

In New Zealand, 1990 was characterised by a contracting economy. This was reflected in the lowest demand for all construction, road and ballast aggregate for at least 20 years (Graph 2.4). Although aggregate production was static in 1989 compared to 1988, demand in roading aggregate was only sustained by a lower price as profit margins were cut to encourage demand (Mackenzie *et al.*, 1990). The 1989 and 1990 drop in overall aggregate production was most significant in the Central and Auckland Mining Inspectorates, reflecting a decline in the building industry since 1986 and greatly reduced construction activity in the cities of Wellington and Auckland. However the volume of aggregate produced was still higher than typical volumes prior to the building boom of the mid 1980's (Mackenzie and Cave, 1991). A decrease in Transit New Zealand's funding for maintaining and upgrading state highways in 1990 contributed to lower demand for roading aggregate in that year. In 1991 aggregate demand for roading and building construction in the Central Inspectorate was again substantially lower in 1989 and 1990 and this trend will probably be reflected in national production figures. A similar trend has occurred in the United Kingdom, with a fall in construction activity in 1990 and the first half of 1991 expected to continue to 1992 (Anon, 1991c). Mackenzie *et al.* (1990) predicted a decrease in the number of aggregate producers resulting from this period of low profitability as small operators were eliminated through difficulties in maintaining plant.

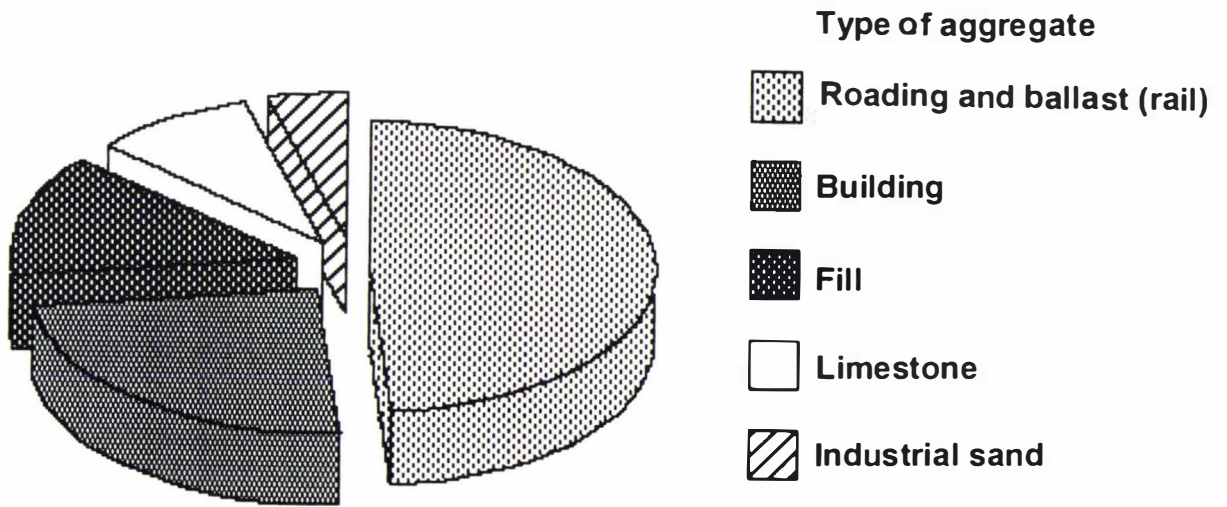
### 2.7.2 Aggregate use in the Central Inspectorate

The Palmerston North Inspectorate stretches from a line approximately joining New Plymouth on the West Coast, Taumarunui in the central North Island and Gisbourne on the East Coast down to and including Wellington (Figure 2.8). In 1990 the majority of producers in the Central Inspectorate produced aggregate for roading use with 91 sites producing aggregate for roads and ballast. Graph 2.5 shows 45% of sites produce road and ballast aggregate, with 15% of sites producing building aggregate. In 1990 65% of industrial sand was sourced from the Wellington region. A small proportion of quarries (12%) produce a wide range of aggregate products including fill, roading material and construction aggregate. Three quarters of these sites are found in Taranaki and Wellington where land extraction and hard rock quarries predominate respectively. Less than one quarter of sites<sup>which</sup> produce a wide range of aggregate products process river shingle, i.e. manufacture fill from a high quality resource.

The majority of aggregate sites produced less than 20,000 cubic metres of aggregate in 1990 and 86% produced less than 60,000 cubic metres of aggregate (Graph 2.6). In the annual quarry production statistics some minor pits are grouped together under a collective name so the proportion of very small pits is higher than 50%. Only 3% of Central Inspectorate quarries



Graph 2.6: Volume of aggregate produced from individual aggregate extraction sites in the Central Inspectorate in 1990 (Figure 2.8 shows the boundaries of Inspectorates).



Graph 2.5: The proportions of specific aggregate products produced by aggregate extraction sites in the Central Inspectorate in 1990.

produce greater than 200,000 cubic metres of aggregate in 1990. Winstone Aggregates is the largest company in the Central Inspectorate with five plants which produced 740,000 cubic metres of aggregate in 1990 or 17% of the region's production.

Details of aggregate extraction in the Manawatu have been recorded since 1977 when all shingle extractors were required to obtain an annual licence and submit quarterly returns for aggregate



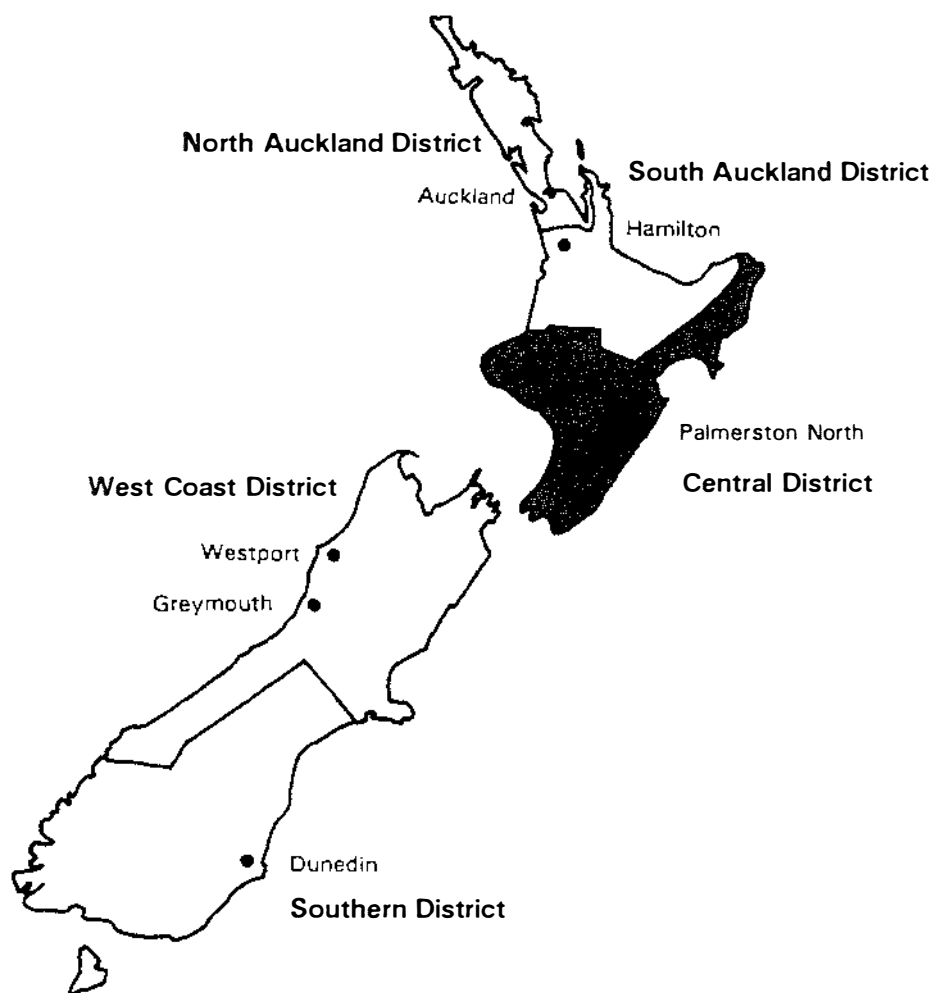


Figure 2.8: Administrative centres (•) and boundaries of mining regions administered by the Mining Inspectorate, Ministry of Energy (Mackenzie and Cave, 1991).

extracted. Figures are probably conservative (Joll, 1980; Brougham and McLennan, 1983) as not all producers submit returns. The monetary value and quantity of aggregate produced exceeds that of any mineral extracted in the Central Inspectorate with aggregates worth \$41 and \$34 million produced in the region in 1990 and 1991 respectively (Table 2.10). Since the closure of Waipipi Ironsands limestone production for agricultural consumption is the second largest mining industry in the Central Inspectorate producing \$1.6 and \$1.4 million of limestone in 1990 and 1991 respectively. Reflecting national trends, 1990 saw a downturn in all areas of aggregate production compared to 1989 with companies producing roading aggregate the worst affected. Total aggregate production has varied between 3.1 and 4.9 million cubic metres from 1986 to 1991.

In terms of monetary value, significant mined products other than aggregate in the Central Inspectorate are limestone for roads, sand for industry and limestone for agriculture (see Table 2.10). However aggregate production for roads, ballast and building are the most valuable mined

Table 2.10: Value (\$) of the main products mined in the Central Inspectorate from 1987 to 1991. "\*" indicates no data was recorded in the category for that year.

Mined material type	Value (\$ 000)				
	1987	1988	1989	1990	1991
Sand, rock, gravel for roads and ballast	20 839	19 970	22 006	22 201	17 045
Sand, rock, ballast for building	12 641	12 685	14 348	10 500	9 431
Sand for industry	1 096	807	770	2 785	2 208
Rock for reclamation or filling	908	2 005	1 791	2 467	3 122
Limestone (roads)	850	*	1 313	3 056	2 653
<b>TOTAL AGGREGATE VALUE</b>	<b>36 334</b>	<b>36 267</b>	<b>40 228</b>	<b>41 009</b>	<b>34 459</b>
Limestone (agriculture)	1 215	941	1 218	1 579	1 378

NB Values are not adjusted for inflation.

materials in total. Since 1987 there has been an escalation in use of lime in road construction (see Table 2.10). Lime is used for stabilisation of low grade road aggregates, which is a cheaper alternative to bringing in basecourse from longer distances. Lime stabilisation allows low quality shell rock to be used as a basecourse on top of existing seal which is then compacted and sealed. The value of sand and fill used fluctuated over the time period shown.

### 2.7.3 Future demand for aggregates

Demand for aggregate historically depends on the state of an economy and presence of large projects which can create anomalies, seen as short term increases, in aggregate demand (Joll, 1980; Nasser, 1987; Taranaki Regional Council, 1992). Large projects are influenced by political and economic considerations. For example from 1982 to 1985 aggregate use in Taranaki increased 130% with construction of "Think Big" and other projects. These included a methanol plant, synthetic petrol plant, ammonia/urea plant, expansion of Port Taranaki and development of the McKee oil field with associated pipeline laying. In Spain the World Expo and associated upgrading of Seville's infrastructure, together with private investment, lead to a boom in the region's construction sector. Aggregate demand rose from 2.38 million tonnes in 1986/87 to 5.4 million tonnes in 1990/91 (Galvez, 1991).

The demand for aggregate can be linked with population growth and numbers (Joll, 1980; Nasser, 1987; Taranaki Regional Council, 1992), car ownership, the number of new building permits issued and miles of new roads constructed (Nasser, 1987; Taranaki Regional Council,

1992). Brougham and O'Connor (1982) reported that aggregate extraction was greater in the Orua area than the Pohangina area due mainly to the higher population in the Orua area. Studies in Colorado have showed population is closely correlated with aggregate consumption if large project anomalies are removed (Aggregate Resources Mining Round Table, 1987; Nasser, 1987). Per capita use of aggregate varies depending on the degree of urban maturity reached within a region. In a 'young' region experiencing fast growth there will be a lot of construction and high consumption of aggregate. In a 'mature' region the consumption of sand and gravel remains approximately constant (Werth, 1980) as growth is slow, fewer new houses are required and supporting infrastructure has been developed (Verney, 1976).

Future demand can also be predicted by extrapolating past individual and total demand. Historical data in Canada, the United States and United Kingdom shows an increase in aggregate consumption over time (Aggregate Resources Mining Round Table, 1987; Nasser, 1987; Gribble, 1989; Tidmarsh, 1991). In Denver aggregate demand increased from 7 tonnes per capita in 1960 to 10 tonnes per capita in 1985 (Nasser, 1987). Use of aggregate in Denver compares with New Zealand consumption of 8.2 tonnes per capita in the same period.

Demand for aggregate is influenced by its price and the degree of substitutability of specific aggregate products. There are no known substitutes that could completely replace aggregate. In England, the United States and Canada increasing aggregate prices resulting from exploitation of less economic and/or more distant resources has led to increased recycling and manufacture of artificial aggregates. However such materials are generally restricted to low grade uses. In New Zealand lower quality aggregate stabilised by lime has increasingly been used where high quality aggregates are unavailable. Substitutes for concrete in the building industry include steel, aluminium and wood, however steel buildings have been unpopular in New Zealand since industrial action on the Bank of New Zealand building in Wellington during the 1980's.

Central and local government policy may influence aggregate demand through increasing the cost of aggregate through increasing environmental standards or increasing road user or diesel charges. Policy affecting the use and maintenance of roads, particularly the State Highways through Transit New Zealand's budget, will also affect aggregate demand. Aggregate costs will increase in the future as river sources close to markets diminish and transport distances increase, land based extraction sites are purchased and developed and plant is adapted to meet site and/or specification changes (C.A.N.G., 1986). Fees and royalties charged by Regional Councils have been increased to meet increased responsibilities for monitoring and control of environmental impacts under the Resource Management Act 1991.

### *Roading aggregate*

Aggregate production and value in 1992 will be similar to 1990 figures as the New Zealand economy has been in a negative or very low growth phase through 1992. Development and maintenance of the State Highway network is strongly influenced by the budget of Transit New Zealand and subsidies under the National Land Transport Programme. Cuts to Transit New Zealand's budget in 1991 meant a halt to new road construction projects and emphasis, as in 1990, on essential maintenance rather than new works. This particularly decreased requirements for sub base and base course. A decrease in subsidies available for maintenance works is a recent trend which also decreases demand for aggregate (Taranaki Regional Council, 1992). The amount of aggregate used in roading is also decreasing as new technology allows alternatives, for example lime road stabilisation (CALNIG 1986). Other changes in aggregate specifications include a trend towards more narrowly defined and rigorous specifications for particular purposes.

Future or potential demand from roading will include additional roading to support needs of major projects such as petroleum exploration in Taranaki and forestry development and harvesting. Forestry development requires the construction of internal roads and upgrading of other roads, however this demand is cyclic over 25 to 30 years once forests are established. In most areas of New Zealand roading aggregate demand will be associated with maintenance of existing roading, small distance (2 to 3 km) road construction and sealing or gravelling unsealed roads as the roading networks are complete. In the short term North Island major construction projects will probably be limited to the present realignment of State Highway One south of Auckland and extension of Wellington airport's runway. Upgrading of class II roads results in significant increases in aggregate demand. Central government indicated in 1992 that upgrading of roads in Waipoua and Haast were future priorities for Transit New Zealand. In the future the extension of the Wellington motorway to Paraparaumu and along Transmission Gully and realignment or upgrading of State Highway One over the 'Desert Road' will probably be major roading projects.

### *Railway aggregate*

New Zealand Railways is a major user of aggregate for ballast with more than 1.5 m<sup>3</sup> of ballast used per metre of track (Joll, 1980). There is no foreseeable alternative to the use of ballast with large volumes needed in the future as ballast is continually replenished and upgraded (CALNIG 1986). New Zealand Railways ballast demand for upgrading will tend to fall off gradually over the next 10-20 years as ballast sections are brought up to standard and the major requirements will then be for maintenance purposes only (CALNIG 1986). Ballast requirements have been reduced by the use of ballast-cleaning machines which remove ballast from a track undergoing upgrading by passing it over a series of screens to remove dirt and fines. A new generation of

ballast regulator machines have the ability to recover some of the ballast presently lost over the sides of the track (CALNIQ, 1986). Aggregate is also required for concrete sleepers which are being used to replace hardwood sleepers.

### *Construction aggregate*

Use of aggregate for concrete is concentrated in the main cities. In the regions demand for building aggregate and fill is more sensitive to large projects, for example the construction of a proposed wharf and timber storage area at Marsden Point in Northland (Grant-Taylor and Watters, 1976; CALNIQ, 1986). Major construction projects have direct aggregate demands stemming from the construction site and indirect aggregate demand from infrastructure development such as upgraded roads, additional services and downstream industry development.

## **2.8 Social and environmental impacts of aggregate extraction**

Surface mining is a localised traumatic land disturbance with a high profile. It is often seen as a destructive and unsightly activity (Boffa, 1991) but it can have beneficial environmental and social impacts, especially through creation of new and secondary jobs, lower aggregate costs and post mining reclamation (Aggregate Resources Mining Round Table, 1987). The impact of an aggregate operation results from extracting, processing and distributing aggregate (Ward and Grant, 1978; Taranaki Catchment Commission, 1981). Impacts may be short term, such as noise caused by excavating machinery, or long term as in the case of loss of agricultural land resulting from creation of a lake.

The impact of an aggregate extraction/processing site is determined by community expectations and the perceived value of social and many environmental impacts (Ward and Grant, 1978). Generally "the public" has the impression that the environmental effects of mining will always be serious (Webb, 1990). Generally "the public" are unaware of trends in environmentally acceptable mining, and extraction at poorly managed sites continues to result in unacceptable environmental impacts with resulting adverse publicity (Happy, 1992). Mining is seen as more damaging than other industries, for example the farming, industrial and chemical industries, with longer term impacts (Boffa, 1991) although mining is a transient activity and may have less impact than a residential development.

### **2.8.1 Factors influencing the impact of extraction.**

Regional factors affecting the impacts of a processing plant or extraction site include the zoning, land uses and population distribution of the area. Land based mines in planning zones that

allow a variety of land uses may have greater impacts than mines in single use zones as where only one zoning is affected impacts are more easily predicted and ameliorated (Bennett *et al.*, 1982). Where extraction occurs in "quarry" zones, for example in Whangarei and Christchurch, people may be more tolerant of impacts, having purchased land with the possibility of aggregate extraction in the locality. In these zones mineral resource extraction is the equivalent of an permitted or predominant use. Concentration of extraction sites within quarry zones may help limit the overall impact of extraction sites in a region. The actual and potential land uses of nearby sites will influence impacts of extraction (Bennett *et al.*, 1982). Some land or water uses are potentially highly incompatible with aggregate extraction. Berry fruit, for example, are susceptible to dust coatings as fruit cannot be washed before sale. This is particularly a problem on peripher<sup>h</sup>ies of urban areas where both extraction sites and lifestyle blocks are most common. Where high populations reside or use air, rail or road transport routes near extraction sites impacts are increased, being exacerbated where mine sites are highly visible (Bennett *et al.*, 1982).

Site specific factors that influence the potential impact of an extraction site include possible land uses, the scale and type of operation and aggregate/overburden characteristics. Aggregate extraction is perceived to be incompatible with highly productive or specialist post mining agriculture or horticulture. For example in 1991, aggregate extraction from stony soils in Hawkes Bay was prevented on the grounds that the soils were highly suited to wine-grape production and the extraction would conflict with the wise use of New Zealand's resources (Anon, 1992d). The Planning Tribunal did not believe the land would be suitable for grape growing after aggregate extraction despite reclamation. Site specific factors that influence impacts of extraction sites include aggregate and overburden characteristics. These affect extraction and processing methods as well as reclamation opportunities. For example large amounts of fines resulting from screening and washing a low grade aggregate resource could be utilised for soil augmentation.

The size and level of activity of an operation is related to its environmental impacts. A large operation with continuous activity will generally have a larger environmental impact. Conversely some intermittent operations have long term adverse visual and safety impacts (Macleod and Rouse, 1991; Happy, 1992). Operators of small extraction sites are less likely to have employees with specific environmental responsibilities and are less likely to engage consultants (Happy, 1992). Location of transmission, gas and petrol supply lines are also site specific factors that may indirectly affect impacts of quarrying. Transmission lines may prevent specific post mining land uses such as yachting through danger of electrocution, forestry through an increased fire risk and housing or industrial uses through height restrictions.

### 2.8.2 Land quality and value

Aggregate mining can result in the temporary or permanent loss of actual or potential agricultural or ecological resources (Joll, 1980; Wilson, 1991) because extraction involves the temporary or permanent removal of existing soil and vegetation (Joll, 1980; Webb, 1990). At the most successful aggregate reclamation operations in the United Kingdom, however, yields of agricultural crops on reclaimed land have equalled or exceeded undisturbed land's yields one year after reclamation. Soils and topography may be made more uniform, encouraging even growth and maturation of crops. In contrast, in New Zealand measurements of reclaimed aggregate sites near Nelson have found decreases in agricultural crop yield and soil versatility (Botham, 1983; Leighs and Duck, 1983; McQueen, 1983; Duck and Burton, 1985)(see Chapter 3.3.7). Habitats and wildlife may be replaceable or relocatable although in New Zealand successful reclamation of mature complex indigenous ecosystems has not yet been achieved.

Mining may affect the value of property in the immediate area during mining operations. Property values are usually depressed during mining (Werth, 1980; Skelton *et al.*, 1990) although in the Manawatu region recognition of the value of aggregate resources has greatly increased some farm values. Increased land and amenity values of mined and surrounding lands may result from beneficial post mining land uses, for example reserves, lakes, or residential or industrial subdivisions.

Aggregate extraction may alter or destroy archaeological, paleontological or geological resources of scientific importance (Aggregate Resources Mining Round Table, 1987; Macleod and Rouse, 1991). Extraction during the 1960's of raised beaches around Turakirae Head near Wellington for example, destroyed part of a unique record of past earth movements in the area (Joll, 1980). At Black Head near Dunedin quarrying is allegedly damaging a distinctive columnar geological rock formation which is also a high grade basaltic aggregate resource. Both the Department of Conservation and sections of the local community want to protect the formation which has spiritual and geological significance (McLennan, 1990).

### 2.8.3 Aesthetic quality

Disturbance of the land surface associated with aggregate mining may be visually dramatic, because most mined material is saleable and removed, creating pits (Joll, 1980; Webb, 1990). Visual impacts are determined by site topography, vegetation, soils, water and structures (Aggregate Resources Mining Round Table, 1987). The visual incongruity of extraction sites is accentuated by slope angles and configurations which differ from surrounding landscape patterns (Bennett *et al.*, 1982)(Photograph 2.2). These may be associated with spoil tips, waste disposal areas and exposed rock of pit faces and pit floors (Coppin and Bradshaw, 1982). Hard rock quarries on hill sides with high wall configurations or exposed sites with contrasting surface



colour or texture are particularly visible. In some Australian mines bitumen is sprayed over scarps to reduce site visibility. Some landforms created by mining, particularly high walls and deep pits, have been utilised as highlights of reclamation activities. Rock climbers benefit from quarry walls in the United States (Zimmerman, 1991b) and in Auckland's Mount Eden quarry. In the United States two adjacent quarries have been used to create a visually spectacular golf course in which rock outcrops are featured and two par-threes plunge into one of the quarries (Rukavina, 1991a).



Photograph 2.2: A quarry at Kiwitahi near Morrinsville, illustrating the visual impact of an unscreened extraction site.

Where aggregate extraction takes place in rivers exposed logs tend to be left on site and rubbish associated with extraction is commonly abandoned (Hawkes Bay Acclimatisation Society<sup>1974</sup>), both of which may be visually unappealing.

#### 2.8.4 Traffic and noise

Noise pollution (unwanted sound) and vibration from trucks, processing plant and blasting (Ward and Grant, 1978; Badham, 1987; Webb, 1990) is generated at most extraction sites. Noise generated by trucks, often the only practical means of transporting quarry products, is the greatest source of complaints from quarry neighbours in the United States (Anon, 1992c) and a common complaint in New Zealand (Anon, 1993a). Trucks may damage roads and bridges not designed to withstand heavy loads. Increased vehicle movements on minor roads or where a main road passes through a town may increase maintenance and street cleaning costs due



to spillage. Truck traffic may increase safety, noise and traffic problems along truck routes (Joll, 1980; Werth, 1980; Taranaki Catchment Commission, 1981; Aggregate Resources Mining Round Table, 1987; Skelton *et al.*, 1990).



Photograph 2.3: Dust generated on an unsealed road by trucks transporting aggregate to a crushing plant near Palmerston North.

The volume of noise generated at aggregate extraction sites is dependant on noise intensity, duration, frequency and variation over time. The volume heard in off site areas is determined by the level of background or ambient noise from other local sources. The volume of noise is affected by distance, vegetation, topography and wind conditions. The impact of noise can be reduced by altering landforms, changing mining schedules, reducing blasting to noisy times of the day, screen planting or flooding the base of a quarry (Badham, 1987). Noise is loudest when deflected from hard, dense surfaces such as quarry floors which have high noise reflection qualities (Joll, 1980). Effects of noise on people are subjective and include annoyance, nuisance, physiological effects such as startle or hearing loss and stress through interference with sleep, speech and learning (Aggregate Resources Mining Round Table, 1987). Intermittent noise can be particularly annoying because it is anticipated by listeners (Badham, 1987). Overseas quarries have broadcast 'white noise' to decrease the impact of quarry generated sound.

### 2.8.5 Atmospheric emissions

Atmospheric emissions from aggregate extraction operations mainly comprise dust derived from extraction and processing areas and trucks travelling on unsealed roads (Aggregate Resources Mining Round Table, 1987; Webb, 1990) (Photograph 2.3). Dust is not usually a health threat unless it contains silica or quartz, but it may aggravate respiratory problems, decrease values of surrounding properties and cause horticultural problems (Werth, 1980; Ward and Grant, 1978; Taranaki Catchment Commission, 1981). Excessive dust deposits on leaves, for example, can reduce photosynthesis and restrict crop growth. This is a rare occurrence in New Zealand as rainfall events are frequent and dust emissions have to be extremely high to significantly reduce photosynthesis over a growing season (Wallace, 1986). Dust has reduced kiwifruit and berry fruit quality as the hairy fruits retain dust and cannot be washed before packing. The impact of generated dust depends on the proximity of proposed operation, ambient air quality, degree of potential degradation, the strength and pattern of winds and the quantity of dust (Aggregate Resources Round Table, 1987).

### 2.8.6 Climate

Pits created by aggregate extraction may provide protection from the wind (Rukavina, 1991b), thus reducing drift from irrigation and spray applications and possibly evapotranspiration. Temperatures in pits may be elevated in summer due to shelter provided by pit walls and reflection of heat from pit walls and floor. Trials in Christchurch showed average maximum temperatures in a pit created by aggregate extraction were higher by 2 to 3 C in summer than on unmined areas (Bennett *et al.*, 1982). In the trial winter maximum temperatures were not significantly different between pits and unmined areas, with winter minimum temperatures in the pit occasionally marginally lower (Bennett *et al.*, 1982). Cool air flows into and ponds in low-lying areas. Mining excavations could, therefore, experience more frequent and severe frosts in winter. Early annual crop plantings and some tree crops are particularly susceptible to frost damage.

### 2.8.7 Characteristics of aquifers

Surface and ground water contamination is possible through oil spills (Skelton *et al.*, 1990; Webb, 1990), sediment disturbance, wash water discharge and storm run off (Quinn *et al.*, 1991). Wash water is produced where aggregates are washed to remove fines and contains large amounts of silt and clay. Storm water contains petrochemicals and lower levels of suspended solids. The impact of stormwater on water bodies is lower because it is usually discharged when natural waters have elevated levels of suspended solids. The impact of both river and land based extraction operations on river and ground water quality depends on water quality, downstream users and aquifer depth and height variation. Siltation and turbidity will more detrimentally effect

the quality of a clear aquifer than a sediment laden aquifer. Near surface, unconfined aquifers or recharge zones are more sensitive to contamination or disturbance than deep confined aquifers. Settling of fines or clays concentrated during the extraction process, or heavy silt discharges into a river, may prevent aquifer recharge (Joll, 1980; Werth, 1980). Brougham (1976a) reported that extraction on a shingle node of the Otaki River that acted as a ground water recharge zone, lowered the water level of an associated aquifer. Similar instances have been reported by Reed and Grant-Taylor (1966) where a 2 metre lowering of the Hutt river bed over a 6 mile length reduced the head in the artesian basin by as much as 1 metre from 1962 to 1966. Leigh and Duck (1983) reported cessation of aggregate extraction from the Waimea River due to lowered aquifer levels and threatened river stabilisation works. Lowering of ground water levels may also occur in land based mines as water may flow into a pit. This can be an advantage as it reduces the potential for pollution travelling off site (Werth, 1980).

At on land extraction sites lowering of the land surface has provided better access to the water table for irrigation (Rukavina, 1991b). On land extraction sites near rivers have been reclaimed for use as flood control and aquifer recharge areas with basins designed to contain flood waters.

#### 2.8.8 Characteristics of river channels

Extraction of aggregate from river channels generally has three main effects on the water body: channelisation, removal of riffle-pool sequences and alteration of the type of riverbed sediment. In-channel extraction may also alter the stability of beds and banks of watercourses. When aggregate extraction in a river channel is greater than the rate of natural supply additional sediment and aggregate is stripped by the river (Brougham and McLennan, 1983). Erosion is particularly common near large, permanently sited plants where small stretches of river bed are heavily mined (Brougham and O'Conner, 1982) and may be associated with both upstream and downstream erosion (Brougham and McLennan, 1985). For example, between 1978 and 1983 almost half the aggregate extracted from throughout the Manawatu was taken from the middle reaches of the Manawatu River around Palmerston North. This situation lead Brougham and Holland (1983) to report that "*failure of river control works is inevitable if high extraction rates continue*". Single thread river systems like the Otaki River are particularly sensitive to lowered river beds (Brougham and O'Conner, 1982).

Channel erosion and/or removal of riparian vegetation associated with aggregate extraction from river-beds can destabilise banks (Taylor, 1985; Macleod and Rouse, 1991) and adjacent structures such as stop-banks, bridges, pipelines and water intake systems (Taranaki Catchment Commission, 1981; Anon, 1985)(Photograph 2.4). Additionally, river straightening and removal of riffle-pool sequences increases the energy of water in floods (Taylor, 1985). Severe degradation of the Otaki river in the 1970's and 1980's, for example, exposed the base of stop banks and threatened the Otaki borough with flooding (Anon, 1985). When excessive aggregate

extraction removes the shingle layer overlying fine and poorly consolidated material, known as the armouring layer, rapid channel and bank erosion occurs until a new channel equilibrium grade is reached (Taranaki Catchment Commission, 1981; CALNIG, 1986). Over-extraction may also be associated with decline in the diameter of in-channel gravels of the Manawatu River (Goodwin pers. comm., 1992). This limits the production of aggregate grades which specify a proportion of broken faces or aggregate diameter.



Photograph 2.4: Exposed pilings of the old Fitzherbert Bridge over the Manawatu River, Palmerston North in 1987, due to unsustainable extraction of aggregate from the river.

Creation of large, shallow areas of low velocity water and removal of riparian vegetation are associated with higher and more variable water temperatures (Taylor, 1985). Pools stabilise water temperatures while providing cover and protection for fish during floods (Taylor, 1985). In extreme situations aggregate extraction may form barriers to fish migration. Removal of riffles or rapids by in-stream aggregate mining removes the natural mechanism which increases levels of dissolved oxygen in water and traps organic detritus which is both a food source and cover for aquatic life. Riffles also provide cover for invertebrates. Additionally the level river profile often resulting from channel extraction may remove seasonally flooded areas which act as tadpole habitat, thus reducing frog reproduction. Aggregate extraction may also remove gravels suitable for fish spawning (Wing, 1979) and alter river habitat for wildfowl (CALNIG, 1986).

There are benefits from in-channel aggregate extraction. Controlled extraction of aggregate from aggrading rivers reduces flood risk by increasing or maintaining channel capacity (Taranaki Catchment Commission, 1981; Brougham and McLennan, 1985). Where wash-water is sourced



from bores or dams water that discharges from aggregate processing plants may increase the baseline flow of small watercourses (Aggregate Resources Mining Round Table, 1987). Conversely, sediment build up in the water channels and banks may provide a medium for vegetation growth, thus reducing channel flood capacity (Joll, 1980).

#### 2.8.9 Quality of surface water

Site sediment, or 'fines' and water discharges have a wide range of potential effects on aquatic vegetation, fisheries and habitats. Discharges of fines or stirring up of sediment associated with channel extraction, make the water cloudy or turbid (Taylor, 1985; Macleod and Rouse, 1991; Quinn *et al.*, 1991). Aquatic organisms may be affected directly or indirectly (Quinn *et al.*, 1991). Aquatic organisms are most affected by a combination of fine-grained sediment (Quinn *et al.*, 1991), high concentrations of sediment and low water flows. The degree of impact is also influenced by the time of year and period of the discharge (Taylor, 1985) with discharges during the main breeding season more harmful and sudden pulses less harmful than continuous discharges.

Quinn *et al.* (1991) have investigated the impacts of alluvial gold mining on six streams between Greymouth and Hokitika. They reported that increased turbidity reduced light levels reaching stream beds and lowered algal photosynthesis. Fine sediment trapped in surface films on stones lowered the quality of films as food for invertebrates. Increased turbidity was associated with a 55 to 90% decrease in numbers of invertebrate downstream of the mines, as well as a reduction of fish and water bird numbers. Turbidity from mining operations was also identified by Livingston (1982) as a causative factor in stress of aquatic life in the Coromandel Ranges. Reduced light levels due to turbidity may also reduce the "self purification" capacity of rivers (Brougham and McLennan, 1985) as some bacteria are killed by exposure to light.

High turbidity reduces the ability of fish which use sight to find food. In extreme cases fine sediments mechanically clog gills of fish (Livingston, 1982) and digestive organs of invertebrates (Taranaki Catchment Commission, 1981; Gilliland, 1990). Fish are particularly susceptible to high turbidity and fine sediment levels during spawning, hatching and rearing periods (Wing, 1979). Fine sediments reduce spawning success by smothering eggs. Smothering reduces the diffusion of oxygen to eggs and larvae, limiting their development (Taylor, 1985; Livingston, 1982).

Concentrations of suspended solids as low as  $100 \text{ g m}^{-3}$  may decrease the growth rate of fish and the resistance of fish to disease (Taylor, 1985). Continuous high concentrations of sediment may affect fish migration within a river system. Indigenous fish, other than eels, are particularly affected by high sediment concentrations, as most have a migratory stage in their life cycle.

Infilling of spaces between gravels in stream beds with sediment decreases the amount of stable substrate for hard surface dwellers. This reduces sheltering sites for invertebrates and lowers the amount of detritus which is trapped. The detritus is a food source for some insect larvae. Additionally, if a stable stream bed is replaced by unstable (fine) sediments aquatic vegetation species may change dramatically (Livingston, 1982).

Pollution of water by sediment may also decrease water quality for domestic, commercial and stock water and recreational uses. Although aggregate extraction and processing may increase suspended solids and sedimentation in waterbodies, these operations may have a minor effect on aquatic life and river use (Brougham and McLennan, 1985) where waters and water beds have naturally high levels of fine sediments or are affected by other discharges.

#### 2.8.10 Recreation

Reduced river access and/or modification of river setting associated with aggregate extraction may adversely impact river bank and aquatic recreation such as running, picnicking and swimming (Taranaki Catchment Commission, 1981; CALNIG, 1986). Shallow, wide, gently graded river channels associated with in-channel aggregate extraction may restrict river navigability while removal of rapids and deep pools decreases the value of sites for kayaking and trout fishing (Taylor, 1985; CALNIG, 1986).

Increased water turbidity decreases recreational and aesthetic values as clear water is more appealing than dirty water. Clear water allows swimmers, kayakers and wader-clad anglers to detect subsurface hazards and estimate water depth. Additionally angling is more successful when fish can see the lure (Hawkes Bay Acclimatisation Society, 1974).

Both land-based and in-channel aggregate extraction have the potential to create or maintain recreational resources such as swimming holes (Taranaki Catchment Commission, 1981). Land based aggregate extraction sites have often been used for planned and unplanned recreational uses at cessation of mining (detailed in chapter 8). In Christchurch a survey of residents within 400 m of an abandoned aggregate pit found that the pit was most commonly used as a playground for children and for disposal of garden refuse. The site was also used for fishing, eeling, picking flowers, seed heads and blackberries, running and walking, bird watching and riding motor bikes, BMX bikes and mountain bikes (Bennett *et al.*, 1982). Planned post mining reclamation has provided for a wide range of recreational activities (see Chapter 8.7) from passive wildlife reserves to theme parks, sports stadiums and golf courses. Where natural lakes are absent, for example in Manawatu, lakes created by aggregate mining may be developed as water sports centres.

### 2.8.11 Other impacts of aggregate extraction.

Major social and environmental benefits may be associated with mining operations. Most of the following benefits which have been documented for Australian mines in Australian Mining Industry Council Workshops and publications could be associated with aggregate extraction sites in New Zealand.

Development of major extraction sites is usually associated with a detailed assessment of the flora and fauna of the immediate and surrounding area. Research may also be undertaken to determine the environmental requirements of species and develop propagation and reclamation strategies. In Australia the selection trials of mining companies have produced saline tolerant eucalyptus which have subsequently been used by farmers to reclaim saline soils. Development of plant propagation and establishment techniques have aided non-mining revegetation projects, such as Landcare, soil conservation and wetland enrichment projects. In both Australia and New Zealand mining companies are involved in a variety of public education programmes about their mining, processing and reclamation operations. The completed reclamation may itself serve an educational and research purpose, for example the Capel and Wellard wetlands in West Australia have a network of observation hides, paths and displays for public use.

## 2.9 Conclusion

Chapter Two has provided an overview of the aggregate industry, particularly in the greater Manawatu region. Aggregate, that is sand, gravel and boulders, is mainly used in the construction of roads, railways and concrete buildings with diameter and hardness specifications differing between consumers. Over the last 20 years aggregate has been the most important mined product in terms of tonnes produced. The limitations of aggregate substitutes mean aggregate will continue to have an important role in New Zealand. In the Southern North Island aggregate primarily comprises greywacke and argillite sourced from fractured rocks in the hills, alluvial terrace deposits, river beds and the sea foreshore. The location of exploited resources is dependant mainly on the distance of the from consumers, cost of production and quality of the resource. High quality, cheaply extracted aggregates are located on sea foreshores and river beds and beaches. The quality of aggregates in river terraces generally deteriorates with increasing terrace age and height.

The aggregate industry is cyclic, following national economy and construction industry trends. It is characterised by the intermittent use of many sand and gravel sites. Extraction ceases in times of low demand, leaving exposed, unreclaimed and sometimes unstable working areas (Joll, 1980; Macleod and Rouse, 1991). These sites are the source of many adverse environmental impacts which are related to aggregate extraction, processing and distribution. Impacts of

aggregate extraction are similar to those of alluvial gold mining with potential adverse effects on surface waters, river channels and aquifer characteristics.



## Chapter Three Reclamation

### 3.1 Introduction

Chapter Two presented an overview of the aggregate industry in the greater Manawatu region of New Zealand and concluded with an outline of the environmental impacts of aggregate extraction. In Chapter Three techniques for amelioration of some of these impacts through land reclamation are reviewed. The chapter presents New Zealand scientific and technical studies undertaken to develop techniques for reclamation of all types of drastically disturbed land from coal mine spoils to hydro-electric dams. International literature on aggregate mine reclamation from Australia, England, California and Canada is also reviewed. The chapter concludes by exploring the applicability of international research to New Zealand reclamation and indicating areas of New Zealand reclamation research that require further trial work and investigation.

### 3.2 Definition of restoration, rehabilitation and reclamation

Three terms are widely used to describe the treatment of drastically disturbed land: restoration, reclamation and rehabilitation (Griffin, 1982; McQueen, 1982; 1983; Norton, 1991). The terms are used interchangeably by some authors. Conversely other authors differentiate between restoration, rehabilitation and reclamation, with definitions sometimes conflicting between authors (Tomlinson, 1984). For example, in the United Kingdom rehabilitation is often associated with treatment of derelict industrial sites and reclamation related to mining activities. In the following sections the three terms are discussed and defined.

#### 3.2.1 Restoration

There is general agreement that restoration means recreating the pre mining state of the land (United States National Academy of Science Committee, 1974 *cited by* Tomlinson, 1984; Griffin, 1982) in terms of topography and land use (McQueen, 1982; Lawrence and Smith, 1983; Norton, 1991). Some authors define restoration specifically to mean reconstruction of land and ecosystems identical to those present prior to disturbance (Brown, 1982; Bell, 1990). There are, however, few situations where restoration to this level is feasible or even achievable (Bell, 1990). Restoration of agricultural land is defined practically as creating soil and topographical conditions that will grow the same crops at the same yields with similar inputs (Younger pers. comm., 1991). In this thesis restoration is defined as replacing the pre-mining characteristics of a site.

### 3.2.2 Rehabilitation and reclamation

Some authors distinguish between rehabilitation and reclamation. McQueen (1982) defines rehabilitation as the creation of conditions allowing a *new*, substantially different use while reclamation is restoring a derelict site to a use with approximately the *original* vegetation cover. The United States National Academy of Science Committee (1974 *cited by* Tomlinson, 1984) concurs<sup>S</sup> with McQueen (1982) in defining rehabilitation and reclamation in terms of different and similar ecosystems respectively. McLellan *et al.* (1979) concurred with McQueen (1982) in specifying that rehabilitation includes both an acceptable physical appearance and a *changed* land use, however McLellan *et al.* (1979) defined reclamation as when either step has occurred, but not both.

Many other authors, however, do not differentiate between reclamation and rehabilitation and use the terms to describe the planned treatment of disturbed land so that it is developed either to its former condition *or* to a different beneficial condition (McLellan *et al.*, 1979; Lawrence and Smith, 1983; Aggregate Resource<sup>Section</sup> Ontario, 1989; Norton, 1991; Ross and Mew, 1991). Authors dissent on the important features that comprise reclamation. Bell (1990) emphasises that reclamation should return land to a stable and sustainable planned land use with predictable and appropriate maintenance inputs.

The California State Mining and Geology Board (1979) defined reclamation as the combined process of land treatment that minimises environmental impacts so that mined lands are reclaimed to a usable condition which is readily adaptable for alternate land uses and creates no danger to public health and safety. Public health and safety is not an absolute requirement of reclamation, however, particularly where water is a feature or sheer faces are part of the reclamation plan. Neither should reclaimed land necessarily be readily adaptable for alternate land uses. Brown (1982) also emphasises that reclamation is a process or treatment of damaged land. He defined reclamation as the process of artificially initiating and accelerating the natural continuous trend toward recovery. Sims *et al.* (1984), in a major review of the international reclamation literature, more broadly defines reclamation to include ensuring plant growth and biophysical productivity. Definitions focusing on productivity or a blending of reclaimed areas into the landscape may exclude commercial, residential and water sport as post mining uses. Key concepts from these definitions are that reclamation or rehabilitation is a beneficial treatment that minimises environmental impacts and allows land use after mining. In this thesis both reclamation and rehabilitation are defined after Bell (1990) and the California State of Mining and Geology Board (1979) as "*The planned treatment of drastically disturbed land that minimises adverse environmental impacts and results in stable landforms and/or ecosystems suited to a beneficial post mining function.*"

Reclamation is the term used by the main professional organisations to describe their activities, for example the Canadian Land Reclamation Association, American Society for Surface Mining and Reclamation, British Land Reclamation Group and the International Affiliation of Land Reclamationists. United Kingdom and American authors generally use the term reclamation, while both reclamation and rehabilitation are used in Canada and Australia. In New Zealand, 1990 and 1991 D.S.I.R. publications have preferred the term rehabilitation. In this thesis reclamation is preferred to rehabilitation as it is less likely to be confused with other fields, such as human rehabilitation.

### 3.3 New Zealand reclamation

New Zealand has both energy deposits such as coal, natural gas and petroleum and non energy minerals such as gold, iron sand and limestone (Taylor and Walker, 1987). These deposits, together with aggregate, are the major mined materials in New Zealand (Chapter 2.7). Mining in New Zealand began with extraction of manganese from Waiheke Island in 1841 (Isdale, 1981). This was followed by a 50 year gold rush era that began in 1861 and which had a dramatic effect on New Zealand society (Bagley, 1980; Taylor and Walker, 1987). Gold mining was an important catalyst in the exploration and settlement of the more remote areas (Bagley, 1980; Weston, 1991) such as Otago and Westland. Revenues from gold comprised a major source of income for New Zealand during this era, providing funds for development of early agriculture and industry (Taylor and Walker, 1987). Additionally, areas of intense gold mining activity often coincided with areas of intensive logging (Watson, 1981). Little reclamation occurred during this period and the Mining Act of 1926, which <sup>remained</sup> in effect until 1970, allowed payment of a levy to government in lieu of reclamation. Consequently many mining operations left an unsightly and unproductive legacy of disturbed land although the area of mined land was, and still is, small (McKenzie and Cave, 1991).

Since the early 1980's there has been another upsurge in prospecting and mining (Taylor and Walker, 1987) especially in the Hauraki Goldfields of the Coromandel (Hansen, 1988). Associated with these modern mines has been the development of land reclamation required by the Mining Act 1971 and Mining Amendment Act 1981 (Chapter 8.2). Most formal New Zealand reclamation research has been associated with Environmental Impact Reports or Assessments required for large mining operation's mining licences since 1971.

#### 3.3.1 Topsoil mining

Three studies have examined effects of removing the surface layers of soil (Figure 3.1). The earliest mining-related experiment in New Zealand began in the 1960's on Karapoti soils and concentrated on methods of pasture management that maximised pasture production. This was followed in the 1980's by two more detailed Wellington-based studies on Judgeford and Belmont

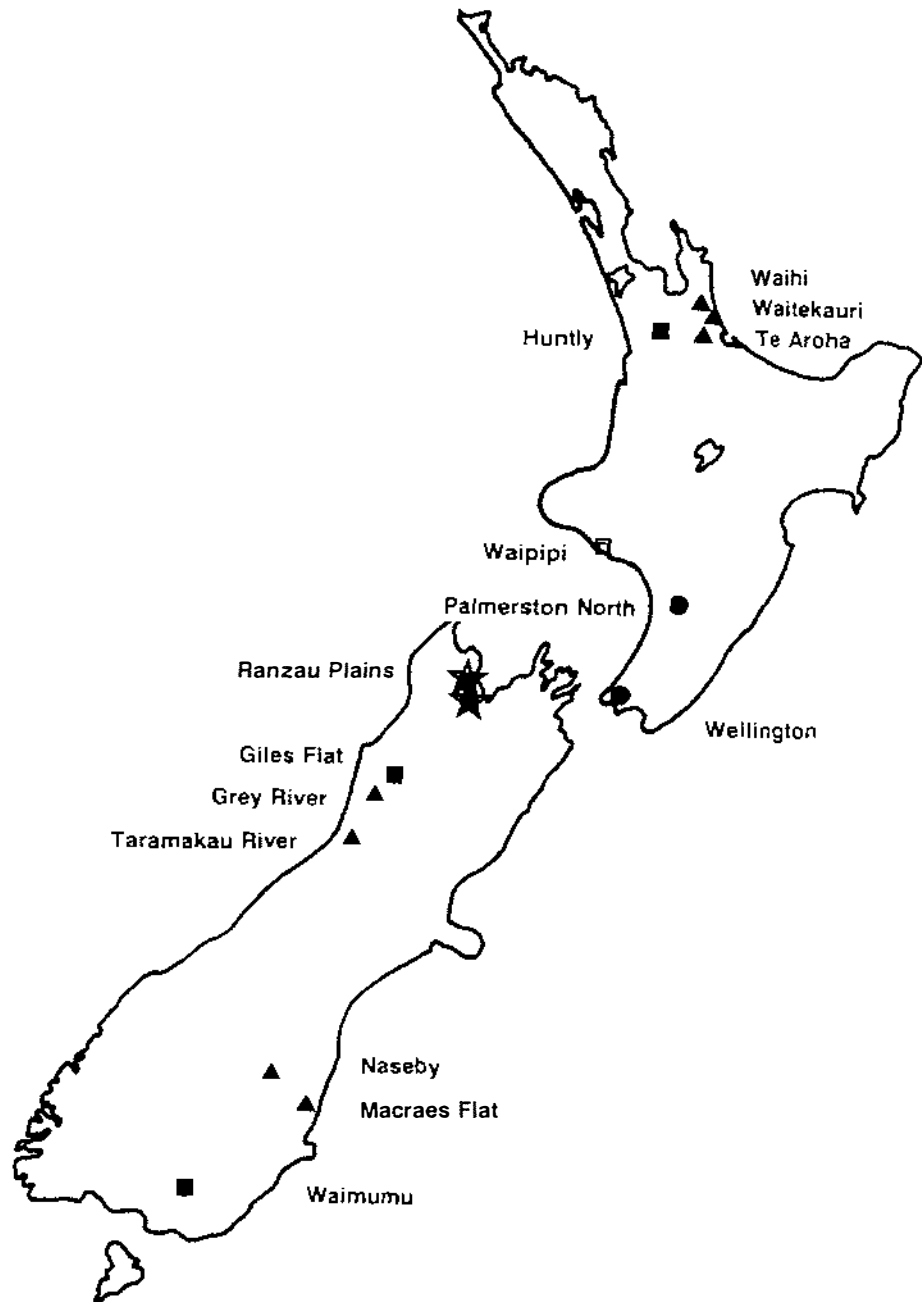


Figure 3.1 Sites associated with research into reclamation of coal ( ■ ), aggregate ( ★ ), topsoil ( ● ), iron sand ( □ ) and gold ( ▲ ) mine sites in New Zealand.

soils, which researched the effects of topsoil stripping on soil physical, chemical and biological characteristics and pasture production.

In the 1960's a six year trial investigated the recovery of pasture production and chemical properties of a recent, non-accumulating sandy soil following removal of the surface 0.15 m of topsoil and mixing of the underlying 0.15 to 0.75 m horizon with subsoil before replacement

(Sears *et al.*, 1965). The reconstructed Karapoti soil had little structure and a negligible, 0.08%, carbon content. High pasture production was quickly obtained from this soil when a white clover and grass sward was sown, fertiliser applied and 80% of mower clippings returned. This management system ensured efficient cycling of nutrients; organic matter increased by 295 kg ha<sup>-1</sup> annually and clovers returned 390 to 670 kg nitrogen ha<sup>-1</sup> year<sup>-1</sup> to the soil. Pasture production on the remaining subsoil was almost as high as that of the unmined soil in the first year after reclamation. In general, the greater the production of herbage dry matter the faster the rate of accumulation of soil nitrogen (Hart *et al.*, 1990). Sears *et al.*, (1965) found no consistent relationship between pasture production and aggregate stability. The rapid recovery of the Karapoti soil was attributed to its "*favourable physical properties*" and a low phosphate adsorption status (Hart *et al.*, 1990).

An ongoing shortage of topsoil in Wellington has led to several attempts at topsoil mining. From 1978 to 1983 a multi-disciplinary trial investigated the short and long term effects of stripping topsoil from Judgeford silt loam soils. Soil chemical, physical and biological properties were measured together with pasture production and composition (Hart *et al.*, 1986). The soil was originally vegetated with a clover and ryegrass pasture. In the trial topsoil was stripped to depths of 0.10 m (Treatment S10) or 0.20 m (Treatment S20) and remaining soil treated with lime, fertilised with N, P and K and resown in pasture species. Measurements found sites stripped of topsoil had markedly lower organic matter contents (Ross *et al.*, 1982), plant nutrient levels (particularly nitrogen and phosphorus) and pasture production (Hart *et al.*, 1986). The number of earthworms, microbial biomass and microbial activity (soil enzyme) were also reduced (Ross *et al.*, 1984; Hart *et al.*, 1989).

Biochemical activity in S10 and S20 treatments was significantly lower than in unstripped sites during the first three years. S20 biochemical activity values were significantly lower than S10 values initially but there were no differences between the two treatments after five years (Ross *et al.*, 1984). Enzyme and herbage yield values increased rapidly in S10 plots but had not reached levels measured in control plots after 3 years (Ross *et al.*, 1982). Invertase and sulfatase activity appeared to be the best indicators of soil fertility status in the stripped soil (Ross *et al.*, 1982; Kiss *et al.* 1989) although the correlations became less marked over time (Ross *et al.*, 1984). Ross *et al.* (1989) proposed that the ratio of microbial carbon to total soil carbon may be a useful indicator of soil biological stability or recovery. Organic carbon and total nitrogen contents increased only slowly (Ross *et al.*, 1982; Kiss *et al.*, 1989). After 5 years soil carbon levels increased from 2.3 to 2.7% and from 1.8 to 2.5% where 0.10 m and 0.20 m of topsoil respectively had been removed (Hart *et al.*, 1986). The total carbon content of the soil appeared unlikely to reach the levels existing before mining 10 years after mining of the topsoil (Hart *et al.*, 1989).

Physical properties of soils in stripped and unstripped areas (S10 and S20) were generally inferior to those of unstripped areas. However, mean penetration resistance and penetration resistance in the top 0.05 m of soil were the only physical parameters that were significantly different at each site (Cook *et al.*, 1986). Some stripped sites displayed reduced macroporosity, total porosity and saturated hydraulic conductivity, higher bulk densities and lower water holding capacity. A lower percentage of pasture cover and/or reduced productivity of stripped sites was hypothesised to be a result of restricted rooting depth and poor aeration. This was attributed to high penetration resistance partly resulting from compaction by earthmoving operations (Cook *et al.*, 1986).

A pot experiment using soil from the site showed that the presence of ryegrass enhanced all biochemical activity which was further stimulated by the presence of earthworms (McColl *et al.*, 1982; Ross and Cairns, 1982). The ryegrass stimulated biochemical activity by providing readily decomposable substrates in root exudates and decaying tissues (Ross and Cairns, 1982). Earthworms contribute to reclamation of pasture productivity after topsoil removal by stimulating biochemical activity and nutrient cycling. The pot trials showed that earthworms alone had little influence on biochemical activity as earthworms need plant materials (nutrients) to effect biochemical changes (Ross and Cairns, 1982).

A significant long term reduction in the potential productivity of the Judgeford silt loam soil was judged to have occurred as a result of topsoil removal (Hart *et al.*, 1986) with an inferior physical rooting medium for plants having been created (Cook *et al.*, 1986). However, three years later Hart *et al.* (1989) reported that most soil biological and chemical properties had recovered to between 80% and 90% of the levels in unmined soils. It was found that pasture production on stripped areas could be boosted to equate to unmined areas with moderate to high nitrogen application. Studies of the effects of topsoil mining were also carried out on Belmont silt loam (August, unspecified date), with similar findings to those reported for the Judgeford silt loam soil.

### 3.3.2 Iron sand mining

Mining of iron sands for titanomagnetite by suction dredge began at Waipipi, located in south Taranaki, in 1971 (Figure 3.1). Rough sand dunes with immature skeletal soils used for sheep and cattle farming were reclaimed following procedures developed by the Australian mineral sand industry (Connolly *et al.*, 1981) (Photograph 3.4). The mined land comprised two distinct physiographic units: rough coastal dunes which carried 3 to 8 s.u. ha<sup>-1</sup>; and sand flats comprising gleyed sand over a cemented ironstone pan at 0.50 m which carried an average 12 s.u. ha<sup>-1</sup>. Both Australian and New Zealand industries were faced with similar wind erosion problems, weakly developed loamy sands with shallow A horizons and mining techniques. Waipipi, however, experienced a

mean annual rainfall of 900 mm (Connolly *et al.*, 1981) spread evenly throughout the year, substantially more than many Australian mineral sand extraction sites.



Photograph 3.1: Reclamation of fore dune (RHS) and first secondary dune (LHS) after mining of mineral sands to the low tide level in Western Australia. Note the placement of tree slash to encourage colonisation by birds and invertebrates.

Reclamation comprised bulldozing the top 0.30 to 0.50 m of 'topsoil' and vegetation to the sides of the dredge's path. Soils on sand flats and more productive areas were double stripped. After stockpiling for up to four months, topsoil was spread onto terraced, levelled dredge tailings (Munro 1980). An initial 50:50 mix of barley:oats (*Hordeum vulgare*: *Avena sativa*) was sowed to rapidly stabilise the wind erosion-prone sands. Legume (*Trifolium* sp) and grass seed at a rate of 40.3 kg ha<sup>-1</sup> was direct drilled when the grain crop was 0.15 to 0.20 m tall. A 12:10:10:8 N:P:K:S fertiliser at 150 kg ha<sup>-1</sup> was spread with both sowings. Thereafter 200 kg ha<sup>-1</sup> of 6:6:5:13 fertiliser was spread annually for 3 years (Connolly *et al.*, 1981). This reclamation technique generally returned land to agricultural use less than six months after completion of mining (Munro, 1980).

In 1980 informal research at Waipipi Ironsands investigated the establishment of lucerne crops to overcome a summer feed shortage. Pot trials of lucerne seed sown into topsoil and tailings showed no chemical toxicity or deficiency problems hindering establishment, however field-grown lucerne suffered high mortality due to pasture pests and required special grazing techniques to maximise yields.



The transformation of topography from rough dunes to flat terraces associated with mining tended to over drain the seaward portion of each terrace. Furthermore, summer pasture production was reduced by a lowered water table which resulted from disruption of iron pans by the mining process. Over drainage was ameliorated by contouring tailings to produce gradual slopes (elimination of terraces) while other trials investigated temporarily damming drains during the summer months to raise the water table (Connolly *et al.*, 1981).

Further trials showed that towed scrapers tended to compact topsoil but were more efficient in producing a uniform depth of topsoil. A study of the reclaimed areas and grazing animal health found that both mined and unmined pasture and soils were deficient in copper and selenium, with a high level of mineral iron (iron sand) contamination in hard grazed juvenile pasture contributing to an induced copper deficiency in animals (Connolly *et al.*, 1981).

During its life Waipipi Ironsands reclaimed an area of 800 ha, creating farm land that had higher pasture productivity and nutritional value and easier contour than the original farmland (Taylor and Walker, 1987) allowing higher stock carrying capacities and more intensive farm management.

### 3.3.3 Alluvial gold dredging

#### *Forest reclamation*

Suction dredging for gold in South Island rivers and river terraces prior to the Mining Act 1971 commonly created a herring bone pattern of mounds of coarse tailings (gravels and boulders) interspersed with dredge ponds. After 20 to 80 years many of these tailings support no vegetation (Ross and Mew, 1991; Gregg *et al.*, in press). Early reclamation in the 1960's and 1970's included attempts to establish production forests of *Pinus radiata* on gold dredge tailings (Ross and Mew, 1991). In some cases 10 year old pine trees were less than 3 m tall (Gregg *et al.*, in press). In 1977 the Forest Research Institute investigated methods of improving the establishment and growth of radiata pine trees and 12 legume species on coarse unmodified tailings in a three year exploratory trial (Fitzgerald, 1981). West Coast trials identified red and white clover (*Trifolium pratense* and *T. repens*) as being more successful at providing nitrogen for tree growth than subterranean clover (*Trifolium subterraneum*) or lotus (*Lotus pedunculatus*), lupins (*Lupinus* sp) or lucerne (*Medicago sativa*) under the high rainfall climate which displayed no marked seasonal rainfall variation. Pasture legumes showed positive responses in dry matter production from applications of superphosphate containing Mo, K and Mg (Fitzgerald, 1981). Tree lucerne (*Cytisus proliferus*), russell lupin (*Lupinus polyphyllus*) and yellow tree lupin (*L. arboreus*) grew well without fertiliser applications. Nutrition of radiata pines, measured by N-content in needles, tree form and tree height was improved by association with a vigorous legume (other than tree lucerne which severely suppressed tree growth). The growth response



of pine trees, however, was not statistically established and was measured over only 3 years (Fitzgerald, 1981).

Three further field experiments on stony sand dredge tailings in the Naseby forest found that legume establishment was markedly improved by the shelter of trees while legumes significantly increased annual height increments of Douglas fir (*Pseudotsuga menziesii*) (Frazer and Keoghan, 1990). Under the mean annual rainfall at Naseby of 0.61 m Tana birdsfoot trefoil (*Lotus corniculatus*) was the most successful legume as it survived droughts and had a positive effect on tree growth and soil conditions. In this trial legumes did not respond to phosphate applications (Frazer and Keoghan, 1990). Metcalfe and Godfrey (1990) also advocated the use of agricultural legumes in production forestry reclamation, citing their ability to supply nutrients to trees and reduce gorse competition.

Review papers on West Coast reclamation by Mew and Ross (1991) and Ross and Mew (1990) recommended replacing topsoil where available as they considered the advantages, of increased soil water retention, fertility and micro organisms, conferred by topsoil outweighed the disadvantage of gorse growth from seeds contained within the topsoil. Metcalfe and Godfrey (1990) reported that for exotic forestry reclamation topsoil spread over levelled dredge tailings and the mixing of fines with tailings have been the most successful options. Mew and Ross (1991) and Ross and Mew (1990) advocated the burial of poorly draining subsoil, traditional silvicultural practices such as contouring to create mounds on which trees are planted and non traditional treatments such as replacing logs and stumps to provide favourable micro sites for seedling survival and growth.

#### *Agricultural reclamation*

The ability of modern gold dredges to place "fines", that is gravel and sand less than c.0.12 m diameter, at the surface has enabled agricultural reclamation of dredged areas. Kanieri Gold and Grey River Gold Mining Ltd are companies that have conducted trials of agricultural reclamation techniques on the West Coast of the South Island.

In 1978 Kanieri Gold, dredging in the Taramakau river, was required to restore land under conditions attached to their mining licence. The affected fine sand and silt soils were shallow with little profile development or organic matter accumulation only supporting poor quality pasture with rushes (*Juncus* sp), sedges (*Carex* sp) and gorse (*Ulex europaeus*) Massey University was engaged to carry out fertiliser response trials and glasshouse pot trials in 1979 (Keating and Buckley, unpublished paper). Fertiliser response and glasshouse trials indicated that lime was not needed initially for optimum pasture growth, however the substrate was naturally deficient in P,K and S. (Gregg et al., in press). A field experiment investigated the requirement for spreading topsoil on dredge tailings (Keating, 1990). Spreading 0.15 to 0.20 m

of soil over the gently rolling coarse tailings was unsuccessful. Surface sealing resulted in the shedding of rainfall with consequent rill erosion, silt transfer to depressions and impeded drainage (Gregg *et al.*, in press). Poor drainage was exacerbated by a sharp textural boundary between the soil and the underlying tailings (Keating, 1988). In the medium term topsoil placement led to heavy gorse infestation, which necessitated intensive grazing management and herbicide spraying (Gregg *et al.*, in press). Satisfactory pasture production was achieved by not spreading soil and utilising heavily rolled mixed fine (diameter less than 0.13 m) and coarse tailings as a rooting medium. When sown with a clover dominant ryegrass (*Lolium perenne*), white clover and aslike pasture at 37 kg ha<sup>-1</sup> pasture and fertilised with 600 kg ha<sup>-1</sup> molybdenic super phosphate fertiliser, tailings grew highly productive pastures (Gregg *et al.*, in press).



Photograph 3.2: The Grey River Gold dredge, Westland 1990 showing the elevated tailings surface at the rear of the dredge (RHS) due to swelling and excavation of the dredge pond.

Grey River Gold Mining Ltd dredged recent alluvial soils and river beds on the West Coast in the 1980's (Photograph 3.2). An initial field trial investigating optimum depths and types of growing media found that over two years pasture production was substantially higher in the undisturbed soil treatment. There was no significant difference in dry matter production between plots consisting of topsoil over subsoil, subsoil only and 0.30 m fines treatments (Morton and Harrison, 1990). Unfortunately results were inconclusive as the trial did not simulate the final hydrology (Gregg *et al.*, 1990, page 97) as swelling (looser packing) associated with dredging raised the ground surface by 3 to 6 m while the water table at the trial site was at times at the surface of the lowest plots. The high water table at the trial distorted soil water availability and resistance to pugging or treading damage. Pugging effects were exacerbated as the trial site was grazed

with rising 2 year old bulls, although the Environmental Impact Report specified that light classes of stock were to graze reclaimed land (Grey River Gold Mining Limited, 1988). Bulls exert higher ground pressures than most other livestock grass harvesting methods, for example hay or silage making with medium sized tractors and 10 tonne trailers. The trial treatments were of different elevation and when grazed together uneven distribution of pugging and nutrient transfer resulted, because stock preferentially camp on higher drier areas. This effect was reflected in high nitrogen levels on the 0.60 m fines treatment (Morton and Harrison, 1990). The trial may have advantaged the 'fines' treatments that were able to withstand heavy loads with minimal compaction.

Review papers on West Coast reclamation by Ross and Mew (1990), Mew and Ross (1991) noted a wide variation in the quality of reclaimed pastoral land, ranging from unsatisfactory pasture, with gorse reversion, to areas which were more productive than the original pasture. The review papers advocated separate stripping of topsoil and subsoil with replacement of topsoils and free draining subsoils and burial of poorly draining subsoils. Replacement of poorly draining subsoils was advocated only for limited areas of dairy farms where wetter soils can provide summer pasture production. Pasture sowing, lime and fertiliser rates similar to those for local farm development were advocated. The critical importance of post reclamation management to control weeds and the development of compaction was emphasised (Ross and Mew, 1990; Mew and Ross, 1991).

#### 3.3.4 Coal mining in Southland and Waikato

Open cast coal mines in New Zealand vary in size from the large Huntly and Ohai mines in Waikato and Southland respectively, to small mines on the West Coast of the South Island. Reclamation at the Ohai Coal field of Southland was initiated in 1982 to decrease water pollution of local streams by run off from unvegetated spoil heaps. Reclamation operations were based on European and United Kingdom technology (Griffin, 1982). The first detailed land reclamation trial was initiated by a proposal to develop a liquid fuels plant utilising Southland lignite (Ross and Widdowson, 1985; Widdowson and McQueen, 1990). Deep loessial soils of the region comprising a silt loam A horizon over a silty clay loam B horizon supported productive farmland. The trial, constructed near Waimumu in 1982, supplied information on soil replacement and management techniques for the restoration to pasture of loessial soil in an area with an average annual rainfall of 850 to 900 mm (Vortman, 1984; Ross *et al.*, 1985). The trial focused on the effects of soil compaction, nitrogen fertiliser, topsoil stockpiling, mole drainage and soil replacement on some chemical, physical and biological properties of soil and pasture production (Ross and Widdowson, 1987; Widdowson and McQueen, 1990). The soil reconstruction treatments constituted replacement of horizons in order (A-B-C), subsoil mixed with topsoil (AB-C) and overburden mixed with each soil horizon (AO-BO-CO) and an undisturbed control (Ross and Widdowson, 1987; Ross, 1988; Widdowson and McQueen, 1990). Overburden mixing was

included because laboratory and glasshouse trials indicated that the overburden was a suitable soil substitute (Ross and Widdowson, 1985).

Trial results indicated that machinery-induced soil compaction resulted in increased bulk density, especially where topsoil and subsoil were mixed or overburden added. These increases were not large,  $0.2 \text{ Mg m}^{-3}$  in the 0.20 to 0.50 m zone, but were thought to be possibly significant where bulk densities were greater than  $1.3 \text{ Mg m}^{-3}$  (Ross *et al.*, 1984; Ross and Orbell, 1986; Widdowson and McQueen, 1990). Soil structure deteriorated for all soil replacement treatments and was associated with development of anaerobic zones in the 0.20 to 0.60 m depths and concentration of plant roots on ped faces, particularly with AO-BO-CO and AB-C treatments (Ross *et al.*, 1984). Saturated hydraulic conductivities were reduced by soil replacement compared to undisturbed soils with surface ~~water~~ logging an intermittent problem on all replaced soils (Ross and Widdowson 1985; Ross and Orbell 1986). Mole drainage did not significantly affect pasture yields (Ross and Orbell, 1986; Ross and Widdowson, 1987).

Soil ripping was effective in the alleviation of compaction in all reconstructed soils (Ross, 1988; Ross and Orbell, 1986; Widdowson and McQueen 1990). Ripping increased subsoil hydraulic conductivity for 5 years following treatment (Ross *et al.*, 1984; Widdowson and McQueen, 1990), reducing 0.10 to 0.30 m soil water contents and improving soil physical conditions. Significant yield increases of between 6% and 54% were recorded on ripped treatments (Ross and Orbell, 1986; Widdowson and McQueen, 1990) with ripped treatment yields equivalent to or less than production from low compaction treatments (Ross and Orbell, 1986). Ripping, low compaction soil replacement and drainage did not significantly alter pasture botanical composition (Ross and Widdowson, 1987). Biochemical activity, net mineralisation and microbial biomass increased more rapidly in ripped compared to unripped plots with the enzyme invertase giving the best correlation with pasture productivity (Widdowson and McQueen, 1990; Ross *et al.*, 1992).

Heavy rates of nitrogen fertiliser increased pasture yields of all reconstructed soils (Widdowson and McQueen, 1990) and reduced pasture yield differences between reconstructed soils and undisturbed soils (Ross and Widdowson, 1985) as nitrogen availability limited pasture growth particularly in the treatments with mixed soil materials (Ross *et al.*, 1992). An annual application rate of  $200 \text{ kg nitrogen ha}^{-1}$  applied as a split dressing increased pasture productivity to undisturbed soil levels (Ross and Orbell, 1986). However, because high rates of nitrogen reduce clover abundance, a lower yielding, higher quality pasture was recommended.

Earthworm populations were seriously affected by soil stripping and replacement (McDonald *and Hall unpublished data*; Ross and Widdowson, 1987). Earthworm numbers were reduced to less than 10% of the population of the undisturbed soil in the first year (Widdowson and McQueen, 1990) and were exceptionally low in the AB-C treatment. Worm numbers increased significantly over four years as a result of migration from surrounding areas (Ross and Orbell, 1986) but were still

substantially higher in the undisturbed soil. Nitrogenous fertiliser applications reduced worm numbers by 10% on undisturbed soils and 20% to 40% on replaced soils. Ripping increased worm numbers by 90% to 200% on reconstructed soils and 13% on undisturbed soils (Widdowson and McQueen, 1990). Researchers concluded that restored soils would benefit from the introduction of earthworms (Ross and Widdowson, 1985) if the natural population surviving soil movement was too low (Ross and Widdowson, 1987). However, if more than 2 worms  $m^{-2}$  survive soil movement, then no introduction of earthworms are necessary (Widdowson and McQueen, 1990).

A pot trial using soil replacement treatments taken from the trial site found that none of three mycorrhizal inocula species had any significant effect on clover yield either in the cultivated control soil or reconstructed soils. In the pot trial white clover germination was depressed in all replaced soils and most depressed in the AB-C treatment (McDonald and Hall, unpublished data). Depressions of growth were associated with lower soil and plant nitrogen levels in all the replaced treatments in both pot trials and field trials, especially where topsoil was diluted (Ross and Widdowson, 1987). Topsoil dilution also resulted in markedly lowered organic carbon levels which persisted after 4 years (Widdowson and McQueen, 1990).

Researchers concluded that soil compaction and nitrogen deficiency were the major adverse consequences of soil stripping and replacement (Ross and Widdowson, 1987). Selective replacement of soil materials and management enabled the return of soil physical conditions and pasture production to levels equivalent to undisturbed soils within five years of soil replacement (Ross *et al.*, 1984; Ross and Orbell, 1986). Undisturbed soils most closely resembled the treatment where soil horizons were replaced in order and ripped. Mixing subsoil and topsoil together consistently produced lower yields by 30 to 50% (Ross and Widdowson, 1987), but the productivity of these treatments could be raised by ripping and applying nitrogen fertiliser at up to 200  $kg\ ha^{-1}$  per annum for several years (Widdowson and McQueen, 1990).

The Waimumu trials were associated with experiments investigating the chemical, physical and biological properties of stockpiled topsoil piles and pasture yield (Ross and Cairns, 1982; McQueen and Ross, 1982; Widdowson *et al.*, 1982). Pot trials on 10 year old stockpiled recent silt loam and gleyed recent soils found that chemical properties of both soils were little affected by storage. Pasture productivity of both ryegrass and clover were either similar to or higher than unstockpiled topsoil where pots had a basal application of all essential nutrients. Higher yields from soils from the lower parts of stockpiles were attributed to higher levels of mineral nitrogen, which had accumulated under anaerobic conditions, or lower populations of clover cyst nematode (Widdowson *et al.*, 1982).

Stockpiling resulted in increased soil dry bulk density and mechanical strength and decreased the proportion of macropores. Soil aggregate stability was decreased and cloddiness increased.



These effects were attributed to compaction from earthmoving during soil stripping and stockpile creation rather than the 'overburden effect' of stockpiling (McQueen and Ross, 1982). Microbial biomass and nitrogen content of soils from the top of stockpiles resembled an adjacent undisturbed soil under pasture. Soils deeper than 1.79 m in the stockpiles had elevated levels of plant available nitrogen with accumulated mineral nitrogen mainly in the form of ammonium. Soils from the lower, anaerobic part of the stockpiles, deeper than 1.79 m, had very low microbial biomasses (Ross and Cairns, 1982).



Photograph 3.3: An open cast coal mine (LHS) and reclaimed pasture with contour drains near Huntly, Waikato, 1990. Inset: contour drains and associated plantings of native species.

Reclamation research at Coal Corporation mines around Huntly has predominantly been informal or non-scientific. Most mined areas are reclaimed to pasture production (Photograph 3.3) with steeper faces planted with manuka (*Leptospermum scoparium*), radiata pine (*Pinus radiata*), tagasaste (*Chamaecytisus palmensis*) or tasmanian blackwood (*Acacia melanoxylon*) (Metcalf pers. comm., 1990). Chemical and physical characterisation of potential plant rooting mediums at Rotowaro and Maramarua mines was used to estimate and delineate volumes of useable soil materials for restoration. High percentages of clay and poor subsoil structures combined with poor to imperfect drainage meant natural soils were easily damaged by earthmoving operations (Ross and Orbell, 1986). At Rotowaro the fertility requirements of pasture and effectiveness of

different lime application rates and seed mixtures has been investigated. Liming to raise soil pH from 5.6 to 6.4 significantly increased white and red clover content of pastures but not the content of lotus. Increasing superphosphate additions from 250 kg ha<sup>-1</sup> (giving an Olsen P level of 3) to 2000 kg ha<sup>-1</sup> (Olsen phosphate level of 20) more than doubled pasture dry matter production (Longhurst and O'Conner, 1990). Longhurst and O'Conner (1990) concluded that soil physical factors such as compaction were more likely than soil chemical factors to limit pasture longevity at Rotowaro. Further trials showed that a 'soil conservation' seed mix, containing grasses which thrive in low fertility situations, produced 60% less dry matter at high fertiliser rates than an agricultural seed mixture which primarily comprised ryegrass, red clover and white clover, thus an agricultural seed mixture was preferred.

Two land reclamation trials have been carried out at Huntly East Mine, an underground coal mine located in the Kimihia opencast mine, which was active from the early 1940's to 1976. In 1976 New Zealand State Coal Mines (now Coal Corporation) decided to reclaim land at the site which was not needed by the new Huntly mine. The aims of reclamation were to plant the margins of the lake which would form at the cessation of mining. The former opencast mine occupied over 80% of Lake Kimihia and mostly lay below the water table. Until the lake formed, New Zealand State Coal Mines wanted to facilitate the productive use of 120 ha of fill area and mine site (Applied Geology Associates, unspecified date).

Subsequently, a pasture reclamation trial compared the productivity of 13 plots with 2 lime treatments, 3 seed mixtures and 4 fertiliser mixtures. The researchers recommended sowing 35 kg ha<sup>-1</sup> of predominantly ryegrass, white clover and maku lotus pasture species onto fill to which 7500 kg ha<sup>-1</sup> of lime had been mixed to 0.20 m (although the trial did not conclusively show an advantage related to this high rate of lime). The researchers also advised spreading 875 kg ha<sup>-1</sup> of superphosphate and 125 kg ha<sup>-1</sup> of di-ammonium phosphate in the first year to boost the chemical fertility of the fill (Applied Geology Associates, unspecified date).

In 1985 an unreplicated trial at Huntly east mine compared the establishment and growth of a range of tree and shrub species in a ripped flat and unripped slope of clay overburden which had very low nitrogen and phosphorus levels and a pH of 6.6. Consistently high performers in terms of height, percentage survival and vigour were hybrid silver polar (*Populus alba* 78353) on the flat while on the steep slopes nitrogen fixing alders (*Alnus* sp) and tagasaste showed the highest growth rates (Bullock *et al.*, 1990).

A report for State Coal Mines in 1986 provided general guidelines for reclamation of land affected by subsidence as a result of underground coal extraction in the Huntly West No.1 Mine. Subsidence had the potential to affect 2460 ha of lowland and rolling hills. Beca, Carter, Hollings and Ferner Ltd (1986) recommended stripping topsoil and upper subsoil layers before low-lying areas slumped, were inundated and formed habitats for water fowl. The consultants also



recommended field trials to investigate the effectiveness of measures to reclaim slumped areas on sloping pastoral land which was unlikely to become inundated.

### 3.3.5 Hard rock gold mining

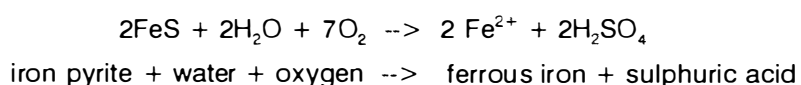
Gold was first found on the Coromandel Peninsula in 1852 (Isdale, 1981). By the early 1870's the Coromandel Peninsula had become a major area of gold exploration and surface mining. Gold mines on the Coromandel Peninsula are sited in small, discrete areas of hydrothermally altered volcanic rocks which tend to be high in pyrite (acid-generating material). In this section the Tui mine is used as an example of a mine approved before the 1971 Mining Act, while the Martha and Golden Cross mines show examples of modern, primarily agricultural, reclamation of dam bunds.



Photograph 3.4: The tailings pond, battery (LHS) and tailings pond bund above the sediment settling pond which contains toxic rust-coloured leachate (RHS) at the Tui mine. Vegetation only grows on "islands" of organic matter on both ponds.



The Tui mine, located on the slopes of Mount Te Aroha in the Kaimai Range, is probably the worst environmental situation arising from a mining operation in New Zealand (Fyson, 1991) (Photograph 3.4). The Tui mine produced lead and zinc concentrate from 1967 until 1973 when the mine was abandoned due to perceived mercury contamination of the concentrate (Hansen, 1989) leaving approximately 100,000 m<sup>3</sup> of potentially unstable acid-generating tailings. Oxidation of pyrite-containing tailings produces a leachate with a pH of about 2 and high levels of water-soluble lead, sulphur, arsenic, zinc, cadmium and mercury (Hansen, 1989 ; Fyson 1991) (Photograph 3.4).



Studies in 1978 and 1979 showed the Tui stream and the northern branch of the Tunakohia stream were polluted by leachate drainage. Levels of heavy metals in the water were above World Health Organisation limits for heavy metals (Waikato Regional Council, 1991), and rendered the Tui stream biologically lifeless (Livingston, 1987; Fyson 1991). Toxic leachate will continue to be generated as ground water and a spring in the base of the tailings dam will allow continued oxidation of the tailings (Waikato Regional Council, 1991).

In 1975 trials were carried out to determine if the area would rehabilitate with pasture grasses. A positive response was gained only with very heavy lime applications due to the acidity of the tailings. However the trial was only short term as it was terminated by a storm in 1976 (Waikato Regional Council, 1991). Revegetation of the dam is now the subject of a PhD study by John Morrell at Massey University.

The Martha Hill area at the base of the Coromandel Range near Waihi was one of the three highest-producing gold mines in the world in 1908 and closed in 1952 (Mathias, 1991). Further extraction of gold and silver from Martha Hill by the Waihi Gold Mining Company began in 1989. The open-cast mine is levelling Martha Hill and will create an artificial lake (Mathias, 1991). Mining involved disturbance of farmland by using it for disposal of waste rock and tailings (Stroud, 1986) (Photograph 3.5). Yellow brown loam soils at the site had a high phosphate retention and stable topsoil structure and were used predominantly for dairying and dry stock farming (Gregg *et al.*, in press). Oxidised waste rock and tailings were identified as having potential to form a surrogate soil from chemical and physical analyses (Widdowson *et al.*, 1984; Keating, 1988; Gregg and Stewart, 1991). Unoxidised waste rock contained acid-generating pyrites, was an unsuitable plant growth medium and was buried and sealed in tailings pond bunds (Gregg *et al.*, in press). Glasshouse clover and ryegrass pot trials confirmed that tailings and oxidised andesite/ignimbrite were suitable pasture growth mediums, provided nutrient deficiencies were corrected. Mixed and unoxidised waste was unsuitable. Additionally, oxidised

waste had satisfactory water retention characteristics but was susceptible to compaction (Gregg *et al.*, in press).

Waihi has a mean annual rainfall of 2150 mm (Lapwood, 1991) with mean rainfall and evapotranspiration figures indicating no water deficit in any month (Gregg *et al.*, in press). Demonstration trials with a variety of tree species, shrubs, cereals and pasture on oxidised waste rock and tailings indicated a wide variety of species not naturally occurring at the trial sites could be incorporated into a final land development scheme. Three replicated trials were established in 1985. Two trials investigated pasture growth on treatments with differing soil depths and fertiliser regimes on either oxidised waste or tailings. The oxidised waste trial also investigated modifications of the waste rock by liming and applications of potassic superphosphate. The third trial measured pasture growth on unmined soils.



Photograph 3.5: The Waihi Gold Mining Company mine. The pit, at bottom centre, is linked by a conveyor belt to the processing plant and the tailings dam at top right.

During the first year a depressed yield of pasture on unmodified waste rock with different soil depths was attributed to aluminium toxicity affecting root growth, especially of clover plants. In the following 1986/87 season the difference between modified and unmodified rock was much smaller, due either to higher phosphate inputs or leaching by rainfall decreasing the concentration of soluble aluminium in the waste rock (Gregg *et al.*, in press). Trials found that depth of yellow-brown loam topsoil was not a critical factor for pasture production (Gregg *et al.*, 1990; Horne *et al.*, 1990). By the third year there were no differences in pasture yield between any soil depth, whether underlain by modified or unmodified waste rock. Pasture yields from

both oxidised waste and tailings trials were similar to those of the reference site. Tailings data showed similar yields and results. The reclamation option chosen was 0.10 m of soil over limed and fertilised waste rock (Gregg and Stewart, 1991) as initial pasture growth was increased by application of lime and superphosphate to waste rock underlying topsoil (Stroud, 1986). By February 1992 12 hectares of reclamation on waste rock tailings dam walls was completed (Lapwood, 1991).

In 1986 and 1988 pot trials investigated the suitability of rooting media and nutrient requirements for horticultural crops and clover-ryegrass pasture (Stroud, 1986; Mason *et al.*, 1990). Stroud (1986) concluded that lime and phosphorus additions increased ryegrass and clover yields, because these nutrients were present in very low levels in modified waste, but potassium additions had no effect on yields. Lime increased clover yields more than ryegrass yields by reducing aluminium toxicity. Mason *et al.* (1990) found that for lettuce and broad bean crops fertiliser additions to pots based on field application rates resulted in excessive salt concentrations and plant death. Additions of poultry manure to waste and tailings resulted in substantially increased yields because the manure increased plant nutrient supply and improved the physical properties of the media. Field trials investigating plant establishment on a wetland created in a simulated tailings dam were implemented in 1992 (Mason pers. comm., 1992).

Cyprus Minerals New Zealand Ltd. submitted an Environmental Impact Report in 1987 for the Golden Cross mine development which included results from reclamation research (Cyprus Minerals (NZ) Ltd., 1987a; 1987b). The 25% opencast and 75% underground mine is located in the Coromandel ranges and receives an annual rainfall of about 3000 mm. Reclamation returned land to pasture with some plantings of native vegetation. Chemical analyses identified only one type of waste rock as suitable for surfacing permanent structures, as the majority of other waste rock types were pyritic (acid-generating) and contained high levels of heavy metals. Pasture trials were designed to determine the productivity of different subsoil, topsoil and subsoil-topsoil depths. Establishment of shrubs and trees in waste rock was also investigated (Cyprus Minerals (NZ) Ltd., 1987a); these results are unpublished.

A further two gold mines on the Coromandel were proposed in the early 1980's. Spectrum Resources Limited proposed to remove tailings from the old Maratoto Mill gold mine over a 22 week period (Commission for the Environment, 1985). The Wainui Road Mill and 20 ha tailings pond (the Martha Hill tailings pond is c.120 ha) was the third part of the Monowai and Maratoto proposal. The proposed tailings pond was located on land zoned Rural A; highly productive land prone to flooding. Pot trials indicated that the quartz and andesite tailings could be a suitable medium for growth of pasture. The company proposed to develop reclamation techniques from trials which would be established on the first tier of the tailings pond (Commission for the Environment, 1986). The 1986 audit criticised the company for not setting any productivity standards relating to reclamation. The 1985 environmental audit of the proposal concluded that

removal of the tailings and subsequent reclamation would substantially improve that part of the Coromandel State Forest Park and benefit future recreational users of the park (Commission for the Environment, 1985). But, the Minister of Conservation declined approval for the Maratoto-Monowai project (Paddington, 1985).

Gold mining commenced in the Macraes Flat area of Eastern Otago, 100 km north of Dunedin, in 1862 (Weston, 1991). Early alluvial extraction has now been replaced by hard rock mining of sulphide ore and weathered oxide ore (Peat, 1991). The area has an annual rainfall of 520 to 640 mm. Shallow yellow-grey earth soils derived from schist on undulating hills, dissected by steep gullies, support low-productivity tussock and introduced grass pastures (Macraes Joint Venture, 1989; Weston, 1991). Reclamation was identified in an environmental scoping report in 1987 as a major issue raised by the proposed development. The primary aim of reclamation was to return the area to a landform which blends with the landscape, requires minimal maintenance and is capable of sustaining pastoral agriculture to levels comparable to the pre-mining state (Macraes Joint Venture, 1989). Reclamation trials commenced in 1988 with glasshouse pot trials to determine the potential of various rooting mediums and soil supplements for pasture production, also to identify phytotoxic elements. Field trials, established in 1988, found pasture establishment and yield in year one were far superior where topsoil and subsoil were replaced in their original order rather than mixed together. In the second year, however, there was no significant yield difference between mixed and unmixed treatments (Cossens and Keating, 1990). Where topsoil was undiluted, sweet vernal (an adventive weed) initially comprised 51% of the replaced surface cover compared to 8% on mixed subsoil-topsoil treatments. Topsoil replaced in two compacted 0.10 m layers grew pastures with low dry matter yields in year one, but the same yields as other treatments in year two. Cossens and Keating (1990) concluded that pasture establishment on reclaimed areas should comprise a 0.30 m depth of soil, incorporating 0.10 m of topsoil, sown at double the normal agricultural seeding rates.

### 3.3.6 Reclamation of West Coast mine sites to indigenous forest

In 1977 possible techniques for reclamation of indigenous beech (*Nothofagus solandri* and *N. menziesii*) forest were included in the Environmental Assessment for the Island Block opencast coal mine, located in the mountains near Reefton on the West Coast (Cawthron Technical Group, 1977). Reclamation techniques were adapted from soil conservation methods and observation of natural revegetation of nearby coal mines, road batters and side cast slopes. Observation of disturbed exposed areas showed a 10 to 20 year pioneer phase of grasses with woody plants sourced from neighbouring trees gradually ingressing after this time. Where a light but sheltered environment and stable surface occurred, beech and other seedlings established without a dominant grass phase. A suggested reclamation technique for establishing forest on the 35 to 40 degree slopes of mine tailings and overburden was mini-terracing in conjunction with poplar or willow pole, green alder or creeping tutu planting. Other reclamation options suggested were

hydroseeding with *Lotus* and *Agrostis spp* and/or planting fast growing exotic trees into which local indigenous tree species would seed naturally, be broadcast or seedlings planted. In a review of naturally revegetated mine sites Fitzgerald (1987 cited by Norton, 1991) concluded that "*workings can regenerate back to (indigenous) forest within one hundred years or so, but it would take several hundred years for the full species complement and natural structure of the forest to be achieved*".

Metcalf and Godfrey (1990) described "tried and tested recipes" for reclamation to indigenous and exotic forests on the West Coast. They advocated spreading of topsoil or, where topsoil was not available mixing fines with tailings. However they also recognised that gorse competition with native species was limited where topsoil was not replaced (Gregg *et al.*, 1990 page 98). Spreading forest trash and slash over exposed sites to create microclimates aids natural reseeding from stockpiled soil or adjacent areas (Metcalf and Godfrey, 1990). Manuka slash was advanced as generally promoting natural regeneration and used in addition to planting except where only manuka was desired. Metcalf and Godfrey (1990) stated that legumes have proven to be very beneficial for exotic and indigenous vegetation establishment, because they supply additional nutrients while reducing competition from gorse and other adventive weed species. Fertilising individual trees was reported to be more effective than broadcast fertilising which promotes competing weed as well as target tree growth (Metcalf and Godfrey, 1990). In their review papers Ross and Mew (1990; 1991) and Mew and Ross (1991) advocate techniques similar to exotic forestry plantings for reclamation to indigenous forest. In addition important principles affecting regeneration were stated as fire, grazing by domestic stock and wildlife and removal or degradation of topsoil, organic layers and/or fines.

Mackenzie and Cave (1991) reported on reclamation trials that were in progress at Slab Creek Hut, Kennedy's Creek and Yanks Road in Westland. The trials, which included ongoing monitoring and planting of indigenous and exotic plants, were being directed by the Department of Conservation on alluvial gold mined areas. Observations at Yank's Road indicated alders planted on contoured tailings were 1 to 1.5 m taller than counterparts grown on topsoiled tailings, possibly due to competition from gorse growth on the topsoiled treatment (Mackenzie and Cave, 1991). No conclusions were reported from the Slab Creek or Kennedy's Creek trials.

In 1990 two linked research projects were contracted by the Department of Conservation to provide information on methods for restoring beech-podocarp forest in Westland. The projects focus on techniques which promote development of a closed canopy of fast-growing native species that provide suitable conditions for establishment and growth of indigenous forest (Ministry of Forestry, 1992). At the Giles Creek Coal mine near Reefton coal was extracted from beneath alluvial terrace gravels covered largely with cut over beech forest. The site has links to both alluvial gold mining, through the presence of gravels, and open cast coal mining through the coal overburden (Mew and Ross, 1991). One project is investigating techniques for establishing

and growing indigenous woody species on raw overburden and overburden covered with soil (Davis and Crozier, 1991; Ministry of Forestry, 1992). A companion project is investigating soil and overburden characteristics. This project is also monitoring a range of soil reclamation techniques in relation to site factors and management inputs. Initial treatments include 0.5 m of stripped mixed soil materials over contoured overburden gravels, soil on coal overburden, both with a ripping treatment, uncovered gravels and uncovered coal overburden (Mew and Ross, 1991; Ross, 1992). Field trials on gravel overburden and associated well drained, strongly leached yellow brown earths, with thin topsoil and litter layers, were constructed from 1990 to 1992. The trials will be monitored until 1997 (Ross, 1992).

A pilot trial at Giles Creek established in August 1990 found that animal damage to reclaimed plantings was minimal. Interim conclusions after one year of the trial were that beech (*Nothofagus* species) establishment using container plants was more successful than using bare root transplants with 10% to 50% compared to a 60% to 100% mortality rates respectively. Broadleaf (*Griselinia littoralis*), kahikatea (*Dacrycarpus dacrydioides*), totara (*Podocarpus totara*) and ribbonwood (*Plagianthus regius*) were successfully established using bare root transplants. High plant mortalities were thought to be due to poor drainage resulting from compaction. Adverse soil physical conditions were proposed as major limitations to *Coprosma robusta* growth as *Coprosma* growth in the field was not advantaged by nitrogen or phosphorus applications, despite glasshouse trials indicating marked responses to these nutrients (Davis and Crozier, 1991). In both field and glasshouse trials using stockpiled soils from the Giles Creek site, growth of native species was poor due to competition from exotic weeds (Ministry of Forestry, 1992). Interim results from the soils project indicate organic matter, contained mainly in undisturbed soils A and O horizons, is diluted in spread, mixed soils (Ross, 1992).

### 3.3.7 Aggregate mining

Detailed research on reclamation of aggregate mines in New Zealand began in 1978 with trials on a commercial aggregate extraction site near Nelson. Experimental mining of aggregate underlying alluvial stony silt loam soils was permitted in a Planning Tribunal decision in order to supply high quality aggregate at a lower cost than alternative distant sources (Ryan, 1985). Extraction was also promoted as a means of land improvement, despite Ministry of Works, Soil Bureau and Nelson Catchment Board concern that the high to very high quality food production soils would be damaged. An experimental extraction operation was permitted on two 5 hectare areas to assess and develop reclamation methods and determine the long term effect on soil productivity. A Soil Bureau study investigated soil physical and temperature changes and crop characteristics associated with reclaimed soils. Physical measurements were monitored over a 14 month period with cropping measurements over two summer growing seasons (McQueen, 1983).



Trial results were reported by the Ranzau Gravel Mining Evaluation Committee in 1982 and published in detail in a New Zealand Soil Bureau Scientific Report by McQueen (1983). The trial found reclaimed Ranzau soils had more variable thicknesses and a greater abundance of stones, gravels and coarse aggregates than undisturbed soils (O'Byrne and Campbell, 1983). Reclaimed soils displayed increased air-dry clod densities, doubled air-dry penetration resistance and decreased total porosity in clods. Disturbed soils had a weaker structure with a lower resistance to dispersion and decreased aggregate stability, which improved over time in topsoils but not subsoils. Infiltration rates were half and one tenth of those in undisturbed soils in the A and B horizons respectively of reclaimed soils, resulting in a material with severely limited trafficability (Leighs and Duck, 1983; McQueen, 1983). A pronounced textural change between the replaced soil and underlying material also impeded water movement (Leighs and Duck, 1983).

Differences in soil temperature between reclaimed and undisturbed soils were mostly small and probably not significant in relation to other soil factors (Aldridge, 1983). Both A and B horizons of restored and undisturbed soils were chemically similar. The lowest horizons showed the greatest chemical difference as the reclaimed soil had an unweathered C horizon of gravels and stones which was a poor medium for plant growth (McQueen, 1983). Cropping trials in the 1978/79 and 1979/80 growing seasons showed significant reductions of pea, barley and turnip yields on reclaimed areas with no indications that yields were recovering in the short term. Physical deterioration of the soil was identified as the major factor causing reduced yields (McQueen, 1983). The Ranzau Gravel Mining Evaluation Committee concluded that the experiment had been disappointing with respect to crop production from the reclaimed soil, that the highly versatile silt loams are easily damaged and that the damage was probably long lasting (Duck and Burton, 1985).

Results from cropping trials were inconclusive as delays in planting reclaimed areas contributed to the large yield differences measured. In 1978 treatments on reclaimed and undisturbed soils were sown in spring 6 weeks apart but harvested on the same date. The control was sown when soils held approximately 54 mm plant available water and the reclaimed site sown when soils held approximately 10 mm plant available water and just before a 3 week period during which soil moisture was estimated to be exhausted. This must have had a severe effect on plant production at the reclaimed site. In 1979 the reclaimed site was sown 3 weeks later than the control and again both treatments were harvested on the same date. In both cases high soil moisture contents (low soil moisture tensions) of reclaimed soils prevented earlier sowing (McQueen, 1983). However adopting differential sowing dates on restored and undisturbed land did illustrate the full advantage of undisturbed land.

Sowing the trial with annual crops would have resulted in greater and longer term soil damage than if traditional restorative crops such as pasture, which avoid annual fallowing, cultivation and seedbed preparation, were sown. The crops sown were also more sensitive than pasture to

adverse soil conditions, so were clearer indicators of poor soil conditions. In the trial topsoil spreading occurred at high soil water contents when the undisturbed Ranzau soil was close to or at field capacity. The inclusion of a trial area where optimum reclamation practices were adhered to would have allowed a separation of soil and management influence on reclamation success.

In 1982 an application to mine aggregate from approximately 4 ha and plant kiwifruit was approved by Waimea County but with conditions. These included: restrictions on soil movement during wet periods, the formation of a consultative reclamation group and the monitoring of reclamation by soil physical measurements and crop growth measurements over five years (Duck and Burton, 1985). Results of the physical measurements after soil replacement showed similar results to those reported by McQueen (1983). Comparative measurements of herbage growth were not possible. Duck and Burton (1985) concluded that extraction and reclamation had resulted in an overall deterioration of soil physical properties and soil versatility especially in its potential for growing arable crops. The main reclamation problems resulted because of deviation from the planned rolling reclamation and the unavailability of suitable machinery (Duck and Burton, 1985).

Leslie (1990) examined six sites in the Nelson-Ranzau plains area that had been commercially reclaimed. Most measurements of soil physical characteristics were fairly inconclusive and comparisons with unmined land were unrealistic as controls were undisturbed soils rather than renovated pastures sown at the same time as the reclaimed areas. This meant plant production could not be compared within sites. Leslie's findings on the effect of reclamation on soil physical properties are generally similar to those of McQueen (1983).

Leslie (1990) found reclaimed areas had greater surface and topsoil stone contents and a more distinct boundary between topsoil and underlying subsoil or gravel. Reclaimed soils had highly variable soil depths and an absence of earthworms. The stability of aggregates in reclaimed sites was half that of undisturbed soil with significant increases occurring in aggregate stability measured over a two year period at the best reclaimed site. Increased compaction and decreases in macroporosity were identified in only a third of sites. Most reclaimed soil profiles displayed gleying at the base with saturated hydraulic conductivity halved in reclaimed sites on average. The least decrease was in very stony soils. Bulk density had a weak negative correlation with saturated hydraulic conductivity. There was little difference in unsaturated hydraulic conductivity between reclaimed and unmined soils indicating that microporosity was little affected by soil shifting and reclamation procedures (Leslie, 1990).



### 3.3.8 Sources of information on mining reclamation

In New Zealand a significant proportion of recent reclamation research has been contracted by individual companies. These largely unpublished reports can be valuable sources of information but are not widely available. Commercial research contracts in which clients require confidentiality of results may also limit technology transfer. For example two review publications in 1991 sponsored by the Ministry of Commerce, "*Restoration of indigenous vegetation on sites disturbed by alluvial gold mining in Westland*" and "*Rehabilitation guidelines for land disturbed by alluvial gold mining in Nelson and Westland*", cited four unpublished private contract reports on mining practices, the use of native plants in rehabilitation, natural regeneration after mining and land rehabilitation guidelines. Publications related to major mining proposals are major sources of information. These include Environmental Impact Assessments and Reports, articles in scientific journals and New Zealand Soil Bureau reports. Soil Bureau reports have also been an important source of detailed information on mining reclamation research. Unfortunately the value of "in house" reports is diminished as many are unreviewed and not able to be referenced.

Conferences are important sources of information on formal and informal reclamation research and practice. There have been increasing numbers of papers on New Zealand reclamation given at conferences, culminating with the 1990 Land Restoration Workshop at Massey University at which 29 papers and posters were presented. In 1981 and 1986 two workshops involved practitioners outlining specific reclamation projects, followed by discussions (Gregg, 1987). Papers on aspects of reclamation have been presented at conferences of the Waste Management Association, Soil Science Society (Widdowson *et al.*, 1989; Gregg and Stewart 1991a; Simcock, 1991), Association of Soil Conservators (Leighs and Duck, 1983; Duck and Burton, 1985) and Institute of Mining and Metallurgy (Gregg and Stewart, 1991b). Experiences of practitioners have been disseminated through technical papers given at Aggregates Association and Institute of Quarrying annual conferences. At the 1990 Aggregates Association conference, for example, papers were presented on reclamation for horse studs (Cohen, 1990), deer farming (Cowley, 1990), bull beef production (Simcock and Stewart, 1990) and an ornamental garden (Hunter, 1990).

In New Zealand there is no group representing reclamation professionals and no specialist reclamation magazine or newsletter. An organisation, which was to be affiliated to the Canadian Land Reclamation Association, was proposed in 1990 but has not been established. Articles on aggregate extraction and reclamation were published in *Soil and Water* (Wing, 1979; Botham, 1983; Anon, 1985a; Ryan, 1985; Ross and Widdowson, 1987). *The Landscape* published articles based on reclamation and revegetation practice relevant to the landscape architecture profession (Jackman, 1976; Heath, 1986<sup>a,b</sup>; Greenup, 1988). Article subjects have included species choice and establishment on road side batters (Milligan, 1986), hydroelectric dams (Scheltus, 1983; Brown, 1986) and railway line revegetation in the Central Plateau region (Nicholls, 1986). *Terra*

*Nova* was a resource management magazine which focused on analyses of environmental legislation and case studies which were often pertinent to reclamation (Roberts, 1991; Weeber, 1991; Buhrs, 1992; Shields and Webber, 1992). *Terra Nova* also contained articles on aspects of the mining industry and reclamation (Peat, 1991; Quinn *et al.*, 1991; Mew and Ross, 1991; 1992). *New Zealand Soil News* has reported on workshops and reclamation experiments (Ross and Widdowson, 1985; Gregg, 1987). Sections detailing existing reclamation work have been included in reports on regional aggregate resources in Taranaki (Taranaki Catchment Commission, 1981; Taranaki Regional Council, 1992), Wellington (Ward and Grant, 1978) and Christchurch (Bennett *et al.*, 1982). New Zealand scientific journals that have contained articles on reclamation include the *New Zealand Journal of Agriculture* (Ross, 1987), *New Zealand Journal of Agricultural Research* (Sears *et al.*, 1965; Cook *et al.*, 1986), *New Zealand Journal of Agricultural Science* (McDonald and Dolby, 1986) and *New Zealand Journal of Science* (McQueen and Ross, 1982; Widdowson *et al.*, 1982).

Much of the work of the National Plant Materials Centre at Aokautere has involved stabilisation and revegetation of soils disturbed by nature or human induced processes. The Centre produced plants to revegetate a range of eroding sites with different fertilities and climates, from sand dune stabilisation and gully erosion control to slip revegetation and roadside or hydro-electric dam batter revegetation (Bulloch *et al.*, 1990). Researchers at the Centre also described the propagation, uses and requirements of over 70 indigenous and 80 exotic plant species in volumes 2 and 3 of the "Plant materials handbook for soil conservation" (Van Kraayenoord and Hathaway, 1986; Pollock, 1986).

Very little postgraduate research has been conducted in reclamation. Chow (1970), Griffin (1982) and Liggins (1984) submitted reports on general reclamation techniques, reclamation of farmlands disturbed by Southland lignite mining and sediment control of surface mined land respectively as requirements for the Bachelor of Mineral Technology degree. Leslie (1990) surveyed reclaimed aggregate mines in the Nelson - Waimea Plains area as part of his masterate. The New Zealand Annual Mining Review has included a section on current research projects conducted by universities and government organisations which are related to the mining industry, including reclamation research, since 1990.

#### **3.4 Non-mining research relevant to reclamation of mined sites**

Research and observations in fields related to reclamation are important sources of information in New Zealand due to the paucity of rigorous scientific reclamation research. Revegetation of disturbed land associated with major engineering works, for example pipeline and dam construction, land contouring and soil relocation also has many similarities to mining reclamation. General principles and practices of soil conservation relating to stabilisation of disturbed land

without using vegetation, for example drainage and erosion control structures, are not examined although many of these techniques are applicable to mining reclamation.

Many reclamation techniques have been adapted from traditional forestry and agricultural practices. Where mined land is to be reclaimed to pasture, reclamation techniques have often been adapted from agricultural experiments and practice, particularly those investigating pasture renovation, species choices and fertiliser applications. Cossens and Keating (1990), for example, identified possible problems and solutions associated with reclamation at Macraes flat gold mine by analyzing previous experimental work on similar Otago soils. Relevant research included pasture trials assessing fertiliser requirements for over-sown tussock and the establishment and production of over-sown legumes. Cossens and Keating (1990) determined fertiliser applications on nearby farms, assessed grass and legume species in areas with the same climate and reviewed methods of enhancing hawkweed-infested tussock. Agricultural research pertaining to prevention, formation and relief of compaction and soil physical conditions required for plant growth are also often directly applicable to mining reclamation practice. Greenwood (1989) and Harrison (1993), for example, researched subsoiling and compaction and Horne (1985) investigated effectiveness of mole drainage. As the research literature on agricultural practices is vast and well reviewed, the area is not included in this review.

#### 3.4.1 Indigenous afforestation

Indigenous, amenity or production forest reclamation techniques may be adapted from studies of natural and planned revegetation of erosion scars, farm land, volcanic materials, railway or roadside cuttings, logged indigenous forests and degraded forests. In most of these situations the degree of land disturbance is much lower than for mining sites (Ross and Mew, 1991a) where soil materials may not be available and large exposed areas are devoid of shelter and limit natural seed ingress. However when faced with extremely limited mining reclamation research in New Zealand such studies provide information and guidelines on potential species for revegetation and species ecological requirements. Studies can be divided into those concerning primary succession, which occurs on bare mineral surfaces that have not supported plants before, and secondary succession which occurs naturally where residual soil and plants survive and artificially where topsoil is returned, forest trash and seed bearing slash spread and/or seedlings planted.

Recent papers in the *New Zealand Journal of Botany* and *New Zealand Journal of Ecology* have examined forest recovery after logging (Baxter and Norton, 1989), characteristics of rainforest soil seed banks (Enright and Cameron, 1988; Partridge, 1989) and vegetation successions on erosion slips (Mark *et al.*, 1989) and burnt areas (Allen, 1988). Baxter and Norton (1989) found that logged Westland rimu forest was dominated by kamahi (*Weinmannia racemosa*), quintinea and rimu (*Dacrydium cupressinum*), 57% of which were not present prior to logging. They concluded

that it was likely that the original forest type would return if the area was left undisturbed. Enright and Cameron (1988) studied the number of transient (less than 2 years old) and dormant viable seeds (greater than 2 years old) in a rainforest soil. They concluded that seed presence of a species was affected by seed longevity, seed accumulation rates and the environment. In the undisturbed forest, light demanding species such as adventive weed species, kanuka (*Kunzia ericioides*), *Coprosma arborea* and putaputaweta (*Carpodetus serratus*) were dormant. Enright and Cameron's (1988) research emphasises the potential of soil stripping and spreading to supply species that are suited to an exposed environment, including potential weed species even though they may be rare in the undisturbed forest. Partridge (1989) concluded that the soil seed-bank plays a minimal role in preserving later successional forest species. He also reported that competition and differential survival of seedlings may result in development of a completely different vegetation from that originally present, especially where the litter layer is burnt. A study of *Pinus* ingression into tussock lands by Allen and Lee (1989) illustrated the importance of a continuous canopy in reducing ingression of adventitious species into native ecosystems. They concluded that establishment of *Pinus spp* was minimised where there was a high density of tussock bases, high cover and density of inter-tussock vegetation and a continuous tussock canopy.

Study of successional sequences of indigenous ecosystems on erosion sites (e.g. Bläschke, 1988; Boase, 1988) can help determine reclamation strategies, such as nutrient level modification and correct soil physical conditions, to promote plant growth. Identification of pioneering species may indicate species suitable for different reclamation situations, which should be introduced to a mined site as seed, seedlings or vegetative material. Additionally, successional sequences may enable monitoring agencies to determine completion criteria within 5 to 10 years of reclamation as it is impractical to hold a mining company responsible for reclaimed land until an ecosystem with pre-mining characteristics has established.

Mark *et al.* (1989) and Allen (1988) found that manuka (*Leptospermum scoparium*) was the dominant pioneer species on eroded sites in Fiordland and burnt sites in Otago, respectively. Species richness generally increased over time as seedlings of forest trees establish under the manuka and gain access to light when old manuka trees die. Allen (1988) found that where seedlings of canopy and understorey species were present without manuka, establishment of the original forest was much faster. Wardle (1980) investigated succession on low altitude surfaces exposed through glacial retreat in Westland. Silver beech (*Nothofagus menziesii*) rapidly colonised bare mineral gravel slopes where a seed source was nearby. Where a beech seed source was not present a long sequence of revegetation over 4000 to 5000 years commenced, beginning with native grasses (*Poa novaezelandiae*). After 40 years *Olearia avicenniaefolia* scrub with an understorey of forest tree seedlings developed. After 130 years *Schefflera digitata* replaced *Olearia* with pole sized podocarps growing above the *Schefflera* canopy after 300 years. These first generation podocarps were still present 1000 years later. Wardle's research highlights

the long time reclamation to the original forest community may take. Basher and Tonkin (1985) investigated the impact of erosion on the ecological stability of indigenous plant communities in central South Island hills. They found that ecological stability was partly dependant on the nutrient availability of exposed subsoils, with exposed subsoils generally inhibiting natural or assisted revegetation due to very low cation exchange capacities and P, S, K and Mg deficiency. Basher *et al.* (1985) investigated successional sequences which correlated with soil development in central Westland. They found that at 800 m altitude low scrub evolved into tall scrub over 140 years, which in turn developed into subalpine mixed scrub and podocarp forest after about 1000 years.

Clarkson (1990) reviewed primary and secondary succession following volcanic eruptions of Rangitoto and White Islands and the Mountains: Tarawera, Taranaki, Ngauruhoe, Tongariro and Ruapehu within the last 450 years. Three studies reviewed revegetation of diverse forests after eruptions of Tarawera, Rangitoto and Taranaki volcanoes. At Tarawera an initially diverse flora was reduced from 50 to 10 taxa as continuous scrub, dominated by tutu (*Coriaria arborea*) developed. Seedlings of kamahi (*Weinmannia racemosa*) and broadleaf (*Griselinia littoralis*), established preferentially beneath tutu species and eventually replaced tutu. The evolving even aged forest had the potential for cohort senescence and dieback which will provide an opportunity for other canopy species to reach the canopy. Timmins (1983) reported that the species present on revegetated areas of Mount Tarawera were influenced by the distance of the disturbed areas from sources of propagules. At Taranaki a vegetation sequence began with *Coriaria*, through kanuka (*Kunzia ericoides*) and *Fuschia exorticata* to kamahi forest. On Rangitoto where conditions were not suitable for pohutakawa (*Metrosideros excelsa*), manuka, koromiko (*Hebe stricta*), tutu and *Olearia turfuraceae* were dominant in primary successions.

Clarkson (1990) reported that where disturbance was extensive and severe with homogenous, excessively drained or exposed habitats, slow "classical" vegetation successions developed. Nitrogen fixers such as tutu and lichen species facilitated ingressions by flowering plants by improving soil conditions. Plant establishment was dependant on the type of rooting medium, with succession being faster where available phosphorus, which promotes tutu, was present. Taxa ingressed through wind blown or bird dispersed propagules. Heterogeneous substrates enabled greater concurrent plant diversity, for example, where higher fertility basaltic tephra (ash) was retained at Mount Tarawera mahoe (*Melicytus ramiflorus*) has dominated with kamahi growing on lower fertility areas. Where vegetation was severely damaged and new surfaces were discontinuous plants established through seed banks, vegetative regrowth and short distance dispersal. Decay of damaged and dead plants may provide an initial nutrient source. Clarkson (1990) identified *Metrosideros* species, kamahi, tawa (*Beilschmiedia tawa*) and mahoe as tall forest trees able to quickly occupy bare areas by wind blown seed or from coppiced material with kamahi and tawa displaying epicormic budding. Clarkson's review illustrates the importance of utilising forest trash and topsoil in reclamation of mined sites. Additionally the review raises

the potential for vegetation establishment using cuttings or direct transfer of vegetative material and illustrates that aiming for a maximum number of species may not be an important reclamation goal in the early years following reclamation.

Follett and Dunbar (1985) reported on a three part research project investigating the use of native plants for riparian revegetation in South Island mountain catchments from 1976 to 1981. They felt native species could provide increased long term effectiveness and stability of riparian zones through increasing diversity of riparian vegetation. Experiments with *Olearia avicenniaefolia*, *Hebe odora*, *Cassinia fulvida*, *Coprosma rugosa* and *Griselinia littoralis* found that cuttings taken in late summer to early winter were the most reliable method of propagation with rooting hormones, bottom heat and misting being unnecessary. In Kowhai Valley, plantings of bare rooted seedlings into gravels in 1977-79 and 1981 showed superphosphate and urea fertiliser applications at planting had no effect on plant survival or growth rate but greatly increased surface herbaceous cover, especially browntop and birdsfoot trefoil species. A pot root growth study showed that *Cortaderia richardii* had the highest root weights but had few fibrous roots that would effectively hold easily eroded material while *Olearia*, *Cassinia* and *Hebe* had favoured fibrous root systems. Pot yields of *Cortaderia* decreased with urea applications. Follett and Dunbar (1985) concluded that *Olearia*, *Cassinia* and *Hebe* were the most desirable native species for riparian stabilisation with *Hebe* able to form new roots from partially buried stems, however no native species were as effective as willow (*Salix purpurea*).

Atkinson (1988) reviewed examples of indigenous ecological restoration in New Zealand of islands and mainland reserves. He contended that continuing active intervention was required to restore native ecosystems and reactivate ecological processes operating within the original biotic community. Tiritiri Matangi, Mana and Mangere Islands, which range in size from 113 to 222 ha, were all farmed with only small, often degraded, remnants of their original forest cover remaining. The exposed nature of the islands has necessitated the planting of intermediate sheltering species. On Mangere Island in the Chatham group, restoration from 1974 to 1979 established flax (*Phormium tenax*) as shelter belts interplanted with *Olearia traversii*. The *Olearia* failed to successfully establish as underestimation of the effects of salt and wind meant that *Olearia* was planted on some over-exposed sites. Atkinson (1988) suggested that the Chatham Island ngaio (*Myoporum laetum*), which has a greater capacity to sprout after salt damage, may have been a better choice of species. A further problem was the death of many plants from wind throw, related to insufficient maintenance of plantings. Reclamation of forest on Mana Island, north of Wellington, focused on establishing wind breaks of flax, ngaio, akekake (*Dodonaea viscosa*) and taupata (*Coprosma repens*). In addition, clumps of these species, spot-planted with successional plant species, were planted in areas to act as sources of seeds as well as food for birds.

Atkinson (1988) advised that control of introduced mammals and fire were priorities in mainland forest reclamation. He also reported that revegetation of roadside slopes in Porter's Pass,

Canterbury, which was initiated in 1974 demonstrated that subdivision and transplantation of mature snow tussock (*Chionochloa flavescens*) plants to stabilise scree slopes was feasible. Atkinson described plantings at Matawai Park, Rangiora, where 2 to 3 m tall podocarps and beech species were achieved 13 years after planting under a kanuka and *Pittosporum* nurse canopy. The nurse crop was 4 to 5 m tall and planted into pasture 2 years before the podocarps were established.

Between 1980 and 1987 a similar project in the Manawatu involved reforestation of 1.7 ha of grass and gorse near Keebles bush. The project utilised 900 tree lucerne seedlings as the major nurse species with koromiko, kohukohu (*Pittosporum tenuifolium*), lemonwood (*P. eugeniojdes*), ngaio, lacebark (*Hoheria populnea*), lowland ribbonwood (*Plagianthus regius*) and karamu (*Coprosma robusta*) utilised as initial native cover species with manuka planted on the wetter sites. Atkinson (1988) described restoration activities at the 106 ha Hinewai Reserve, which comprised steep farmland with patches of red beech forest, kanuka forest and secondary hardwoods between 240 to 600 m altitude on Banks Peninsula. Gorse, broom and kanuka were used as nurse cover for taller native trees which would eventually overtop and shade out the shorter gorse and broom.

Methods of revegetation developed through trial and error by landscape architects have been described in *The Landscape* periodical. These have included techniques of laying manuka slash (Nicholls, 1983), establishing nursery raised native plants (Heath 1986a; 1986b) and choice of species (Milligan 1986). Heath (1986a; 1986b) with Brown and Heath (1987) contended that revegetation by natural seeding was not suitable for large areas of disturbed land distanced from forest and advocated planting the smallest nursery-grown seedlings that would readily establish to avoid development of a contrived-looking landscape. Heath (1986a; 1986b) emphasised spreading forest litter where possible to introduce mycorrhizae, sourcing seed from within the same ecological district and using tree lucerne as a cover crop to facilitate native forest establishment. Brown (1986) noted that there were few examples of successful native revegetation of extensive, highly modified areas and that native toetoe and tussock species were most suited to direct seeding, with limited success achieved with other native species. Brown and Heath (1987) specified the benefits of root-trainer grown nursery stock over conventionally grown container plants as reduced establishment, nursery and transport costs, rapid planting and fast growth.

Milligan (1986) identified the potential fire hazard and impact on the landscape of plant species as critical factors governing the location and selection of species for revegetation of the earthquake gully highway realignment on the eastern side of Lake Taupo. These were also factors which prevented the use of toetoe and bracken for revegetation of rail embankments, cuttings and retired sections of railway tracks along an 8 km section of the main trunk railway line 600 to 800 m a.s.l. within Tongariro National Park (Scheltus 1990). The railway line passed through both virgin and degraded podocarp/kamahi/rata forest (Photographs 3.6 and 3.7), broadleaf forest/shrubland, bracken fern and toetoe grassland (Keller, 1985; Scheltus 1990).





Photograph 3.6: Reclamation of a stockpile of laharic material adjacent to the main trunk railway, Ohakune. Manuka slash was either laid directly on the laharic material (LHS) or on a 0.3 to 0.5 m layer of replaced forest soil (RHS).

Topsoiled and bare Tertiary siltstone (*papa*), cemented lahar material and ash substrates with low levels of N and P had to be revegetated to an indigenous forest cover. Most sites were exposed to sun, wind and 120 to 140 ground frosts per year (Scheltus, 1983). A policy of encouraging native succession starting with hardy pioneer species and allowing natural regeneration to forest was adopted (Nicholls 1986; Scheltus 1990). Many sites were stabilised and seeded with a 50 to 60% coverage of manuka slash containing seed capsules (Nicholls, 1983; Nicholls, 1986) (Photograph 3.6). Where possible forest *trash* comprising logs and branches was spread to create sheltered microclimates for growth of naturally seeded species (Nicholls, 1984; 1985; 1986) (Photograph 3.7). On inaccessible and steep sites revegetation was assisted by hydroseeding with *Agrostis* (browntop) at 3 kg ha<sup>-1</sup>. This low seeding rate allowed ingress of native seedlings while stabilising the rooting medium.

In 1990 quadrats were established at six sites adjacent to the railway line to facilitate monitoring of plant succession and comparison of paired revegetation treatments. A comparison of areas of *papa* embankment spread with viable or non viable manuka slash showed that both sites had the same total number of species and no difference in density of manuka seedlings on embankment slopes with very little manuka germination. Comparison of *papa* areas covered with stockpiled or unstockpiled soil found the stockpiled area had a lower percentage of vegetative cover and lower height of vegetation. This was postulated to be due to loss of leachable N generated in anaerobic piles of stockpiled soil. Additionally domination of *tutu* and *toetoe* limited





Photograph 3.7:

Forest trash has been spread to create microclimates for seedling growth adjacent to the railway, Ohakune. The original podocarp-hardwood forest is in the background and mudstone (papa) has been washed onto the site (foreground).

species diversity in the unstockpiled soil area which had 6 compared to 33 species. Comparison of lahar stockpiles with or without soil found that topsoiled areas had more species present (35 compared to 18 species), greater vegetative cover and taller vegetation (Photograph 3.6). This was because the topsoil contained viable seeds and <sup>was</sup> a more favourable environment for seedling germination and growth. The report concluded that the manuka slash used was ineffective at producing persistent seedlings on papa substrates but seedlings survived in areas of topsoiled lahar, that topsoil and forest trash were valuable resources and that the most successful colonisers in terms of height and species density were toetoe (*Cortaderia richardii*), *Coprosma* species (*C.robusta* and *C.australis*), *Hebe stricta* and tutu (*Coriaria arborea*) (Simcock, 1990).

Additionally Scheltus (1990) stated that the major revegetation lessons included that the best time of year for tree felling, vegetation removal and topsoil stripping was mid March to May, as at this time vegetation had developed dormant buds, fruit and seeds were ripe and topsoil was driest. Scheltus said that siltstone revegetated satisfactorily naturally. Control of exotic weed species could be achieved by blanket spraying over native species and was necessary for at least the first 2 years after reclamation.

In 1988 a revegetation programme to screen a radiata pine plantation adjacent to the Wanganui river by establishing a belt of indigenous podocarp/hardwood forest was proposed by Winstone Afforestation (Nicholls, 1988). Most of the affected area was in pasture. The strategy entailed planting large nursery grown native seedlings in highly visible areas and creating an environment suitable for successful natural regeneration of remaining areas. Exclusion of livestock and control of wild animals (opossum, goat and hare) were the first steps. This was to be followed by spraying exotic grasses, identified as the major threat to native species, with a selective herbicide to leave legumes to supply nitrogen and broadleaf weeds to shelter and shade native seedlings

and help decrease damage by hares. Group plantings of nursery grown stock were proposed to shade naturally-regenerating seedlings. The nursery stock were either unpalatable to grazing, such as totara, manuka, kanuka and kowhai, or resistant to grazing, such as mahoe and tutu. Plantings were not fertilised. This aimed to develop hardened, unpalatable, well-rooted plants with minimal weed growth. When natives plants were established, it was proposed to introduce Romney sheep to control grass, thus decreasing the risk of fire. Application of acidic fertilisers, such as ammonium sulphate, were proposed to decrease clover growth (although the fertilisers would boost growth of grass species).

### 3.4.2 Revegetation of eroded areas

Principles from research on pasture establishment of subsoils and rooting media low in organic matter may be applicable to reclamation of mining sites. Quilter and Korte (1990) investigated plants that would establish without fencing or fertiliser on subsoils exposed by slip erosion. They found that Yorkshire fog (*Holcus lanatus*) and the legumes white clover (*Trifolium repens*) and red clover (*Trifolium pratense*) established most vigorously but took longer to develop a complete cover than traditionally established vegetation, which relied on high <sup>seeding rates</sup> and applications of nitrogenous fertilisers. Work by Trustrum *et al.* (1983) indicated that organic matter critically affected the potential productivity of a medium. They found that slips in Wairarapa hill country under a mean annual rainfall of 980 mm revegetated rapidly over the first 20 years after slipping to within 70 to 80% of uneroded pasture productivity but even after 75 years productivity was still reduced by 21%. Soil nitrogen and carbon levels showed a similar trend to pasture production indicating that restoration of the organic phase took a long time, resulting in an impaired nutrient supply to the plants. Production was most severely reduced in mid winter and summer.

Carran *et al.* (1985) reported that scrub clearing by root raking, which removes topsoil with a result similar to topsoil mining, resulted in a reduction of mineralisable nitrogen and carbon. Water holding capacity in the exposed surface was also reduced. An increased slope accentuated the adverse effects of topsoil loss. Carran *et al.* (1985) concluded that prospects for restoration of normal nutrient cycling were slight, even in the medium term. A production forestry experiment by Dyck *et al.*, (1985) found that removal of topsoil decreased growth rates of *Pinus radiata*. Combined with either heavy or light compaction, topsoil removal decreased pine tree height and diameter in the first and second years of growth, with an increased effect in year two. Unfortunately a treatment of topsoil removal only was not included in the trial.

In the early 1980's, staff of the Ministry of Works in Northland carried out several trials to determine techniques which promoted revegetation of road-cuttings through acidic argillite. At Smeaton's Hill, south of Whangarei, establishment of grasses on plots with combinations of straw, bitumen and lime applications were investigated. The exposed surface with a pH of c.2.0 was

successfully revegetated with kikuyu and low fertility grasses following application of c.100 tonnes of lime/hectare and sewage sludge (Cathcart and Alexander, pers. comm. 1993).

#### 3.4.3 Revegetation of alluvial deposits

Revegetation of alluvial deposits is similar to reclamation of non toxic mine tailings and sediment ponds. Both media are unstructured, have an even particle size and are deposited in laminar beds. Techniques and species suited to revegetation of poorly structured river silt deposits were investigated by Gray and Korte (1990) and Quilter and Korte (1990). Trials showed that revegetation was successful if seeding occurred while the silt surface was still damp and had not formed a crust. Crusting resulted in poor root penetration and increased bird predation. *Lolium multiflorum* (Italian ryegrass) and *L. perenne* (Perennial ryegrass) yielded more than all other agricultural species trialed even though *L. multiflorum* did not respond to applications of nitrogen and phosphorus.

Ross *et al.* (1990) implemented trials on revegetation and stabilisation of silt loam lake sediments up to 6 m thick resulting from decommissioning of the Morton Reservoir in the Wainuiomata River catchment in 1988. Trials aimed to establish vegetation that would blend with surrounding indigenous forest and scrub. Low lying sediments were nearly completely vegetated with rushes, kanuka, tutu, hard fern (*Paesia scaberula*) and a range of exotic adventitive species within a year of lake drainage. Crusting and large polygonal cracks on higher terraces resulted in poor plant establishment. This area was rotary hoed, fertilised with 300 kg ha<sup>-1</sup> 15% potassic superphosphate and sown with 31 kg ha<sup>-1</sup> legume/grass pasture mixture. Pasture establishment and growth was luxuriant and with grazing by feral animals maintaining a dense sward, native plants did not establish (Ross *et al.*, 1990a). Periodic physical measurements were used to monitor the drying out or *ripening* of the sediment. Ripening was associated with increased bulk density from 0.6 t m<sup>-3</sup> to 1 to 1.5 t m<sup>-3</sup> for mature soil and hydraulic conductivity increased an order of magnitude in the 0 to 75 mm and 100 to 175 mm depths. Measurements of unsaturated hydraulic conductivity indicated that microporosity had not developed to the same extent as macro-scale cracking and macro void formation. Ripening was dependant on time, depth of water table and texture with the ripening process moving downwards and, to a smaller extent, laterally into the matrix from large polygonal cracks.

#### 3.4.4 Revegetation of pipelines

Revegetation of pipelines involves the same total disruption of the soil profile as mining activities, however, the narrow corridor shape of the disturbed area aids natural seed and vegetation ingress. Additionally, the ability to adopt specialised post revegetation management, especially where pipelines cross agricultural land, is limited due to the narrowness of the affected area. Reclamation techniques were developed in association with construction of the 300 km

Maui pipeline from 1976 to 1978 and 48 km methanol pipeline during 1982 and 1983 in Taranaki. Pipeline installation comprised excavation of a 30 m wide strip and burial of a pipe 2 to 2.5 m below the surface. Reclamation techniques aimed to "*ensure no permanent loss of farm productivity and to minimise erosion*" (Environmental Impact Assessment cited by Simmons, 1983).

Reclamation of land disturbed by the Maui pipeline generally encompassed vegetation removal, soil removal and replacement, surface working and sowing to pasture (Simmons, 1983). In very steep and/or forested areas soil horizons were not separately stripped. Sowing rates of legume/grass pasture seed varied from 72 kg ha<sup>-1</sup> on access ways to 178 kg ha<sup>-1</sup> on debris slopes. Legumes were inoculated at 3 times the recommended strength and 625 kg ha<sup>-1</sup> of superphosphate and 125 kg ha<sup>-1</sup> of sulphate of ammonia spread. Where the pipeline affected water courses erosion was limited by construction of punga or manuka and iron standard debris dams, earth detention dams, or pegged down hay bales. Layering of manuka and willow, and willow pole planting were soil conservation techniques used to stabilise steep slopes (Simmons, 1983). Reclamation frequently resulted in decreased pasture production through disrupted surface drains, mixing of soil horizons (decreasing plant nutrient and water supply), a long working length which caused soil stockpiling for long periods and waterlogging through compaction and siltation (Patchett, 1983; Simmons, 1983). Inadequate reclamation was also suggested to be the result of working in wet weather and poor liaison between landowners, contractors and project staff (Simmons, 1983).

Contract specifications associated with laying of the later methanol pipeline required separation of topsoil and subsoil, construction only during the (drier) October to April period and a limited length and area of disturbed soil at any time. Patchett (1983) concluded that these requirements had generally lead to stable, satisfactorily vegetated reclamation.

#### 3.4.5 Soil relocation and land contouring

Studies by Soil Bureau investigating the relocation of soils used for stone fruit production were associated with construction of the Clyde high dam and creation of Lake Dunstan. Cromwell sandy soils were excavated to 1 m and relocated over cultivated shallow Molyneux stony sand and loamy sand soils (brown grey earths) (Gregg, 1987). Replaced soils were harrowed, deep ripped at 0.80 m spacings to increase mixing and break up compacted layers and sown with a variety of crops (Beecroft and Keenan, 1983). Dump trucks and small bulldozers were recommended for soil relocation rather than scrapers (Beecroft and Keenan, 1983).

Orbell (1985) formulated guidelines for land contouring following concern expressed by Tauranga County Council that some land contouring, mainly for kiwifruit growing, had resulted in long term reduction of soil productivity and water quality. Orbell determined that the main problems were



soil compaction, topsoil burial resulting in A horizons less than 0.10 m thick and replacement of adjacent layers of texturally contrasting material which caused inadequate drainage, erosion and poor infiltration. Orbell's recommendations for contouring of friable, free draining soils derived from volcanic ash were based on agronomic principles. The main recommendations included separate stripping and stockpiling of topsoil and subsoil to 1 m depth, with minimum soil handling, use of light machinery and deep ripping to minimise soil compaction.

### **3.5 International information on reclamation of aggregate mining**

Historically, surface mining developed with little regulation requiring return of mined land to suitable after uses, resulting in the despoiled, unproductive land which occurs in many countries. International literature on land reclamation after mining has grown rapidly since the early 1970's (Table 3.1). Reclamation has a relatively long history in the United Kingdom and Germany where high population densities have caused pressure to reclaim land, for example coal mining reclamation began in England in the 1940's. Initial reclamation concentrated on greening a site with little concern given to land use, productivity or sustainability but over time reclamation quality became an issue. Canada and the United States have become leaders in reclamation technology with both countries passing legislation requiring high standards of reclamation. In the United States individual states passed land reclamation laws as early as 1962. The United States Federal Surface Mining and Reclamation Act of 1977 introduced a regulatory programme and enforcement system and mandated 8 performance standards which included topsoil segregation, reconstruction of approximately the original contour and a permanent vegetative cover capable of supporting pre-mining land uses. In Canada the central government agency, Environment Canada, has state offices with specific reclamation branches. Individual Canadian states also publish reports and guidelines on reclamation, for example the Ontario Ministry of Natural Resources. Canada and the United States have active associations of reclamation professionals, the Canadian Land Reclamation Association and American Society of Surface Mining and Reclamation respectively, which publish regular newsletters, sponsor publications on aspects of reclamation, provide access to a reclamation database and organise annual national conferences.

In remote areas and countries with low population densities such as Australia and New Zealand, legislation was originally designed to facilitate mining rather than protect environmental quality. Proceedings from conferences, including Australian Mining Industry Council Environmental Workshops, are the major widely available source of information on reclamation research and technology (Keating, 1990). Publications by government organisations are also valuable sources of information. In New Zealand the Ministry of Commerce and Department of Scientific and Industrial Research (D.S.I.R.) have been the main government organisations that have published reports on reclamation activity and technology. Equivalent groups in England are the Department of the Environment and universities and mining industry groups.

Table 3.1: Growth in numbers of publications on land reclamation during the 1970's (from Bell, 1980)

Year of publication	Number of publications* <sup>1</sup>
1972	17
1975	51
1979	105

\*<sup>1</sup> articles identified by predominantly European and North American information gathering systems.

The third major source of information on reclamation are articles in a wide range of periodicals such as:

<i>Applied Geography</i>	<i>Arboricultural Journal</i>
<i>Environmental Geochemistry and Health</i>	<i>Mining Congress Journal</i>
<i>Mining Equipment International</i>	<i>Mining Engineering</i>
<i>Minerals and the Environment</i>	<i>Rock Products</i>
<i>Ohio Journal of Science</i>	<i>Journal of Soil Conservation</i>
<i>Soil Science Society of America Journal</i>	<i>Advances in Agronomy</i>
<i>Journal of the British Grassland Society</i>	<i>Landscape Architecture</i>
<i>Chartered Surveyor Land Hydrographic and Minerals Quarterly.</i>	

The diversity of magazines reflects the multidisciplinary nature of land reclamation. Journals which regularly contain papers on land reclamation include *Landscape and Urban Planning* which describes itself as an international journal of landscape design and reclamation, planning and urban ecology. This journal subsumes the previously independent *Landscape Planning* and *Reclamation and Revegetation Research* journals. It contains both specific scientific and general papers on topics ranging from reclamation legislation (Alexander, 1989) and direct seeding of trees (Hughes and Garthe, 1989) to selection methods for deciding post mining land use (Rowe, 1977), evaluation of reclamation (Tomlinson, 1984) and general papers (Skaller, 1981; Evans et al., 1986; Eastment et al., 1989; Sanchez and Wood, 1989; Vimmerstedt et al., 1989; Wade, 1989). The *International Journal of Surface Mining and Reclamation* is a specialist magazine with scientifically reviewed articles from around the world on subjects ranging from establishment of trees (Ringe, 1989; Ringe et al., 1989; Larson, 1990; Ringe and Graves, 1990; Davidson et al., 1991) and agriculture on mine spoil (Sweigard, 1990) to modelling the vegetative productivity of different rooting mediums (Burley, 1991). *Landscape and Urban Planning* and the *International Journal of Surface Mining and Reclamation* generally relate to coal and metalliferous extraction, however has included articles applicable to aggregate mining. *Soil Use and Management* has published articles on reclamation of opencast coal mines, aggregate restoration and general topics applicable to reclamation, for example quality of rooting mediums and erosion control

(Ramsay, 1986; Scullion and Mohammed, 1986; Bradshaw, 1989; Harris and Birch, 1989; Hodgkinson, 1989; Marrs, 1989; McRae, 1989; Stewart and Scullion, 1989; Younger, 1989). Regular popular articles on reclamation techniques, for example hydraulic seeding and use of erosion matting, have appeared in *Landscape Design*, an English magazine for landscape architects. Articles often feature innovative post mining land use design and planning projects (Jefferies, 1981; McRae, 1983; Roberts and Bradshaw, 1985; Brandt and Rimmer, 1987; Macdonald-Steels and Haigh, 1988; Putwain and Gilham, 1988). *Landscape Architecture* is the American equivalent of *Landscape Design* and has a similar format, containing articles on general reclamation practice (Holden, 1989; Krohe, 1989) and specific reclamation projects (Beardsley, 1989).

### 3.5.1 California

Californian aggregate deposits are typically alluvial and are mined from areas with overburden depths of 6 to 10 metres (Mackintosh and Hoffman, 1985), much greater depths than deposits mined in New Zealand, reflecting higher localised demand for aggregate. There are three main climatic regimes in the state of California comprising mediterranean, mountain and desert climates (Kekerix and Kay, 1986) with precipitation ranging from 1125 mm in the mediterranean areas to 250 mm in the desert lands. Reclamation priorities, strategies and plant materials vary depending on the climate and soil type at a site (Van Kekerix and Kay, 1986).

Much of California at a lower elevation has a mediterranean climate with cool, rainy winters and hot, dry summers. In this climate, extensive areas of fertile soils have been rehabilitated to agriculture and production of speciality crops (Mackintosh and Hoffman, 1985) such as peach, almond, walnut, strawberry and grape. At some sites crop yields are equivalent to or higher than pre-extraction yields. Major reclamation emphases include land contouring to allow drainage of water and cold air (frost), cross ripping subsoil to depths of 1.2 to 1.5 m to relieve compaction and establishment of cover crops for 2 to 4 years to allow land subsidence and promote soil recovery (Mackintosh and Hoffman, 1985).

Where aggregate is mined from beneath less fertile soils, erosion control and reduction of fire danger are priorities of reclamation. Soil retention was found to be highly correlated with plant ground cover and annual grasses, for example *Lolium multiflorum* and *L. rigidum*, consistently gave the best soil protection (Van Kekerix and Kay, 1986). These species, however, required fertiliser to persist and were extremely competitive with other plants in the first year. In California use of perennial grasses is usually restricted to areas requiring deep rooting species, minimum maintenance and/or minimum foliage for fire protection. In the mediterranean climate, grass

species grow during the cool winter and spring months. Flowers were recommended by Van Kekerix and Kay (1986) in California to provide visually appealing, short duration cover on prominent sites of low erosion potential.

A mountain climate occurs in California at elevations greater than 1000 m. Cold winters and spring moisture combine to favour plant species, which can take advantage of a short growing season. Priorities of reclamation are minimisation of erosion and fire. This favours species with large root masses and fairly short foliage. Van Kekerix and Kay (1986) advocated sowing blends of bunch and sod-forming grasses at seeding rates of up to 50 kg ha<sup>-1</sup> in exposed areas. *Dactylis glomerata*, bluegrass (*Poa ampla*) and crested wheatgrass (*Agropyron desertorum*) are the most important bunch grass species used in California characterised by fast establishment. Sod-forming grasses usually establish more slowly but are considered valuable as they spread over large areas through extension of rhizomes.

Mining reclamation in the Californian desert climate generally focuses on soil stabilisation through plant establishment. In the very dry desert climate characterised by low unpredictable rainfall, high winds and high summer temperatures irrigation increases germination and establishment of plants. In desert areas seeds must be covered with soil to prevent desiccation and bird or animal damage, thus hydroseeding is not successful. Important reclamation techniques include creation of rough surfaces to aid natural accumulation of seeds and drilling of a nurse crop of barley, which provides a rapid ground cover and traps moisture and seeds. Native shrubs have been the most successful group of plants used in reclamation in desert areas. These include californian buckwheat (*Eriogonoum fasciculatum*), saltbush (*Atriplex canescens* and *A. polycarpa*) and rabbitbrush (*Chrysothamnus sp.*).

End uses of depleted Californian aggregate mines depend as much on community needs and adjacent land uses as deposit characteristics and site factors. Post mining land uses have included refuse disposal, public and commercial developments, recreational facilities, flood control and ground water recharge stations and methane gas generation (Bennett *et al.*, 1982). The best and most innovative reclamation developments are featured in *Rock Products* magazine which is produced for the United States aggregate industry and features annual reclamation awards to landscape architecture students (Zimmerman, 1991b) and individual company reclamation projects (Wassenaar, 1989; Rukavina, 1991a ;1991b). *Rock Products* also includes articles on reclamation methods (Carter, 1989a; 1989c; 1990; <sup>2; 1990b;</sup> Dietrich, 1990) and legislation (Carter, 1989b).

### 3.5.2 United Kingdom

The United Kingdom has a moderate maritime climate very similar to many areas of New Zealand with mild winters, cool summers and rainfall distributed throughout the year. Resources of aggregate underly a wide range of alluvial soils and poorly draining soils <sup>are</sup> mined in preference to



more agriculturally productive and versatile soils. Mined areas are generally reclaimed to arable and pastoral agriculture, however, since the late 1980's reclamation to wetlands and reserves for amenity and leisure purposes has increased. This change has been associated with surpluses of agricultural production and environmental criticism of intensive agricultural practices (Proctor, 1990).

From 1974 to 1987 the Sand and Gravel Association, together with the Ministry of Agriculture, Food and Fisheries (M.A.F.F.) and the Department of the Environment, ran the first long term experiments in England to assess techniques of land reclamation after aggregate mining (Tomlinson, 1984). These experiments, known as the Joint Agricultural Land Restoration Experiments, were implemented at Bush Farm and Papercourt Farm in Surrey (Department of the Environment *et al.*, 1988) to "*investigate the feasibility of restoring land back to a high standard of agricultural quality after gravel extraction under viable commercial conditions and without unnecessary loss of agricultural production in the process... (and) to formulate guidelines for general application*". The study investigated soil handling, cropping and post reinstatement agricultural management methods.

Important recommendations from the study, which are now practised at many reclamation sites, were progressive or continuous reclamation, a wet weather shut-down policy based on direct soil measurements and separate stripping of topsoil and subsoil. The study also recommended fertiliser and soil organic matter amendments and ripping to relieve compaction. Although bulk densities were significantly higher in scraper-reclaimed areas compared to areas that were reclaimed using an hydraulic excavator and back dumping trucks, there was no corresponding significant difference in crop productivity between the two treatments. There were no differences in yield between stored or directly spread soils. The Bush and Papercourt Farms experiment reports concluded that, except for sites where exceptionally difficult physical problems occur, high standards of agricultural restoration following aggregate extraction can be achieved with a restoration plan tailored to the physical conditions of the site; the proposed method of working; close site supervision and appropriate aftercare (Department of the Environment *et al.*, 1978). However, study results were not conclusive as trials were not designed as scientific experiments (McRae pers. comm., 1991). An unmined control treatment was not included and the experimental design was partly flawed as until 1983 different final surface materials and scarification methods occurred on soil replacement treatments, which were compared. Additionally, treatments laid down in different years were compared and operational constraints meant two different fill materials were placed parallel to the two different filling methods and crop yields were adversely affected by unexpected landfill gas emissions.

Two of the most prolific writers of papers and publications on English aggregate mining reclamation are S.G. McRae and A.D. Bradshaw. McRae was involved in the latter stages of the Bush Farm experiments (McRae pers. comm., 1991) and conducted a case study of Hatfield

Quarry in Hertfordshire where three different techniques of reclamation to arable agriculture were implemented under commercial, non experimental conditions (McRae, 1982b). Successful reclamation was associated with separate stripping, storage and spreading of topsoil and subsoil under dry conditions and thorough ripping of the reclaimed area. McRae (1982b) recommended full rather than minimum cultivation techniques and very high pasture seeding rates. McRae has published review articles on restoration guidelines for aggregate mines (McRae, 1982b; 1983 ; 1989; 1990) and is currently researching assessment of the quality of reclaimed land (McRae pers.comm., 1991).

Bradshaw has published papers and articles on general aspects of reclamation (Bradshaw, 1981; 1982a; 1982b; 1983a; <sup>Bradshaw et al., 1983</sup> 1984a; 1984b) and topsoil quality (Bradshaw, 1989). Coppin and Bradshaw (1982) wrote *Quarry reclamation: the establishment of vegetation in quarries and open pit non metal mines*. The book discusses environmental factors affecting reclamation, after use possibilities, restoration procedures, analysis of site and soils, soil movement and storage, fertiliser applications, plant species selection and methods of vegetation establishment, management and aftercare for agriculture and wildlife conservation. Coppin and Bradshaw (1982) advised a regular monitoring programme involving measurement of soil physical changes and nutrient accumulation as the best way of determining resilience of a new soil system and the effectiveness of reclamation and post-reclamation management.

The United Kingdom Sand and Gravel Association and the Ministry of Agriculture, Forestry and Fisheries (M.A.F.F) conduct research programmes, produce aggregate industry guidelines on reclamation to specific post mining uses <sup>Ministry of Agriculture, Forestry and Fisheries, 1982</sup> (McRae, 1982b) and publish case histories of reclaimed sites. In 1978 the Agriculture Development and Advisory Section of M.A.F.F. examined 15 aggregate extraction sites in West Sussex. They concluded that the main causes of poor restoration were poor quality planning at each stage of restoration, insufficient attention paid to infill material, variability in the quality and amount of topsoil used, insufficient time spent on after care management (A.D.A.S. Land Service, 1979 cited by Tomlinson, 1984). The Sand and Gravel Association publishes the *Sand and Gravel Association Bulletin* which has regularly included articles on restoration.

The United Kingdom branch of the Institute of Quarrying, a professional organisation for aggregate producers, which complements the National Sand and Gravel Association, recently published *Sand and gravel planning and restoration* and pamphlets *Land restoration to agriculture*, *Restoration of quarries by controlled landfill* and *Amenity banks and quarry landscaping*. The Institute of Quarrying also publishes *Quarry Management*. This journal regularly features articles and reports on a wide range of reclamation activities from the release of otters at a reclaimed wetland to award winning reclamation projects (McGown, 1989; Mercer, 1989; O'Keefe, 1989; Bellamy, 1990; McRae, 1990; Proctor, 1990; Wilson, 1990; Blackwell, 1991; Anon, 1991e; 1991f; Wilson, 1991; Happy, 1992).

Individual aggregate producers have conducted or sponsored research by themselves or in conjunction with private conservation groups, for example the Game Conservancy established a wildfowl research project with the Amey Roadstone Corporation (AMC) on their pits at Milton-Keynes (Kelcey, 1984). Tarmac, another large British aggregate company sponsored the publication of *Gravel Pit restoration for Wildlife* written by The Royal Society for the Protection of Birds. The RMC group of aggregate producing companies has a reputation as a pioneer in reclamation of aggregate pits. In 1986 RMC produced a practical guide to restoration which aimed to interpret the latest technical and academic developments into practical recommendations.

In addition to proceedings of reclamation conferences, several important early books on mining reclamation were published in Britain, which are applicable to aggregate mining reclamation, unlike many American publications which generally concentrate on metalliferous and coal mining. In 1981 the Land Decade Educational Council published *The productivity of restored land* which included papers on productivity of restored gravel workings (McRae, 1981), common reclamation problems, worm enrichment, afforestation and nitrogen requirements (Bradshaw, 1981) of reclaimed land. *Landscape Reclamation: a report on research into the problems of reclaiming derelict land* by a research team of University of Newcastle upon Tyne (1972) included several articles applicable to aggregate reclamation on drainage, erosion control and landscaping of reclaimed sites. Scientists at Newcastle upon Tyne University have had ongoing contracts with British Coal from 1980 (Younger pers.comm., 1991) researching reclamation of strip mined heavy clay soils to arable and pastoral agriculture. Research concentrated on amelioration of compaction, through cultivation of topsoil and subsoil, drainage, fertiliser applications to topsoils and subsoil, organic matter and earthworm amendments and methods of crop utilisation (Younger, 1989).

Many aggregate extraction sites, especially in South East England, have been used for landfilling before final reclamation. Reports on covering and revegetation of landfills are often directly applicable to aggregate reclamation. McRae (1983; <sup>1985a; 1985b</sup> 1986) has written review articles on the subject. The Department of the Environment Landfill Practices Review Group compiled a report on landfill reclamation and aftercare that emphasised the importance of a post restoration treatment aimed at improving soil structure, organic matter and fertility levels rather than making an enterprise immediately profitable (Department of the Environment, 1984). A later Department of the Environment technical publication (*Landfilling Wastes*, 1990) included a comprehensive section on landfill reclamation. Most of these publications recommend progressive restoration to allow monitoring and adjustment of techniques, moving soil only under dry conditions and ripping with winged tines to minimise compaction, with pasture seeding rates of 45 kg<sup>-1</sup> compared to agricultural renovation rates of approximately 23 kg ha<sup>-1</sup>. Publications do not concur whether a grass ley or arable cropping is appropriate immediately following reclamation.

The recommended depth of rooting material ranges from 0.10 m (for amenity grass establishment) to 1 metre where a clay cap is present or drainage is required.

### 3.5.3 Australia

Coaldrake (1979) states that serious reclamation efforts began in Australia in the mid 1970's (*cited by Tomlinson, 1984*). There has been little research specifically into reclamation of aggregate mines, however reclamation experience and research of the mineral sands industry may be directly applicable to the aggregate industry. Both types of extraction generally involve shallow, non toxic excavations although some mineral sands are radioactive and few mineral sand excavations leave depressions as ore concentrations are generally low, at 2% to 10% of mined material. The Australian mineral sand industry has funded a large amount of basic and applied research with many research projects conducted in association with universities. AMC Mineral Sands Pty, for example, has supported research based on company reclamation projects and minimisation of environmental impacts, which has been presented in over 82 publications (Webb, 1990). Near Capel, Western Australia, 44 ha of lakes created by AMC extraction of mineral sand is being reclaimed to a series of diverse, interconnected wetland habitats for water birds. Since 1987 a multidisciplinary research programme involving students and scientists from Murdoch University, Curtin University of Technology and University of Western Australia have studied water quality, algae and fringing plants, aquatic invertebrates, frogs, reptiles and birds at this site to help develop successful reclamation techniques. The Australian mineral sands industry has developed successful agriculture, wetland, fore dune, arid heath lands (Unwin, 1987; Jefferies *et al.*, 1991) and indigenous forest (Davie, 1991) reclamation programmes.

Australian Mining Industry Council workshops <sup>have been</sup> held annually for the last fourteen years. The resulting publications have not included papers specifically on aggregate mine reclamation, however papers on community involvement in environmental management (Smyth, 1991; Sprague, 1991; Verschuer, 1991), completion criteria (Chandler *et al.*, 1991) and sustainable development (Aitken, 1991; Carbon, 1991; Gould, 1991) are directly applicable to reclamation of aggregate mines. The national Australian government reclamation research agency, the Commonwealth Scientific and Industrial Research Organisation Minesite Rehabilitation Research Group, has concentrated on non aggregate mining research (Milnes, 1991a; 1991b). The Department of Agriculture at the University of Queensland has been one of the major research centres in Australia for over 10 years. Research in the Department has mainly been linked with mining of coal and mineral sands (Bell *et al.*, 1992).

### 3.5.4 Canada

Canada produces more tonnes of aggregate per capita than any other country in the world (Anon, 1992a) and has a well established land reclamation profession, which is particularly active





Photograph 3.8: A seasonally-inundated pond created after extraction of clay to facilitate frog reproduction, Western Australia.

in Ontario and Alberta. Ontario experiences a subarctic, continental, taiga climate with very severe winters and mild summers. Temperatures exceed 10 degrees Celsius in less than four months each year and an annual precipitation of 370 to 750 mm falls throughout the year. In Ontario land sterilisation resulting from aggregate extraction has been an issue since the mid 1960's (Robinson, 1988). This has resulted in research and development of reclamation guidelines by the Ontario provincial government. Ten publications have been published by the province between 1970 and 1990 on general principles of reclamation and specific guidelines for reclamation to fruit, forest, fish and wildlife uses. Recommendations are based mainly on assessment and comparison of well-reclaimed and poorly-reclaimed sites. Reports on reclamation of land to agricultural and horticultural use emphasise careful treatment of the soil resource through avoidance of soil compaction, stone picking and a three to four year legume/forage crop cover to restore soil structure before tree planting or annual cropping. Progressive rehabilitation and separate soil horizon stripping and stockpiling in dry conditions are also advocated (Mackintosh and Mozuraitus, 1982; Mackintosh and Hoffman, 1985; Michalski *et al.*, 1987; Hilditch *et al.*, 1988). Sometimes a mulch of hay or straw is used to reduce erosion while pasture germinates. It also supplies supply organic matter and helps retain soil moisture (Miller and Mackintosh, 1987).

The province of Alberta may be divided into two main climatic regimes. Northern Alberta has a climate similar to Ontario. Southern Alberta has a cold, dry, steppe climate with hot summers, less than 125 mm precipitation in winter and 125 to 250 mm precipitation in summer. The Land

Reclamation Division of the provincial government department Alberta Environment has produced guidelines specifically for reclamation of aggregate mines and general guidelines for reclaiming specific habitats, for example prairie wilderness (Alberta Environment, 1988). Emphasis is placed on conservation of topsoil and overburden materials and maintenance of undisturbed buffer zones (Alberta Environment, 1987). From 1980 to 1986 the Alberta Land Reclamation and Conservation Council, part of the Land Reclamation Division, has conducted research into principles of reclamation with wide application, for example the selection, propagation, establishment and management of grass, shrub and tree species. Other research projects have investigated the use of mycorrhizae, reconstruction of forest soils and the development of an agricultural capability rating system for reclaimed land. Most industry specific research conducted by the Council is in the coal and oil industries.

The Canadian Land Reclamation Association (C.L.R.A.) has chapters in both Alberta and Ontario. The C.L.R.A. holds annual conventions at which both specific papers on aggregate mine reclamation (Robinson, 1988) and general papers of relevance to reclamation of aggregate extraction sites are presented. At the C.L.R.A. 1989 conference, papers on reclamation techniques for wildlife and fish habitat creation, revegetation of herbaceous and woody plants, forest succession and soil handling were presented. Quarterly newsletters contain information on reclamation techniques, post mining land uses and research results (Powter, 1988; Nawrot and Sandusky, 1991; Houser and Fedkenheuer, 1992). *Canadian Aggregates Magazine* is produced for aggregate producers. This monthly magazine primarily includes technical reports on methods and types of reclamation (Consedine, 1990; Swanson, 1990) and publicises award winning company reclamation projects. Since 1971 the Aggregate Producer's Association of Ontario has presented Property Development Awards annually to members who have made significant efforts to improve the general appearance of their sites and/or implemented progressive land reclamation programmes.

### 3.5.5 The applicability of international research

Some New Zealand researchers contend that overseas research is of little relevance to New Zealand (Gregg *et al.*, in press) as the variability of site characteristics mean a programme of research shown to be successful at one site cannot necessarily be used at another site (Department of the Environment *et al.*, 1988) or even different parts of a single site (McRae, 1986). Some reclamation practices and general principles, however, have been shown to be common to all sites which have similar substrates and climates. This allows transfer of research between regions and countries (Department of the Environment *et al.*, 1988). Such technology transfer may enable savings in time and money as new technology can be adapted without the initial development costs.

Reclamation has been divided into general, regional and site specific research (Bell, 1980). General research is readily transferable between different types of mining and different countries. Results may be adapted from principles, for example general research on soil handling has found that handling soil at water contents above the plastic limit results in physical deterioration and compaction of soil. The principle is adapted to individual sites by determining the plastic limit of each material at the site. General research guidelines may provide a 'skeleton' on which to build detailed site guidelines. For example, research indicates that reclaimed wetlands should have irregular shorelines and islands with gently sloping shallows less than 0.5 m deep for growth of water plants and steeply shelving areas 2 to 3 m deep for fish habitat. The Alcoa mining company adopted these standard recommendations when creating the Wellard Wetlands near Perth, and determined the proportion of deep and shallow areas from the availability of fill materials and requirements of individual species. Large, shallow, seasonally flooded areas were constructed for frog reproduction (Photograph 3.8) and narrow, bare sand spits encouraged water birds. General research may sometimes be used with little modification, for example using geographic information systems to characterise and schedule reclamation of large sites (Elliott and Wake, 1991). Similarly, techniques which assist retention and conservation of moisture such as gouging depressions, creating rock structures and condensation traps or constructing contour banks can be applied to many sites (Johnson *et al.*, 1985).

Research may be specific to certain ecological types. In Western Australia 'dieback' fungal pathogen is a regional problem associated with jarrah (*Eucalyptus marginata*) eucalyptus forests (Boland *et al.*, 1984). Research by Worsley Alumina involved determining longevity of dieback in stripped soil and methods of mapping, predicting and limiting the spread of dieback. Results have been applied at other mine sites in Western Australia's jarrah forests (Elliott and Wake, 1991; Nichols *et al.*, 1991). Similarly, research into seed collection, propagation and mycorrhizal inoculation techniques for matai (*Prumnopitys taxifolia*) would be applicable throughout New Zealand. In Canada research has identified the habitat requirements of individual species of ungulates including elk, bighorn sheep, moose, pronghorn antelope, mountain goat and white tailed deer. This has allowed specification of landform, water body and vegetation features which enable creation of appropriate habitats at mine sites throughout Alberta. Monitoring techniques are usually specific to vegetation and fauna, for example agricultural reclamation is often measured by dry matter production, with measurement techniques applicable internationally. Successful reclamation of indigenous forest is often measured by species diversity, percentage ground cover and presence of wildlife. Techniques of measurement vary according to the wildlife types or species, for example presence of ants may be measured by trapping and presence of birds by sightings or calling responses to tape recordings.

Some research is only applicable to individual sites, for example site characterisation, which includes site specific determination of the characteristics of climate, flora and fauna, hydrology, geological and soil, extraction and processing techniques, post mining land use and the

requirements of regulatory authorities. Characterisation allows the identification and adaptation of compatible research from other reclamation situations and can prevent the transfer of inappropriate techniques. For example a variety of fences around reclaimed barriers in Australia have been designed to reduce the impacts of diverse problems at sites which range from wind erosion and vandalism by people in four wheel drive vehicles to damage by sheep, emus and scavenging ants.

Another form of site specific research, which is commonly undertaken, is to determine the limitations, potentials and distribution of potential rooting media (Bell, 1980). This research usually includes determining chemical, physical and microbiological characteristics of potential rooting media. Pot trials are used to assess the potential of available media for plant growth and optimum application rates of amendments. Results from this kind of research can be applied to sites with similar geology and/or soil types, for example in Western Australia characterisation research revealed the potential of caustic alumina tailings as an amendment to local coarse sandy soils. Mixing tailings into the soil removed the hydrophobic soil coating and increased the cation exchange capacity thus improving pasture production. These results can be applied to sites with similar ore processing techniques and soils. On the West Coast of New Zealand relatively successful techniques have been developed for establishing pine forests on coarse gravel tailings created by alluvial gold dredging operations. The techniques can be used in many areas where the characteristic 'herring bone' deposits are present.

Table 3.2: Comparison of climatic regimes in California, England, Coastal South Australia, Ontario, Alberta and New Zealand (using information from Espenshade, 1982).

Location	Mean Temperature (°C)		Annual Temp range (°C)	Precipitation (C m)	
	Jan.	July		1/11 to 30/4	1/5 to 31/10
<b>California</b>	10-16	16-21	6-17	12.5-100	< 12.5
<b>England</b>	-1-10	12-20	11-17	25-50	25-50
<b>Coastal South Australia</b>	21-27	12-20	6-22	25-100	25-100
<b>Ontario</b>	-7--18	16-21	22-39	12.5-25	25-50
<b>Alberta</b>	-1--12	16-25	39	<12.5	12.5-50
<b>New Zealand</b>	16-20	5-16	6-17	50-100	50-100



International research on reclamation is most successfully transferred to New Zealand from areas with similar climates, soils and vegetation. The climate of most areas of New Zealand is similar to England and coastal California (Table 3.2). Many techniques used in the United Kingdom for reclaiming aggregate mines to pastoral agriculture, horticulture and commercial forestry may be directly utilised by New Zealand aggregate operations. Pasture seed mixtures and post-reclamation management may differ between the countries because New Zealand pasture management revolves around encouraging legume production rather than using nitrogen applications and a non-leguminous sward (Gregg and Stewart, 1991). Additionally, New Zealand farming systems are based on feeding pasture to animals all year round, thus having less emphasis on hay and silage production. Techniques for creating wetland habitats to encourage water birds, invertebrate and amphibian establishment in New Zealand can also be adapted from English methods using indigenous New Zealand plants, as has successfully occurred in Western Australia.

Research related to Ontario and Alberta in Canada may not be directly applicable in most areas of New Zealand, which experience light frosts and no long lasting snow. For example compaction near the soil surface is an important problem in New Zealand but is ameliorated naturally in Canada through frost heave and formation of ice. The cold climate of Canada probably slows development of structure in reclaimed soils so that the 3 to 4 year lay period recommended before tree planting or annual cropping in Canada (Mackintosh and Mozuraitus, 1982) is able to be reduced in New Zealand. Arid land research carried out in desert and mountain regions of California and Australia is mainly applicable to Central Otago, the driest region in New Zealand. Current reclamation at Macraes Flat in Otago, however, aims to maximise pasture production, which is inconsistent with the dominant aim of fire risk minimisation, a major problem in California and parts of Australia. Conversely, Californian surface treatments which maximise water harvesting and infiltration could prove useful in Central Otago reclamation. Most areas of New Zealand, especially Westland and the Coromandel Range, experience 1000 to 3000 mm of evenly distributed rainfall necessitating reclamation techniques which minimise the development of anaerobic media with poor trafficability and thus reclamation programmes need to maximise shedding of rainfall.

International research is probably least applicable to reclamation of New Zealand forest because of the high proportion (approximately 82%) of endemic vascular plants (Dawson 1988). Despite the temperate latitudes of New Zealand the common podocarp-broadleaf forest type resembles montane tropical rainforests and is very different from forests reclaimed in other countries, for example, Canada, England and the United States. Unlike forests in these countries and dry-land Australia, New Zealand rainforest has a complex structure with many vines and epiphytes and few colonisers of open ground. Most seedlings require shelter, shade and soils high in organic matter. Research into reclamation of indigenous forest most applicable to New Zealand would

come from central Chile, south east South Africa and parts of New South Wales and Victoria in Australia (Dawson, 1988).

Where indigenous reclamation has similar aims, some techniques and technology may be able to be transferred. For example reclamation in Western Australian and New Zealand aims to quickly stabilise the soil surface, maximise biodiversity and accelerate plant succession to a self sustaining community. Major limitations in both countries are a limited knowledge of the ecology of indigenous species and the presence of highly competitive exotic species. Australian mining companies have implemented comprehensive programmes, which are carried out before mining begins, to characterise the site and reproduction of plants on the site to help achieve the reclamation of indigenous ecosystems. These programmes could be modified to assist reclamation of forests in New Zealand.

### **3.6 Research requirements in New Zealand**

When the major Waipipi, Waimumu and Waihi mines were proposed in the 1970's to mid 1980's few people involved with environmental assessment had prior experience of open cast mining and there was a very limited data on New Zealand reclamation (Griffin, 1982). Although reclamation now generally forms an integral part of mine feasibility, planning and operation studies in New Zealand, there are still major areas of reclamation which are either inadequately studied or not successfully implemented.

Reclamation research has mainly concentrated on determining guidelines for agricultural reclamation and, more specifically, determining the suitability of mined materials for reclamation purposes and the management of these materials for maximum production. Traditionally investigations have started with chemical and physical analysis of potential rooting media, followed by pot trials and small scale field trials. The most commonly researched areas have been determination of the type and depth of optimum rooting medium and rates of fertiliser application. This trend continued in more recent research associated with Grey River Gold, Cyprus Gold and Macrae's Joint Venture mining proposals (Figure 3.1).

#### **3.6.1 Reclamation of sites mined for aggregate**

The paucity of aggregate mining reclamation practice and research was noted at the 3rd National Soil Drainage Conference (McAuliffe and Boag, 1986, page 210). When reporting on aggregate reclamation in the Nelson region, Duck and Burton (1985) advised that clear procedures for reclamation that would prevent long term soil damage were needed for aggregate mining. Little reclamation research has been carried out by aggregate companies, partly due to the highly competitive nature of aggregate mining, the small size of most companies, and mining and land use consents that have focused on land stability rather than land productivity.

Aggregate mining research to date has focused on measuring plant and soil characteristics on commercially reclaimed sites. Only 1 of 4 studies compared soil or plant measurements from adjacent undisturbed areas with reclaimed areas. There has been no research comparing different methods of soil replacement or cropping regimes which maximise soil recovery. No trials have included best case reclamation practices. Unsatisfactory agricultural reclamation has occurred even under trial conditions at three closely monitored sites in the Nelson region (McQueen, 1983; Duck and Burton 1985). All reported research indicates that the assumption that pastoral production following aggregate extraction can be unimpaired is invalid in New Zealand. This is despite technology transfer from England being seemingly straightforward. Additionally, reclamation trials and practices associated with alluvial gold mining, which primarily affects recent alluvial soils, have illustrated successful pastoral reclamation can be achieved in Westland. To my knowledge, however, aggregate mines have not been reclaimed using the sands and fine gravels which, in Westland's medium to high rainfall, provide a favourable, aerated plant growth medium.

### 3.6.2 Reclamation of agricultural and horticultural land

New Zealand reclamation practitioners at a Land Reclamation Workshop agreed that adequate information on establishing pastures with similar productivity to undisturbed pastures was available (Gregg *et al.*, 1990, page 310). This was being achieved with applications of fertilisers, particularly nitrogenous fertilisers, in Waimumu (coal), Waihi (gold), Wellington and Manawatu (topsoil mining) experiments. The ability to replace land with the same *versatility* or *potential* has not been established and has been examined by McQueen (1983) who trialed a range of arable crops in soils and Mason *et al.* (1990) who investigated the growth of lettuces and beans in gold tailings. Reclamation of land which enables unreduced productivity of horticultural crops has not been researched, probably largely because there has been little requirement to restore potential productivity of land in New Zealand. Such research has particular relevance to the aggregate industry which was recently prevented from mining land in Hawkes Bay as it was considered highly desirable for wine-grape production, despite a proposal to reclaim the site.

### 3.6.3 Reclamation of exotic and indigenous ecosystems

Current New Zealand Department of Conservation policy requiring reclamation of indigenous forest where it existed prior to mining has exposed a dearth of knowledge and information on appropriate techniques for reclamation of indigenous forest (Davis and Crozier, 1991; Metcalfe and Godfrey, 1990; Ross and Mew 1991). Even the feasibility of reclaiming mined lands to indigenous forest is not certain (Davis and Crozier, 1991) with West Coast Department of Conservation staff stating an urgent need for independent trial sites for alluvial gold and coal mining in 1989 (Ministry of Energy, 1989).

There are four main areas where research on reclamation of indigenous ecosystems is needed. Firstly, investigations into the ecology of indigenous plants is needed. This includes screening native plants for site tolerances i.e. tolerance of exposed conditions, compaction and low organic matter and palatability to feral animals. Seed production and dispersal characteristics, propagation techniques, mycorrhizal relationships and soil, water and nutrient requirements are unknown for a wide range of indigenous taxa (Norton, 1991). Secondly, the most effective methods and seasons for establishment of many native plants should be determined (Timmins *et al.*, 1987; Parker, 1991). Most reclamation trials to date have used expensive container grown plants and/or laying manuka slash containing viable seed capsules. The benefits and methods of utilising forest duff (organic horizon) and topsoil were identified at the 1990 Land Reclamation Workshop as being key research goals in this area. The benefits of forest materials as mulches, cuttings or organic amendments also needs to be researched with the effect of different timing, amounts and types of fertiliser. Thirdly, the impact and role of exotic soil-stabilising species such as grass/legume mixtures and exotic quickly-growing nurse crops such as gorse, tree lucerne and lupin on the establishment and growth of native species is needed (Brown, 1986; Parker, 1991). And lastly, research into indigenous successions on disturbed sites is required to determine effective monitoring techniques which can be used to predict the long term success of reclamation. The monitoring should enable specification of goals in conditions of mining and specification of standards of reclamation required before the release of bonds. Research and practice in all these areas would be aided by an evaluation of information from the New Zealand literature in related fields, and the overseas literature as it applies to reclamation of indigenous ecosystems in New Zealand.

#### 3.6.4 General reclamation research

The 1990 Land Reclamation Workshop identified a need for general compaction and soil handling research, particularly in defining parameters associated with soil compaction, which are indicative of poor plant performance. Determination of critical values for soil compaction in different climates would aid regulatory authorities to determine whether reclamation was likely to be successful without time-consuming and expensive plant growth measurements. Soil compaction treatments with adequate control treatments to date have only been included in the Waimumu trial (Section 3.3.4). Associated research culminating in development of species with high root production, turnover and penetration ability could be used to boost inputs of organic matter and to break up compacted zones.

Parker (1991) identified a need for research into soil depth requirements for pastoral farming under different rainfalls. To date only Waihi Gold (Section 3.3.5) and Grey River trials (Section 3.3.3), experiencing mean annual rainfalls of 1500 and 2150 mm respectively, have directly investigated soil depth requirements. Hart *et al.* (1990) stated that one of the most pressing reclamation problems in New Zealand was to quantify the relationship between input of organic

matter to soils and the rate of organic matter accumulation under different climates, planting and management regimes. This was based on the observation that organic matter accumulation and decomposition is critical to the nutrient availability and productivity of drastically disturbed land, with higher accumulation rates of organic matter relating to increased plant yield. Quantification of the relationship would allow the development of rational and effective restoration regimes through plant species selection, grazing management, fertiliser applications and mulching. Review articles by Mew and Ross (1991) and Ross and Mew (1991) raised the need for trials to determine if the return of free draining subsoil was beneficial for exotic forestation.

Sims *et al.* (1984) in a review of international reclamation literature stated that research into the characterisation of site soils, overburden, flora and fauna was needed. Within soil, spoil and overburden characterisation Sims *et al.* (1984) emphasised the importance of developing a substrate rating mechanism that can be applied to a wide range of soil and spoil types considering chemical and biological properties and encompassing the use of amendments.

### 3.7 Conclusion

Chapter Three presented an overview of mining reclamation research and allied research on the revegetation of disturbed land undertaken in New Zealand and overseas. Restoration was defined as *recreating the pre-mining characteristics of a site*. Rehabilitation and reclamation were both defined as *planned treatment of drastically disturbed land that minimises adverse environmental impacts and results in stable landforms and/or ecosystems suited to the beneficial post mining use*.

New Zealand mining research and practice was reviewed from a trial in the Manawatu in the 1960 investigating the recovery of pasture production of a soil following topsoil removal to an ongoing 1990 study of indigenous forest reclamation following coal mining in Westland. Most research into mining reclamation in New Zealand has been associated with procedures related to environmental impact reporting which have been required since the 1971 Mining Act. Initial research was based on an agronomic approach, investigating fertiliser requirements, as most mined areas were reclaimed to ryegrass/legume pasture. The philosophy was to recreate the soil profile and provide an adequate nutrient supply for plant growth. Soil conservation knowledge gained from studies of revegetation of eroded land and alluvial flood deposits was also used. General conclusions that can be made from a study of New Zealand literature are that topsoil is a valuable resource which aids plant establishment and growth (Trustrum *et al.*, 1983; Carran *et al.*, 1985; Dyck and Messina, 1985; Hart *et al.*, 1990), while mixing topsoil and subsoil reduces soil quality (Patchett, 1983; Simmons, 1983; Ross *et al.*, 1984; Orbell, 1985). High fertiliser applications and/or pasture seeding rates maximise plant cover (Quilter and Korte, 1990) and pasture productivity (Fitzgerald, 1981; Hart *et al.*, 1986; Widdowson and McQueen, 1990). Compaction adversely affects plant productivity (McQueen, 1983; Duck and Burton, 1985;

Davis and Crozier, 1991), except in reclamation of gravelly tailings, with dump trucks and small bulldozers recommended for soil relocation over scrapers (Beecroft and Keenan, 1983).

Recently the reclamation of indigenous ecosystems has become a desired post mining outcome, especially in the West Coast and Coromandel regions. There has been very little scientific research conducted in this area and few examples of successful reclamation. Recommendations have generally been based on observation of natural revegetation of mine sites and erosion scars. Conclusions from this literature are that *Nothofagus spp* (southern beech) (Cawthron Technical Group, 1977; Wardle, 1980) and *Metrosideros* (pohutukawa and rata) species (Clarkson, 1990) are the only indigenous trees that can establish directly onto a mineral surface. Beech trees require an open, stable and sheltered surface (Cawthron Technical Group, 1977; Wardle, 1980). Establishment of most indigenous forest species is best achieved by encouraging and accelerating natural succession using hardy pioneer species of *Coriaria* (tutu), *Coprosma*, *Hebe*, *Olearia*, *Cassinia*, *Kunzia* and *Pittosporum* species. Some *Olearia*, *Hebe* and *Cassinia* species have extensive fibrous root systems which aid soil stabilisation (Follett and Dunbar, 1985). Nitrogen fixers such as *Coriaria* may be particularly valuable for reclamation of bare mineral surfaces and benefit from phosphate fertiliser applications (Clarkson, 1990). Generally sowing of pasture grasses should be avoided except in very low seeding rates (@ 3 kg ha<sup>-1</sup>) (Nicholls, 1988; Ross *et al.*, 1990). Initial broadcast applications of nitrogenous fertiliser should be avoided as they increase weed competition with native species (Metcalf and Godfrey, 1990; Nicholls, 1988), although Scheltus (1990) disagrees. Spreading forest trash, litter, and topsoil onto the mineral substrate is important (Nicholls, 1984; 1985; 1986; Metcalf and Godfrey, 1990; Simcock, 1990; Mew and Ross, 1991), with the exception of mudstone (Scheltus, 1990), as exposed subsoils generally inhibit reclamation due to macronutrient deficiencies (Basher and Tonkin, 1985). Forest trash may provide an initial nitrogen source (Clarkson, 1990), establishment sites for kamahi and rata (Wardle, 1966) and source of vegetative propagules. Forest litter provides inocula of mycorrhizae (Heath, 1986a; 1986b; Brown and Heath, 1987). Where gorse seeds are present in the topsoil germination may cause gorse competition with native seedlings (Gregg *et al.*, 1990 page 98; Mackenzie and Cave, 1990) although authors disagree on the potential of gorse as a nurse crop. Spreading of forest topsoil has the potential to introduce both indigenous and exotic species suited to exposed environments (Enright and Cameron, 1988; Scheltus, 1990; Simcock, 1990). Layering of manuka slash may promote natural regeneration (Nicholls, 1986; Mark *et al.*, 1989; Metcalf and Godfrey, 1990; Scheltus, 1990), however manuka should be thinned to maximise the amount of light reaching seedlings of later successional plants which establish beneath it.

There is a wealth of international literature on mining reclamation, however most reclamation research can only be applied to New Zealand sites at a general level. The applicability of overseas research and experience depends primarily on similarities in climate, soils, vegetation, and post mining land use. Techniques for reclamation of "artificial" systems such as intensive

recreation, landfill, industrial developments and housing subdivisions may be transferred with minor alterations. Agricultural and horticultural reclamation techniques are most easily transferred at a general level from England, south-eastern Australia and lowland California as these areas have climates closest to New Zealand's. Agricultural technologies must be adapted to New Zealand's low-input, year-round grazing systems and differences in size of operation and equipment. Information from local field trials should be used before specific techniques are adopted by the mining industry in New Zealand. Reclamation of indigenous ecosystems is the most difficult area in which to apply overseas technology. The most easily transferred research in this area involves seed collection, treatment and germination practices and reclamation methods which encourage fauna to colonise mined areas.

Chapter Three concluded by outlining the major areas where further mining reclamation research is required in New Zealand. No multiple-treatment trials have been implemented to date in New Zealand which have included optimum soil replacement techniques for reclamation of aggregate mines. Research is needed into critical levels of compaction in moderate rainfall climates. There is also a great requirement for basic and applied research into the ecology and reclamation of indigenous New Zealand ecosystems.



## 4. Field Trials

### 4.1 Introduction

The greater Manawatu region is part of a coastal plain which extends along the west coast of North Island from Taranaki in the north to Paekakariki in the south. The region incorporates the former Wanganui, Rangitikei, Manawatu, Horowhenua, Oroua, Pohangina, Kiwitea and Kairanga counties which are separated principally on catchment boundaries (Figure 4.1). The greater Manawatu plain comprises from east to west: terraces abutting the axial ranges, river flats and a dune complex adjacent to the coast. The sand country extends approximately 15 km inland from the coast, consisting of a complex of dunes, sand plains and peaty swamps (Molloy, 1988). An east-west strip of Holocene river flats transects the terrace and dune topography with flights of aggradational and degradational terraces lining each river valley.

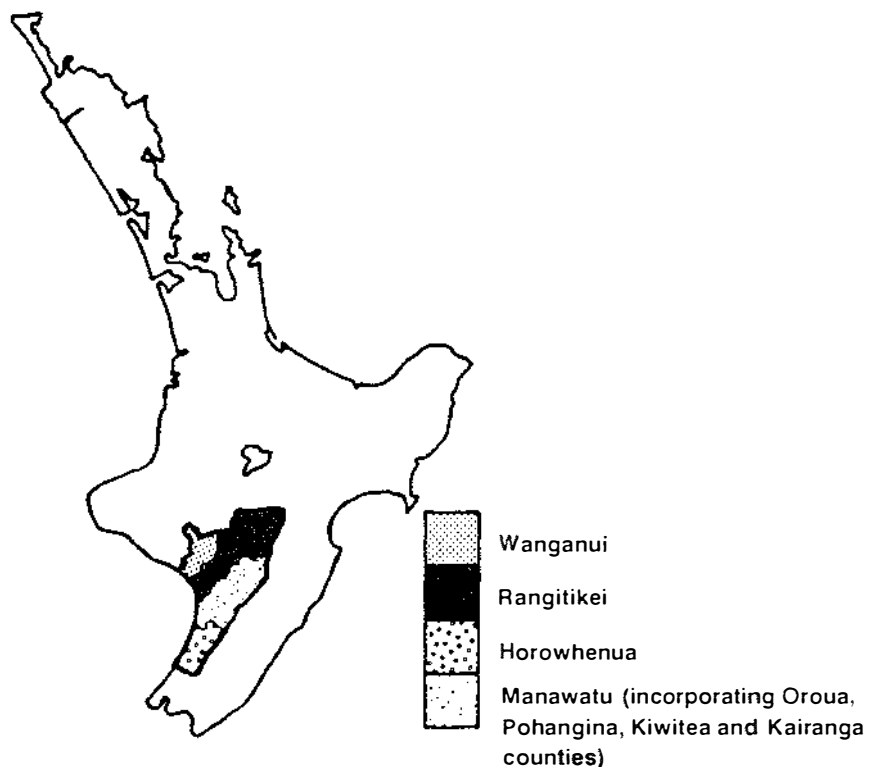


Figure 4.1: Map of the North Island, New Zealand, showing the greater Manawatu region and former constituent counties (adapted from Wards and Shearer, 1976).

The three field trials were located within 10 kilometres of Massey University (Figure 4.2). The Ohakea and Ashhurst trials lay within the Best Estate, owned by Massey University, and contain soils representative of those overlying extensive aggregate deposits that are currently mined commercially near Otaki and Palmerston North. The Ohakea and Ashhurst trials, on the Ohakean terrace were approximately 50 m above sea level and 8 to 12 m above the Tiritea river. The third site was located on the western bank of the Manawatu River approximately 5 kilometres north-east of Palmerston North and was actively mined for aggregate until 1990.

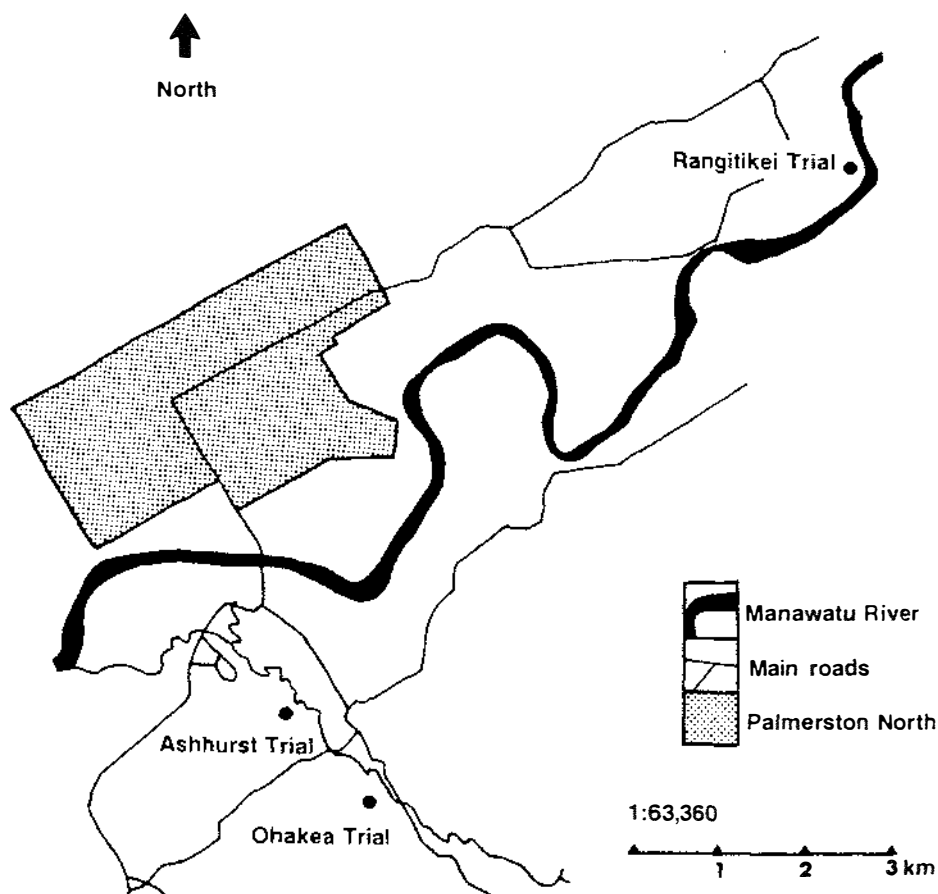


Figure 4.2: Location of Ohakea, Ashhurst and Rangitikei trial sites in relation to the city of Palmerston North.

#### 4.1.1 Vegetation and land use

Following exploratory trips up the Manawatu river in the 1840's, E. Wakefield described the Manawatu area as "level and fertile in character and abounding in the finest timber". J.T. Stewart, surveying the Manawatu block in 1859, described the large areas of forest as variable in nature including lightly scrub-covered areas. The lowland forests comprised mixed podocarps and hardwood forest with rimu (*Dacrydium cupressinum*), matai (*Prumnopitys taxifolia*), miro (*Prumnopitys ferruginea*), totara (*Podocarpus totara*) and kahikatea (*Dacrycarpus dacrydioides*)

represented among the large podocarps and northern rata (*Metrosideros robusta*), kamahi (*Weinmannia racemosa*), tawa (*Beilschmiedia tawa*), pukatea (*Laurelia novae-zelandiae*) and black maire (*Nestigis cunninghamii*) represented among the hardwood trees (Pollok and McLaughlin, 1986). Manuka (*Leptospermum ericoides*) was the most prevalent pioneer on frequently flooded areas (Rangitikei and Parewanui soils), with kanuka (*Kunzia scoparium*) found on more stable soils. Totara dominated free draining, sandy river levees (Manawatu and Karapoti soils), being tolerant of periodic drought and accumulation of alluvium around its base. Totara also dominated the stony drought prone Ashhurst soils of the Ohakean terrace and poorly drained Tokomaru soils that experienced summer deficits (Esler, 1978). Kahikatea and pukatea were most common on the young and fertile imperfectly to poorly drained soils of the river flats (Kairanga soils). Rimu was common in non accumulating river soils and terrace soils (Dawson, 1988). Above 700 m the lowland podocarp species gradually diminish and are replaced by montane totara (*Podocarpus cunninghamii*) with leatherwood (*Olearia colensoi*) at even higher altitudes (Esler, 1978).

Initial clearance of forest in Manawatu began with the first land sales in 1868. The arrival of Scandinavian settlers in the 1870's, and passing of the 1871 Settlement Act accelerated forest clearance. The 1871 Act deferred land payments for five years provided a house worth more than 10 pounds was built on the property and  $\frac{1}{10}$ th of the land was cleared, cropped, or grassed within two years (Adkin, 1948; O'Conner, 1984). Adkin expressed the attitude of an early settler towards the forest "*The ground seemed level, the soil rich, water plentiful, but oh, the work of clearing this huge growth of trees, scrub and logs*". Logging and burning between 1870 and 1891 (O'Conner, 1984) converted most of the Manawatu's native vegetation to grass (Pollok and McLaughlin, 1986) with only small, isolated patches of the original forest remaining in 1992. The largest remnants are in the upper reaches of the Tiritea Stream catchment forming a water conservation reserve (Cowie, 1978), Keebles Bush, a 15 hectare remnant near Massey University and Totara Reserve on the Pohangina River (Esler, 1978). Land use in Manawatu today is dominated by pastoral and arable farming. Highly productive dairying, cropping, sheep and cattle fattening practices feature on the river flats, terraces and easy to undulating foothills. Arable cropping in the Manawatu region includes malting and feed barley, maize, potatoes and process vegetables. Sheep and cattle breeding farms dominate on the medium to steep foothills of the Ruahine Ranges with bull beef production expanding since the late 1970's.

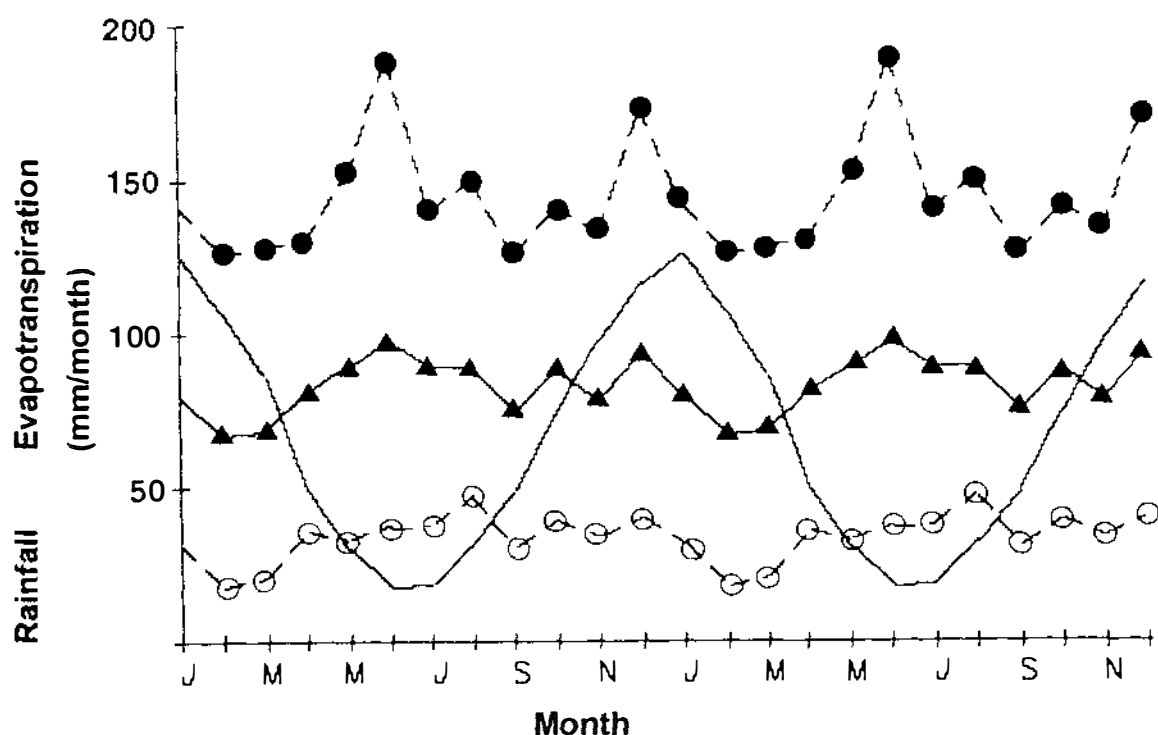
#### 4.1.2 Climate

Manawatu has a mild, subhumid, marine climate (Cowie and Rijske, 1977) with mild winters and cool summers (Espenshade, 1982). Mean annual rainfall ranges from 858 mm at Foxton on the coast and rising due to an orographic effect to 995 mm at Palmerston North D.S.I.R. and 1350 mm at the Tiritea water treatment plant in the foothills of the Tararua Ranges (Scotter, 1988b). This pattern is repeated throughout the region (Table 4.1). Climate recording stations applicable

to the trials are situated at Massey University, Palmerston North D.S.I.R and Palmerston North airport. Longer term climate statistics, recorded at the D.S.I.R. site from 1928, are used in this description as climate has only been recorded at Massey University since 1970 (New Zealand, Meteorological Service, 1981).

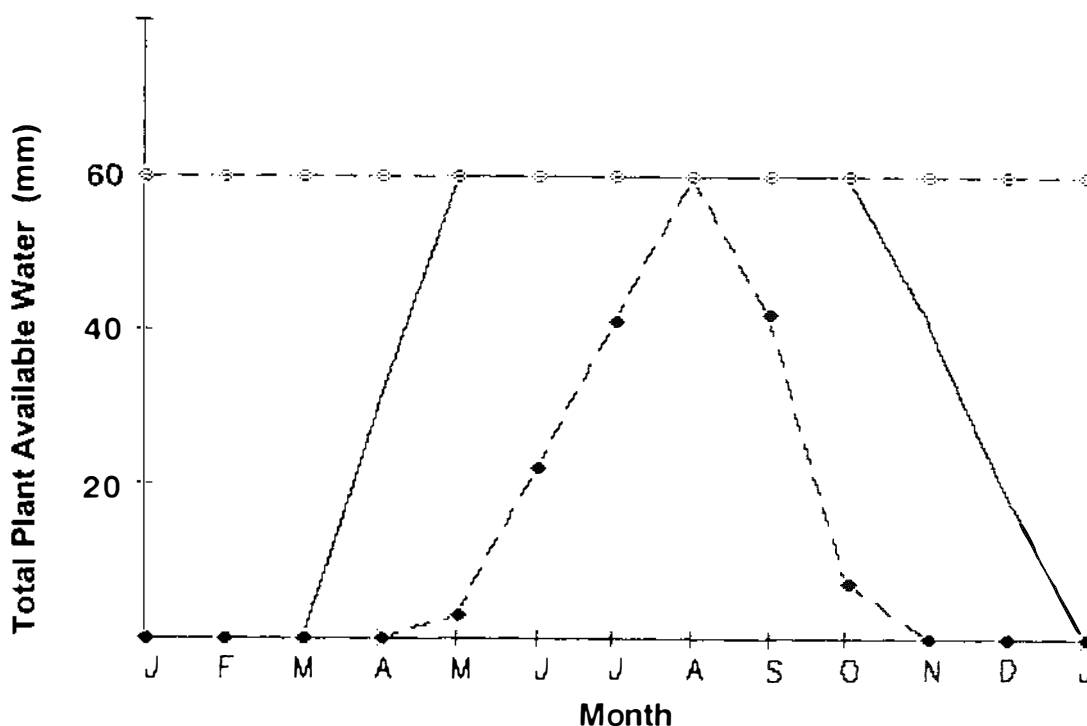
Table 4.1: The orographic effect on rainfall in the Pohangina catchment from Fielding to Table Flat (Rijske, 1977).

Rainfall Station	Mean Annual Rainfall (mm)	Elevation (m)
Feilding	950	90
Te Awa	1017	318
Apiti	1300	455
Table Flat	1830	680



Graph 4.1: Mean (1928 to 1980) rainfall (-▲-), 10 percentile rainfall (-○-) and 90 percentile rainfall (-●-) and evapotranspiration (-○-) at Palmerston North. Data from New Zealand Meteorological Service, 1981.

Rainfall in the region is fairly evenly spread throughout the year with 631 mm mean winter rainfall, (May to August) and 568 mm mean summer rainfall (December to March) (Graph 4.1). In an average year there is a winter and spring (May to October) rainfall surplus (Horne, 1985) and a water deficit from January to March inclusive (Molloy, 1988) (Graph 4.1 and 4.2). On average, soils contain high levels of moisture from April to October which requires soil management techniques to avoid damage of soils with low hydraulic conductivities or impeded drainage (Graph 4.2). Serious droughts are uncommon, although water deficits usually occur from January to March. In a year where 10 percentile rainfall occurs plants would experience a six month water deficit from November to April in a soil with 60 mm of total plant available water in the surface 0.35 m (Graph 4.2).

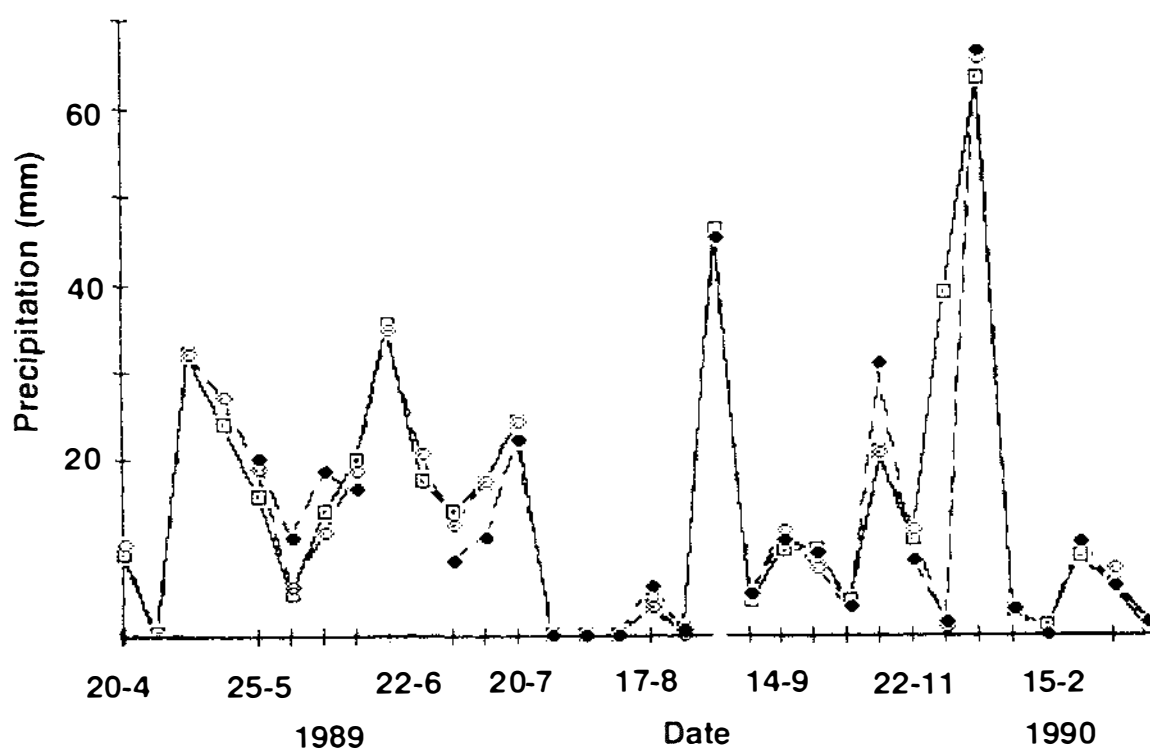


Graph 4.2: Total moisture available for plant growth (PAM) (mm) at the end of each month in a year with mean rainfall (---), 10 percentile rainfall (●) and 90 percentile rainfall (○) for a soil with 60 mm PAM in the surface 0.3 m.

An 11 month comparison of weekly precipitation measured at Ohakea and Rangitikei trial sites with precipitation measured at the Palmerston North D.S.I.R. showed that precipitation at the Ohakea trial site 3.2 km distant was very similar to that of the D.S.I.R. site with less than 5 mm difference between measurements (Table 4.2). Weekly precipitation at the Rangitikei site 8 km away generally mirrored that at the D.S.I.R., with 20 percent of weekly precipitation measurements having a difference greater than 5 mm, due to isolated rain storms (Graph 4.3). Temperature fluctuations are moderated by proximity to the Manawatu and Tiritia Rivers at the Rangitikei and Ohakea-Ashhurst sites respectively. Mean annual air temperature is 12.9 degrees Celsius with a average daily range of 8.6 degrees Celsius. The average monthly minimum (lowest temperature each year) is -1.9 degrees in July with the monthly maximum of 27.4 degrees

Table 4.2: Summary of differences in total weekly precipitation between the Ohakea trial site, Rangitikei trial site and AgResearch (Palmerston North D.S.I.R.) climatological station.

Comparison	Measurement Site	
	Rangitikei	Ohakea
Mean % difference compared to DSIR site	17	12
Percent DSIR records >5 mm different	20	0
Percent DSIR records <0.5 mm different	40	47



Graph 4.3: Comparison of weekly rainfall measurements from AgResearch (Palmerston North D.S.I.R.) (-□), Ohakea (-○) and Rangitikei (-●) trial sites from April 1989 to March 1990.

occurring in February. Ground frosts occur mainly in the months of May to September and infrequently (one year in five) from December to February. Air or screen frosts are generally restricted to the months from May to September. The degree and distribution of frost is markedly affected by topography, terrace height and presence of shelter belts which may prevent drainage of cold air.

Palmerston North has 1794 mean annual hours of sunshine (42% of possible sunshine each month). Palmerston North has a mean daily wind run is 242 kilometres and 4.2 days per month with winds over 63 km hr<sup>-1</sup>. North west and west winds associated with active fronts frequently

reach gale force (Cowie and Rijske, 1977) with north east storms arising from tropical depressions. September to February are the windiest months of the year (see Figure 4.6).

## 4.2 Rooting media at the three trial sites

### 4.2.1 Ohakea soil

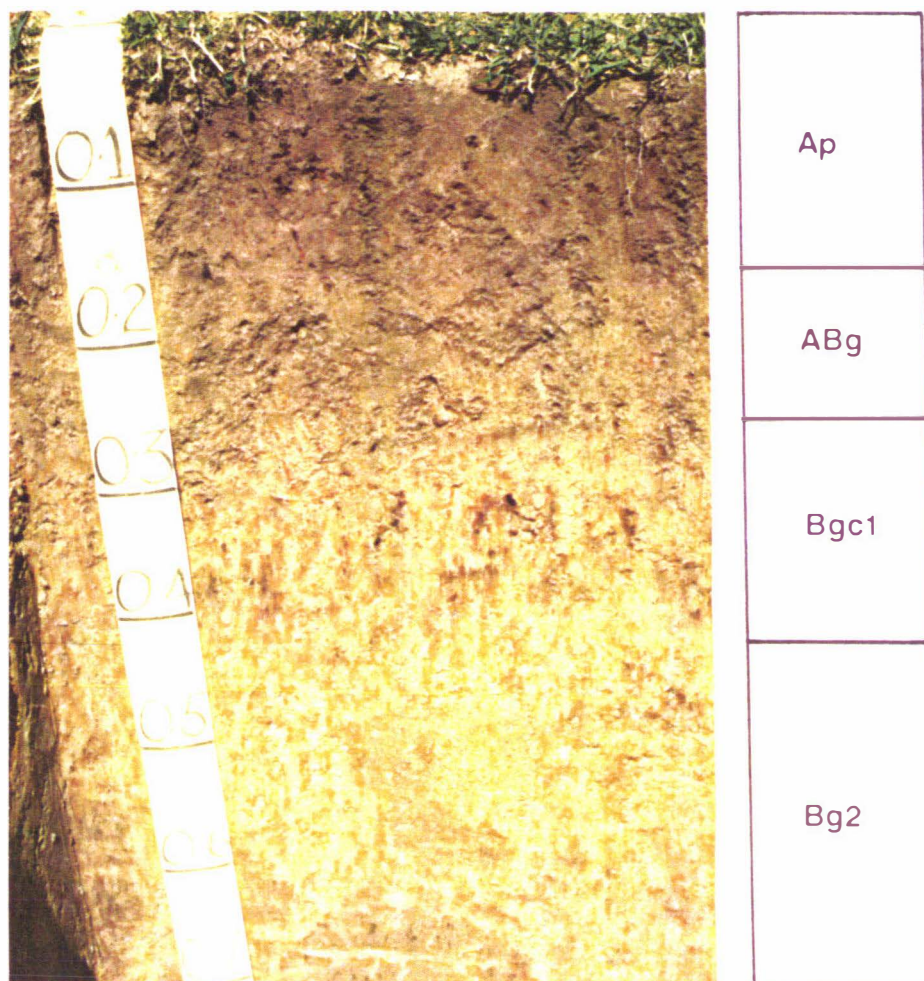
Ohakea soils are the youngest yellow-grey earths in the Manawatu region. Yellow-grey earths are a group of soils mainly formed from silty loess under a climate with a summer water deficit (Cowie, 1974; Cowie, 1978; Pollok and McLaughlin, 1986). New Zealand Soil Bureau has used the Ohakea soil series to include yellow grey earths which lack the 22,500 year old 'marker' bed of Aokautere ash. Thus Ohakea soils are found on the Ohakean (intermediate) terraces in former stream courses. Ohakea soils are also found on colluvial fans which extend onto older terraces (Pollok and McLaughlin, 1986)(Figure 2.5) and are found around Ohakea airport in Rangitikei and mapped in large areas of Manawatu (Rijske, 1977).

The upper horizons of Ohakea soils are characterised by 0.45 to 1.80 m of fine-grained, silty material (Rijske, 1977; Cowie, 1978) forming silt loam topsoils and silt loam or silty clay loam subsoils (Photograph 4.1). Gley features dominate Ohakea silt loam soil profiles, which naturally have slow unsaturated hydraulic conductivity (poor drainage). Topsoils are typically greyish-brown and may display mottling, while subsoils are pale with yellowish-brown and dark brown mottles. A prominent band of black iron and manganese concretions occurs in many profiles (Pollok and McLaughlin, 1986). Sometimes thin bands of sandy material separate the colluvium-derived Ohakea soils and 2 to 15 m of aggradational gravels (Cowie, 1974; Lieferring, 1990). In places where the water table is very high, iron pans and packed gravels may occur at this silt/sand/gravel interface (Palmer pers. comm., 1991).

The chemical status of Ohakea silt loam reflects its relative youth. Topsoils contain medium to low levels of total carbon with very low organic carbon subsoil levels probably indicative of additions of colluvium disrupting vegetative growth (Rijske, 1977; Cowie, 1978). Moderate leaching is indicated by moderately acid topsoils and slightly acid subsoils with moderate to high % base saturation (Rijske, 1977; Cowie, 1978; Pollok and McLaughlin, 1986). Medium to low cation exchange capacities, which are lower in subsoils than topsoils, indicate little downward movement of clay and little weathering. Ohakea soils typically have medium to low exchangeable and reserve potassium (Cowie *et al.*, 1967), low phosphate fixation (Pollok and McLaughlin, 1986) and low reserves of total and plant available phosphorus (Cowie *et al.*, 1967; Rijske, 1977; Cowie, 1978).

Ohakea soils are mainly used for intensive sheep and cattle farming, with small areas used for arable cropping, dairying, perennial and annual horticulture. The major limitations to production





Photograph 4.1: Profile of an Ohakea silt loam near the Ohakea trial site. Note the orange and grey mottled subsoil containing black iron concretions (see Appendix 4.1 for a profile description).

on undrained Ohakea silt loam are poor drainage and susceptibility to damage through pugging by stock or machinery in winter. This limits pasture utilisation and restricts tillage and harvesting operations for horticultural or arable crops. Variations in soil depth, a generally silty subsoil and erratic occurrence of iron pans make drainage with mole drains unsatisfactory (Cowie, 1974), however, tile drains may be effective. Ohakea soils are ideally farmed in conjunction with Ashhurst soils with the reliable summer pasture growth of Ohakea soils complementing wintering pastures of Ashhurst soils.

#### *Ohakea soil at the Ohakea trial site*

The Ohakea trial soil was sited on the Best Estate 2 km north east of Massey University. The trial was on a colluvial fan which spills onto an Ohakean Terrace associated with the Tiritea River. Soils on the trial terrace were mapped as Ohakea silt loam by Cowie (1974) at a scale of 1:15,840 (4 inches to 1 mile) and Cowie (1978) at a scale of 1:63,360 (Figure 4.4). Ohakea soils at the trial site comprised 0.35 to 0.70 m of silty loess interbedded with lenses of colluvial loess,

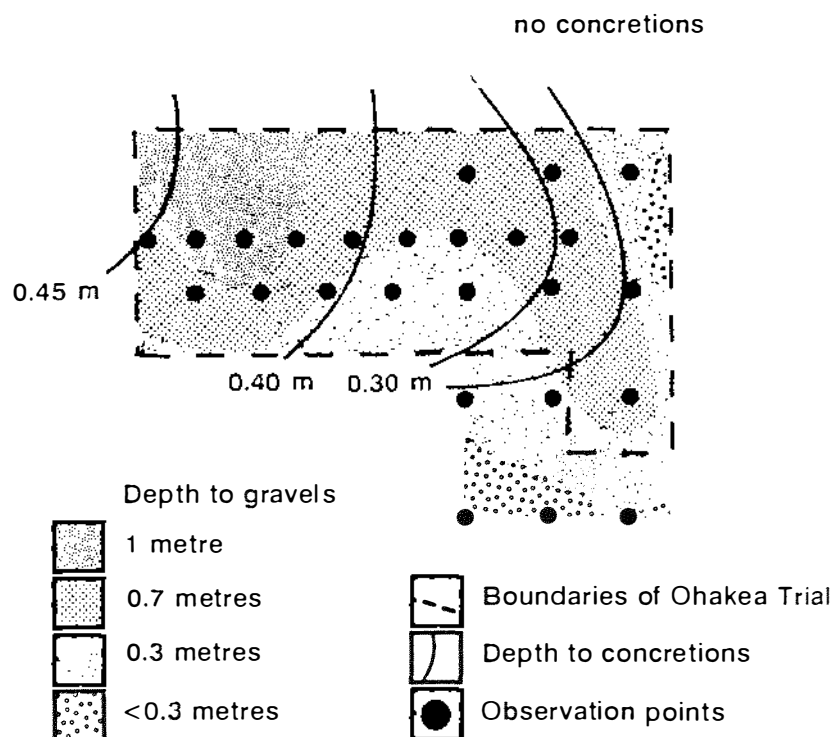


Figure 4.3: Depth to concretions and iron-stained gravels (m) within the Ohakea trial site. Depth to concretions is indicated by contour lines which link points with concretions at equal depths.

sand and gravel from the adjoining higher Tokomaru terrace over tightly packed gravels. Sedimentation on the fan (changes in the depositing stream's course with time) had caused a slight variability in profile properties over the trial area (Figure 4.3) with the lower gleyed (Bg2) horizon becoming sandier within 0.10 m of the gravel interface in some places (Appendix 4.1). Soils in the vicinity of the trial graded from Ohakea soils at the apex of the fan to stony Ashhurst soils at the terrace lip (Figure 2.3). Spot heights in the Tiritea valley and exposed road cuttings indicated 8 to 12 m of alluvial gravels and sands underlay soils at both sites.

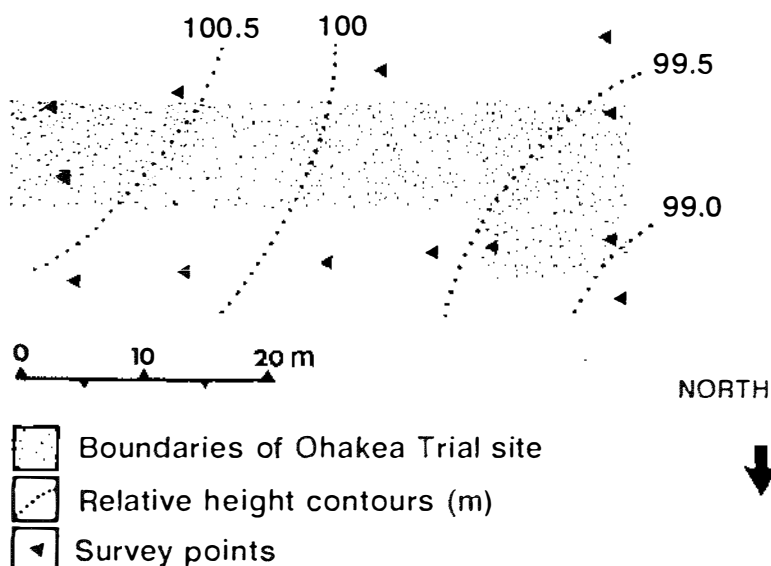


Figure 4.4: Contour map of the Ohakea trial site showing the relative heights of the ground surface. The colluvial fan slopes from top left to bottom right.

Ohakea soils at the trial site comprised a 0.18 to 0.20 m dark yellowish brown silt loam ploughed topsoil (Ap) horizon overlying a 0.28 m horizon of weathered silt loam (Bwg) with black iron nodules and orange and grey mottles indicating saturated and reduced soils conditions at this depth occur (Singelton, 1991)(Appendix 4.1). This Bwg horizon passed into a light grey gleyed (Bg) horizon on top of cemented iron stained gravels in a stained sand matrix. Ohakea soils at the trial site were similar to the type profile described by Cowie (1974) at Massey University site (Appendix 4.1) but remained a silt loam throughout the profile rather than displaying clay accumulation in the lower horizons. At the trial site dry bulk densities increased with depth from  $1.15 \text{ Mg m}^{-3}$  at 0.05 m to subsoil values at 0.30 m of  $1.59 \text{ Mg m}^{-3}$  which may limit plant root growth. Soil macroporosity decreased by 12% down the soil profile from 35% at 0.05 m to 23% at 0.30 m.

The paddock in which the trial site was located had been regularly fertilised and had been renovated in 1984-84 by ploughing and drilling with perennial ryegrass and white clover cultivars for grazing lamb, sheep and bulls. Soil tests taken from the trial area in late 1988 showed a moderately acid pH, medium to high Olsen phosphate due to recent fertiliser history and medium exchangeable potassium, magnesium and calcium values (Appendix 4.3).

#### 4.2.2 Ashhurst soils

Ashhurst and the closely related Kawhatau soils are found on extensive terraces at Ohakea, Palmerston North, Ashhurst, Ohau near Levin and the Hautere Plains south of Otaki, as well as along the Rangitikei, Oroua and Pohangina Rivers (Molloy, 1988). Under the New Zealand

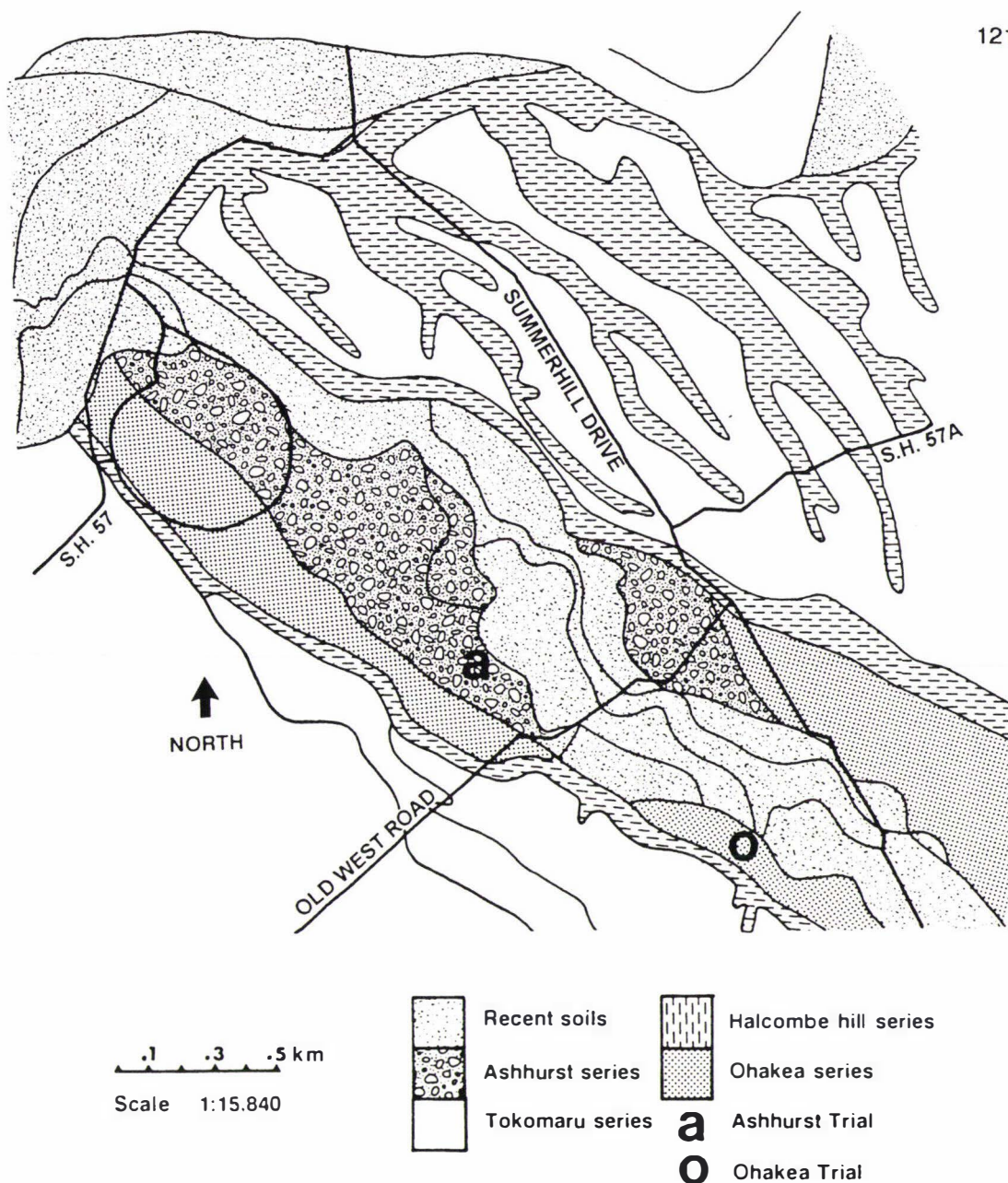


Figure 4.5: Soils in the vicinity of Ohakea and Ashhurst trial areas. Part of New Zealand Soil Survey Report 24 (Cowie, 1974).

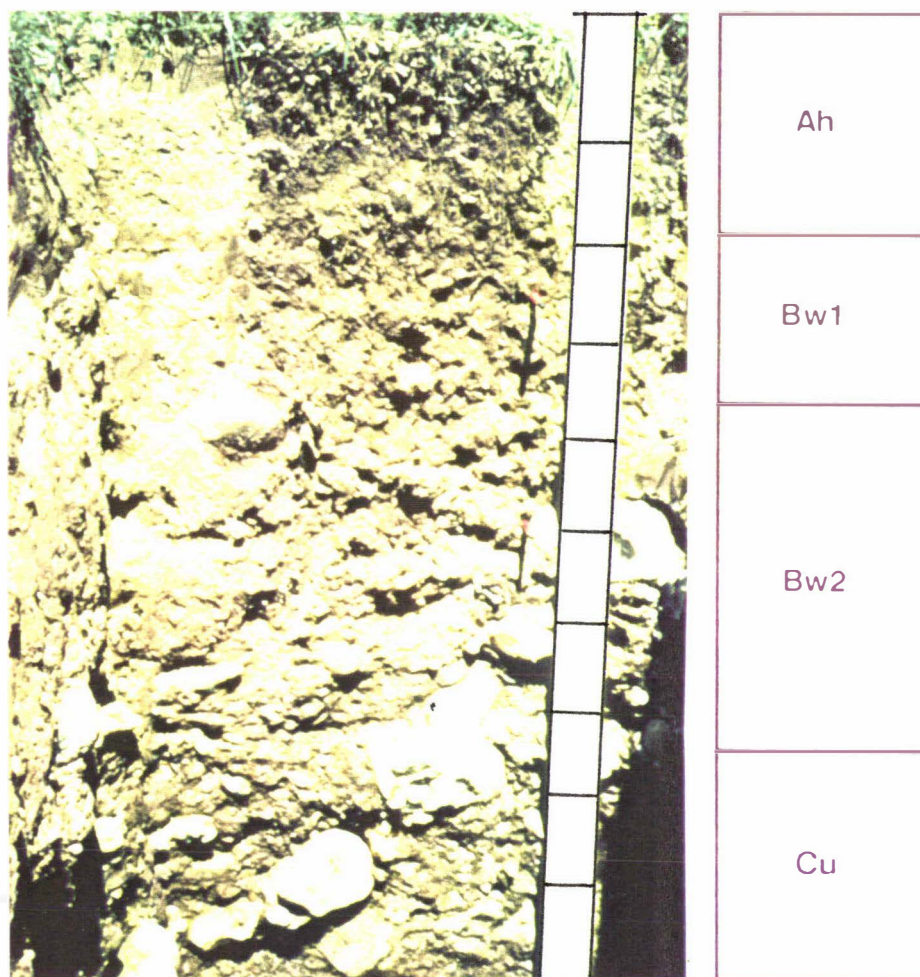
genetic classification Ashhurst stoney silt loams are weakly leached yellow brown shallow and stoney soils associated with yellow grey earths (Cowie, 1978).

In some areas Ohakea and Ashhurst soils are so intricately associated they are mapped as a soil complex (Cowie, 1978). Ashhurst soils are derived from thick gravelly alluvium, sometimes covered with a thin layer of colluvium (Cowie, 1978) or loess, and develop under an annual rainfall of 950 to 1200 mm.

Ashhurst soils comprise more than 35% stones by volume in the top metre of soil with stone contents ranging from 35 to 75% (by volume) throughout the profile and increasing with depth (Photograph 4.2). Ashhurst soils are found near the edges of the Ohakean terrace (Cowie, 1978) and on undulating broad ridges.



Topsoils are black where the original vegetation was scrub and bracken and brown where the original vegetation was forest (Cowie, 1978).



Photograph 4.2: Profile of an Ashhurst stony silt loam near the Ashhurst trial site. Note the increase in the volume of stones with increasing depth. The intervals on the tape are 50 mm apart.

Total porosity and macroporosity values of Ashhurst soils are medium to high, with macroporosity increasing with depth as a function of increasing sand and stone content. Ashhurst soils in Otaki had a macroporosity of 17% and 21% with total porosity 65% and 60% in the 0 to 0.20 m and 0.38 to 0.63 m horizons respectively (Palmer, unpublished<sup>data</sup>). Ashhurst soils have high hydraulic conductivities (Cowie, 1974) so store less than 50 mm of plant available water (Palmer, unpublished<sup>data</sup>), which limits summer production. These soils are used for dairy, intensive sheep and cattle farming, and perennial horticultural cropping such as stonefruit and kiwifruit. Similar soils in Hawkes Bay, Wairarapa, Marlborough and Canterbury are highly prized for wine-grape production. Arable cropping is limited by the high proportion of stones in topsoils (Cowie, 1974).

Ashhurst silt loam soils are weakly leached despite their high unsaturated hydraulic conductivity, with moderately acid to slightly acid topsoil and subsoil pH and medium to very high topsoil base saturation (on fertilised farmland), which decreases with increasing stone content (Rijske, 1977; Cowie, 1978). Medium levels of organic carbon (4 to 6%) in topsoils drop to very low levels of less than 2% in subsoils (Rijske, 1977; Cowie, 1978; Palmer, unpublished). The presence of small amounts of allophane, results in a moderate phosphate retention (Rijske, 1977). A low subsoil cation exchange capacity and medium topsoil cation exchange capacity (Palmer, unpublished) with medium to high topsoil sulphuric acid-soluble phosphorus values indicate little weathering or clay movement of the Ashhurst soil.

#### *Ashhurst soil at the Ashhurst trial site*

Soils in the vicinity of the trial site were mapped by Cowie (1978) at a scale of 1:63,360 and by Cowie (1974) at 1:15,840 as Ashhurst silt loam, stony phase (Figure 4.4), similar to Pollok (1964) who also mapped the area as Ashhurst shallow silt loam, stoney phase. The Ashhurst soil displayed the characteristic physical properties of the series described by Cowie (1978), Rijske (1977) and Palmer (unpublished) with low bulk densities and subsoil gravel contents greater than 40% (Photograph 4.2). During construction of the Ashhurst trial it was noticed that 3 of the 24 plots contained charcoal to 0.30 m depth, which may result from burning of the original totara forest. Some plots were finer textured with low volumes of gravels in their subsoils to 0.7 m, which indicates a shallow, infilled stream channel.

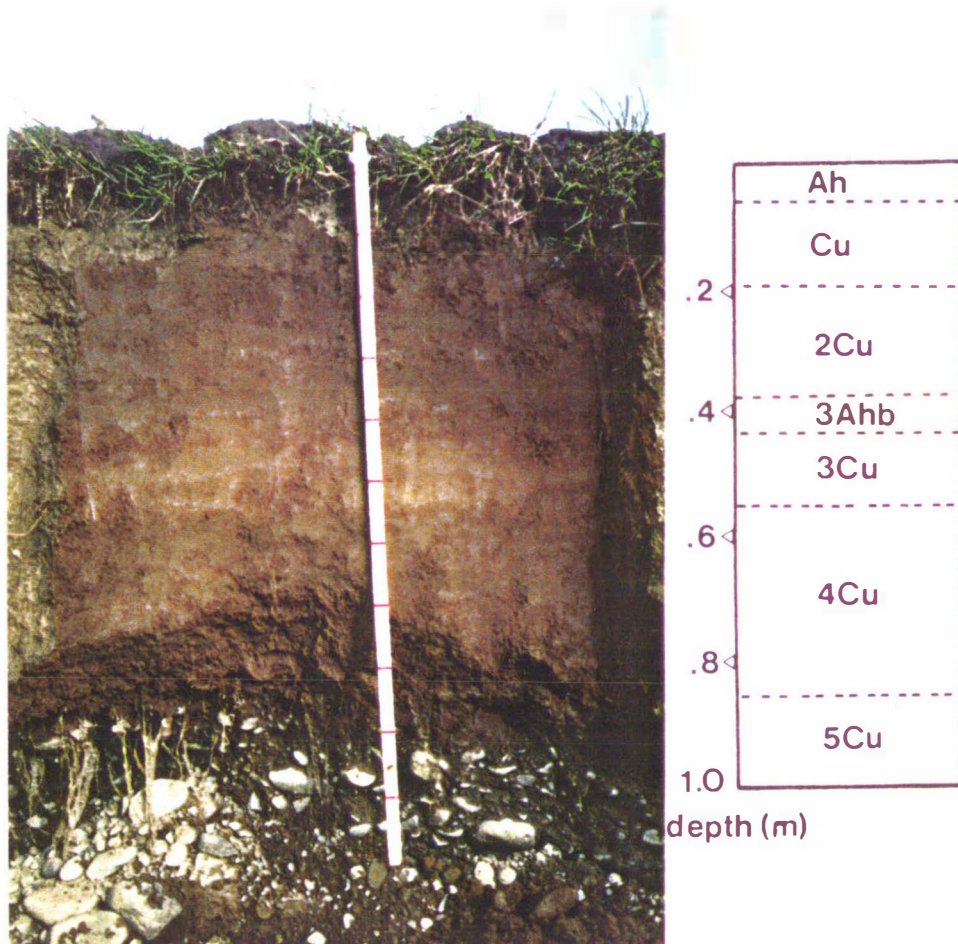
The trial site paddock was part of a intensively farmed bull beef and lamb production unit used occasionally as a holding paddock for sheep. Chemical analyses of the topsoil revealed medium to high levels of Olsen phosphate, reflecting regular maintenance dressings of fertiliser soils. No major plant nutrients were limiting with high levels of exchangeable potassium and medium levels of sodium, magnesium and calcium (see Appendix 4.3).

#### 4.2.3 Rangitikei soils

Rangitikei soils are the youngest freely draining alluvial soils in the Manawatu region. They are situated on the lowest, most frequently flooded river flats, levees and islands and develop in fine-grained alluvium 0.15 to 3 m deep (Photograph 4.3). This alluvium overlies weakly-packed, unweathered, alluvial, greywacke gravels and sands (Cowie, 1974) which in turn overly mudstones or older gravels (Cowie, 1974; Lieffering, 1990).

The variable and complex nature of flood deposits create a wide range of profiles with variable depths, however, all Rangitikei soils are characterised by a shallow A horizon (topsoil), low in organic matter, which is visually little different from the underlying C horizon. Frequent flooding interrupts soil forming processes and the incorporation of organic matter into the topsoil. This

creates flood banding, which is seen as dark greyish brown bands of buried rudimentary topsoils and sharp textural changes (Photograph 4.3). Four Rangitikei soils comprising loamy sands, sandy loams, fine sandy loam and mottled fine sandy loams were recognised by Cowie *et al.* (1967) and Cowie 1978. Additionally a shallow or gravelly phase has been described by Rijske (1977) and Cowie (1974). Generally sandy loams have deeper and finer textured profiles than loamy sands and are not as variable.



Photograph 4.3: Profile of Rangitikei fine sandy loam near the Rangitikei trial site. Note the presence of a buried organic (Ah) horizon and absence of a B horizon.

The chemical properties of Rangitikei soils reflect their extreme immaturity. Rudimentary topsoils with very low to low total carbon contents (0.4-2.3%) reflect the short plant establishment time between floods (Cowie *et al.*, 1967; Rijske, 1977; Cowie, 1978) Weak weathering is evident by low clay contents (Rijske, 1977), low to very low cation exchange capacities (Rijske, 1977; Cowie, 1978) and very low levels of extractable iron and aluminium in topsoils and subsoils (Cowie, 1978). Weak leaching is indicated by base saturations in excess of 80% (Rijske, 1977; Cowie, 1978) moderately acid topsoil pH with near neutral subsoils pH of 5.7-6.7 (Rijske, 1977; Cowie, 1978). Rangitikei soils also display low phosphate retention (Palmer, unpublished data).

The use of Rangitikei soils is primarily determined by their susceptibility to flooding and low water holding capacity. Rangitikei soils protected by flood banks or flooded only occasionally are intensively farmed with high quality pastures maintained with low applications of fertiliser. On deeper and finer textured Rangitikei soils high yields of arable crops are achieved in wetter years (Cowie *et al.*, 1967). Where flooding is more frequent Rangitikei soils are used for extensive rough grazing or recreation.

#### *Rangitikei soil at the Rangitikei trial site.*

Soils in the trial area were mapped at a scale of 1:63,360 (inch to a mile) as Rangitikei loamy sand by Cowie (1978) (see Figure 4.9). Palmer (pers. comm., 1988) confirmed soils from the trial site as Rangitikei loamy sands and fine sandy loams. Rangitikei soils at the trial site were uncharacteristically even in depth to gravels, however, profiles were variable in both texture and horizon thickness, with layers of single grained coarse to fine sands and silts (Photograph 4.3)(Palmer, 1989). Typically a 0.06 m dark brown, weakly structured Ah horizon overlay a series of olive brown C horizons with one or more thin, buried organic horizons. There was a sharp break between the sands and silts and the coarse gravel layer comprising unweathered greywacke pebbles and cobbles in a clean, coarse, sandy matrix (Photograph 4.3)(Palmer, 1989). A type profile for Rangitikei fine sandy loam described by Cowie was very similar to soils at the Rangitikei trial, but displayed no buried humic horizons (Appendix 4.1).

Rangitikei loamy sand at the trial site had relatively high subsoil bulk densities of 1.44 to 1.49 Mg m<sup>-3</sup>, which reflected the particle density (i.e. high sand content) and structureless nature of the sand, and total organic carbon levels of approximately 1%. The bulk densities measured did not visually impede plant root growth, with plant roots extending to at least 0.46 m. Soil macroporosity levels were 37% (high) in the topsoil and 19 to 21% in the underlying C horizon. The Rangitikei soil was well-drained with high hydraulic conductivities (Cowie, 1974). Ground water levels at the Rangitikei trial site, as observed in the adjacent mined area which was excavated to approximately 10 m depth, fluctuated between 4 and 5 metres depth and consequently had little effect on subsoil moisture.

Soil samples before trial construction showed a medium Olsen phosphate status resulting from regular additions of superphosphate and a slightly acid pH of 6 to 6.5 (Appendix 4.3). Medium to high exchangeable potassium and low exchangeable magnesium and sodium reflected the soil's unweathered status and coarse quartzofeldspathic alluvial parent material (Appendix 4.3).

#### 4.2.4 Fill material

Fill material covered c.4 hectares at the Rangitikei trial site. The fill comprised 0.05 to 0.2 m layers of crushed and whole river gravels, in between and intermixed with organic and inorganic





Photograph 4.4: A fill area adjacent to the Rangitikei trial site. Note the variety of organic and inorganic materials. Similar materials were used as fill at the trial site.



Photograph 4.5: The surface of the filled area at the Rangitikei trial site prior to reclamation. Note the surface water and sparse, low fertility vegetation.

debris derived from road and building construction sites (Photograph 4.4). Large inorganic objects such as concrete slabs, plaster, ceramic tiles, asphalt and reinforcing steel were distributed throughout the fill to within 0.1 m of the surface. During fill construction there was no separation of organic and inorganic materials. The fill was deposited in layers by trucks and a large bulldozer used to level and stabilise each layer by compaction. The variable profile had a predominantly anaerobic, grey clay and silt matrix with a high proportion of gravels. The resulting medium was extremely dense with very low saturated hydraulic conductivities. Water ponded for days in ruts created by heavy machinery on the fill surface.

Vegetation present on the fill areas was dominated by low fertility grasses such as browntop (*Agrostis tenuis*), cocksfoot (*Dactylis glomerata*) and sweet vernal (*Anthoxanthum odoratum*) (Photograph 4.5). Rush species and paspalum (*Paspalum paspaloides*) occupied wet areas where water frequently ponded for long periods and legumes dominated 0.10 to 0.30 m high excessively draining gravel ridges between wheel ruts. The area was grazed one or two times a year by bulls during summer feed deficits but was otherwise not utilised and was an undesirable source of weed seeds such as stinking mayweed (*Anthemis cotula*).

#### 4.3 Field trials.

##### 4.3.1 Ohakea Trial.

The trial was located on a gently sloping colluvial fan, the contours of which are shown in Figure 4.5. The Ohakea trial comprised an approximately 10 m wide and 45 m long strip which minimised differences in soil depth to gravels and mottles between plots. The trial was uneven in shape as the Ohakea soil abruptly changed to a Hautere and Ashhurst soil to the south, which necessitated the resiting of two drained plots on Ohakea soils, creating a dog-leg (Figure 4.6). The Ohakea trial was based on a split plot design with undrained and drained treatments overlying eight soil replacement treatments (Figure 4.6). There were four blocks of seven soil replacement and compaction treatments and two of the four blocks were drained. Plots were 3 m wide by 4 m long with 0.5 m separating plots within rows and a 1 m wide strip between each row of plots.

The 'Aonly' treatment, in which the A horizon was replaced on the lowermost B horizon (Figures 4.6 and 4.7), was included as a replacement of a reduced profile, which in a commercial reclamation, would be considerably cheaper than reconstructing the whole soil profile. The treatment was also included to investigate the removal of the poorly structured and poorly drained upper B horizon. This may create improved soil physical conditions, thus allowing more flexible land management and increasing pasture production. The 'AonB' treatment was included as the separate stripping, storage and replacement of the topsoil is an intrinsic part of most reclamation operations, and is may be a requirement of site conditions concerning reclamation.

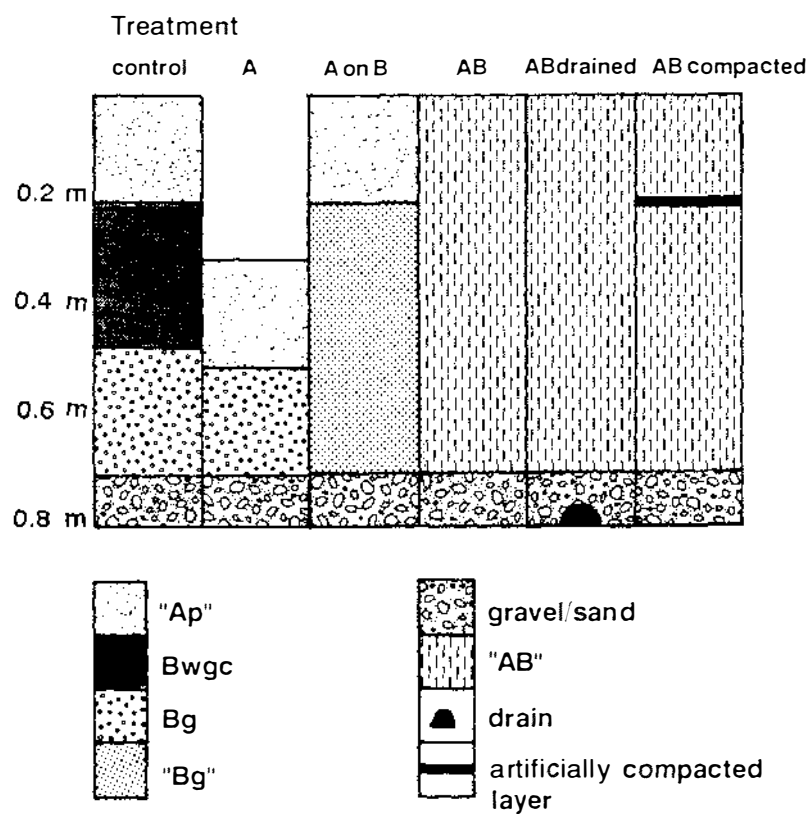
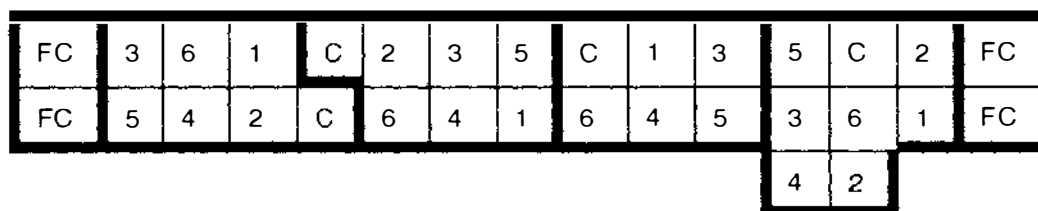


Figure 4.7: Schematic cross-section of soil replacement treatments at the Ohakea trial site.

Figure 4.6: Design of the Ohakea trial site and location of individual soil replacement treatments.



#### Key to Treatments

Soil replacement treatment	Aonly	ABmix	AonB	Control	Undist.
High compaction	1	2	3		
Low compaction	4	5	6	*	*

- Aonly** A horizon replaced on lower B horizon  
**ABmix** A and B horizons mixed to 0.70 m and replaced  
**AonB** A horizon replaced on mixed B horizons  
**Control** Disturbed to 0.20 m depth (dimulated cultivation)  
**Undist.** Undisturbed plots  
 \* Compaction level unaltered from natural state  
 1-6 Treatment numbers for above trial diagram  
 FC False Control (Undisturbed)  
 NOTE Thick lines identify blocks of treatments. Thin lines identify individual plots. The two LHS blocks were drained.

The 'ABmix' treatment, where all horizons were mixed to 0.70 m depth (Figure 4.7), was included because separately stripping soil layers is more expensive, and time consuming, than removing all soil or overburden layers together, which causes a mixing of the soil horizons. I also wanted to know whether topsoil mixing, compared to replacing soil horizons in their natural order, would influence growth of pasture. Compaction and drainage treatments were included because soil disturbed by opencast mining is often compacted and hence poorly drained (Chapter Six).

Plots at both ends of the trial were replicates of a treatment where neither pasture nor soil was disturbed. This treatment was included for interest and is often included in reclamation trials. I have called it a 'false' control as without resowing at the same time as the rest of the trial with the same species and cultivars, pasture growth comparisons are not valid. Replicates were sited at either end of the trial as experience gained during construction of the Ashhurst trial indicated that machinery was incapable of constructing plots without seriously damaging adjacent areas.

Soil replacement treatments were unbalanced, with no compacted undisturbed or compacted control treatments. Compaction of an undisturbed site to create a high density layer 0.20 m below the surface would have been practically impossible. Using a vehicle which would be heavy enough to achieve the desired compaction would have caused surface compaction that

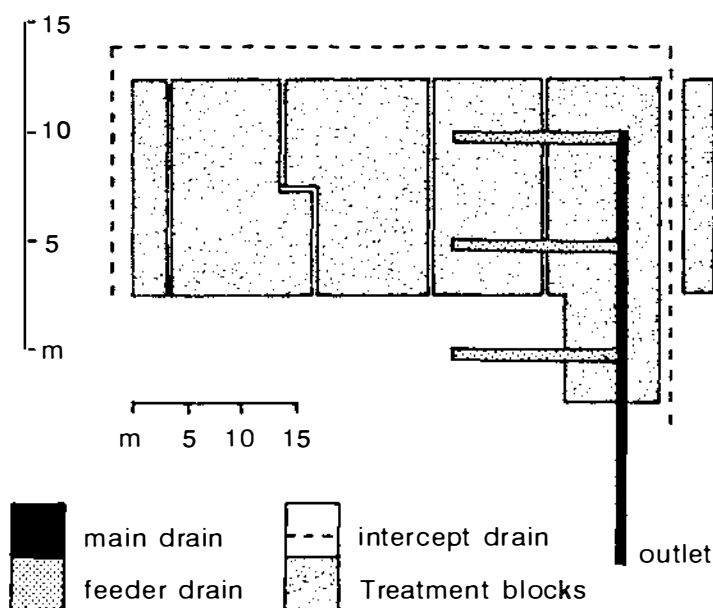


Figure 4.8: The drainage system, comprising main drain, feeder drains and intercept drains, installed at the Ohakea site.

would have prevented or severely limited pasture growth. Treatment 2 is found twice in one of the drained blocks due to a construction error.

#### *Construction of the Ohakea trial*

Construction of the Ohakea trial was preceded by spraying of the site with non-selective herbicides glyphosate (*Roundup*) (once) and glufosinate-ammonium (*Buster*) (twice) over a six month period while waiting for drainage contractors to put in an intensive tile drainage system over half the treatments. This comprised east-west orientated 'Nova-flow' feeder drains at 5 m spacings and 0.80 m depth (Figure 4.8). Intercept drains 0.20 to 0.30 m deep were dug on three sides of the trial to divert surface waters around the trial site. Soil water contents in excess of the plastic limit during an unusually wet winter and spring also delayed trial construction. As the trial was designed to compare worst case and best case restoration, earthworks could not begin until topsoil and subsoil moisture contents were below their plastic limits.

The main trial construction was implemented with a Gradall hydraulic excavator. The dark grey Ohakea A horizon was easily distinguished from the paler underlying B horizons as previous ploughing had created a distinct boundary by mixing the surface 0.18 to 0.22 m of the soil profile (Photograph 4.1 and 4.6). Compaction was applied by passing a vibrating roller 4 to 5 times over the soil surface at a depth of 0.18 to 0.22 m to create uniform compaction across each plot (Photograph 4.7). Compaction increased soil dry bulk densities at 0.20 m by  $0.33 \text{ Mg m}^{-3}$  on average (Table 6.4). After compaction the surface 0.20 m of material was replaced evenly. The





Photograph 4.6: Construction of the Ohakea trial: The darker A horizon is being replaced on top of the lighter B horizon of an "AonB" treatment.

thin dense layer imitated the laminar bands of compacted soil typical of poorly reclaimed mine sites. This uniform compaction simulated the "worst case" restoration scenario, testing the ability of roots to grow into a soil of a particular density, rather than around denser soil, or find fractures and zones of weakness. Soil "swelling" associated with excavation raised plot surfaces, other than "Aonly" treatments, approximately 0.05 m higher than the original ground surface between plots and prevented surface water flow over plots.

Plots were levelled, hand-raked and sown with a mixture of 23 kg ha<sup>-1</sup> perennial ryegrass (*Lolium perenne* var Ellet) and 3 kg ha<sup>-1</sup> white clover (*Trifolium repens* var Pitau) following recommended pasture renovation rates and species. A single pass of a non-vibrating roller stabilised the surface. Three weeks after germination superphosphate fertiliser was broadcast over the trial at a rate of 30 kg P ha<sup>-1</sup>.

#### 4.3.2 Design of the Rangitikei trial

Aggregate has been extracted from the vicinity of the trial site since the early 1960's (Spall pers. comm., 1988). Aggregate was initially taken from the bed and banks of the Manawatu River adjacent to the trial site. Extraction was moved to a former river channel by request of the local catchment authority who were concerned about the effects of a degrading river bed (Jurgen pers. comm., 1988). In 1988 the oxbow was mined out (mined and backfilled area in Figure 4.9) and the extraction company negotiated to begin mining part of the adjacent "island" which



Photograph 4.7: Ohakea trial construction. The base (c.0.5 m deep) of an "Aonly" treatment is being compacted with a vibrating roller.

contained a major aggregate resource of sands and unweathered, clean gravels under 1 to 3 metres of alluvial sands (Palmer, 1989). The island was used for dairy and sheep production until 1984. From 1984 to 1992 the island was stocked at 14 to 16 stock units  $\text{ha}^{-1}$  with bulls for beef production. Wheat, barley and maize have been regularly grown on the island with a maize yield of  $10\frac{1}{2}$  tonnes  $\text{ha}^{-1}$  (dry) achieved in 1991 (Spall pers. comm., 1991). Aggregate extraction on the island began in October 1988 and ceased in late 1990 (Photograph 4.8). The farm was subsequently sold to an aggregate company for large scale aggregate extraction and possible relocation of a city crushing and processing plant (Spall pers. comm., 1991).

The farmer who owned the island until 1992 wanted to specify guidelines to the extractor for reclaiming mined farmland after aggregate extraction and subsequent landfilling. A trial was laid out in two areas. Control treatments were sited approximately 150 m from the main trial site on unmined Rangitikei soils adjacent to the fill site. The main trial site was constructed on a derelict fill area created by previous extraction operations. The main trial site comprised four replicates of six soil replacement treatments (Figure 4.10).

Names of treatments are presented in bold type when first described in Section 4.2.3. Treatments 2 to 5 were randomised. Topsoil was defined as the practical minimum depth able to be stripped by the contractor's light bulldozer, which was 0.10 m, although the Rangitikei A horizon was approximately 0.06 m deep. A treatment with only 0.10 m of topsoil over fill (**10A**)



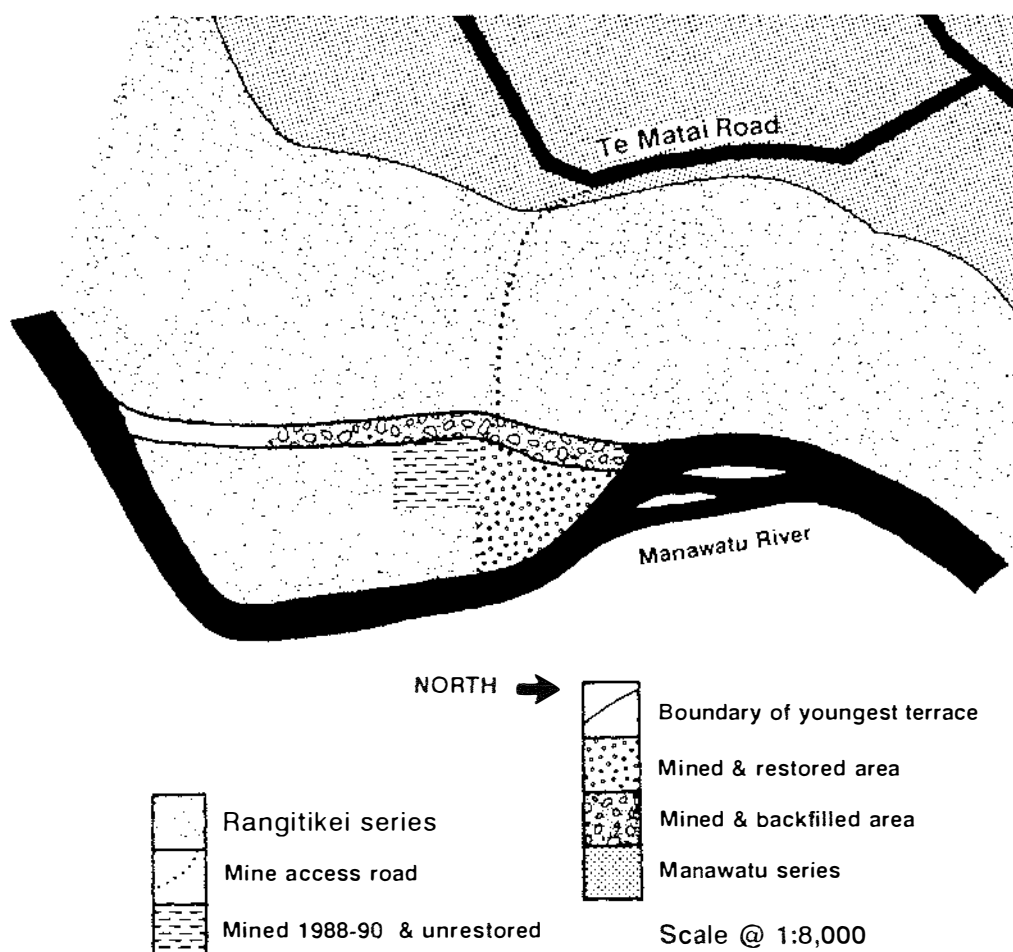


Figure 4.9: Map of Te Matai Road, 9 km north east of Palmerston North, showing the pattern of aggregate extraction and soil series near the Rangitikei trial site. Modified from N.Z. Mosaic map series 3 Sheet N.149/5 aerial photograph, 1951.

was constructed to determine the effect of a minimum soil depth on pasture production (Figure 4.10 and 4.11). Treatments with a total sand depth of 0.40 m, settling to between 0.30 and 0.35 m (**40C** and **10A+30C**), were selected as a compromise depth to maximise pasture growth and minimise earth moving costs, which are a large component of the cost of reclamation. Over short distances, transport costs are closely related to the volume of soil moved. A 0.30 to 0.40 m depth of rooting medium may provide adequate levels of plant available water for pasture establishment and long term survival. The treatment without replaced topsoil (**Fill**) was introduced to investigate whether skeletal soils could be reclaimed to pasture without the expensive separate stripping and replacement of topsoil and subsoil usually recommended in reclamation guidelines.

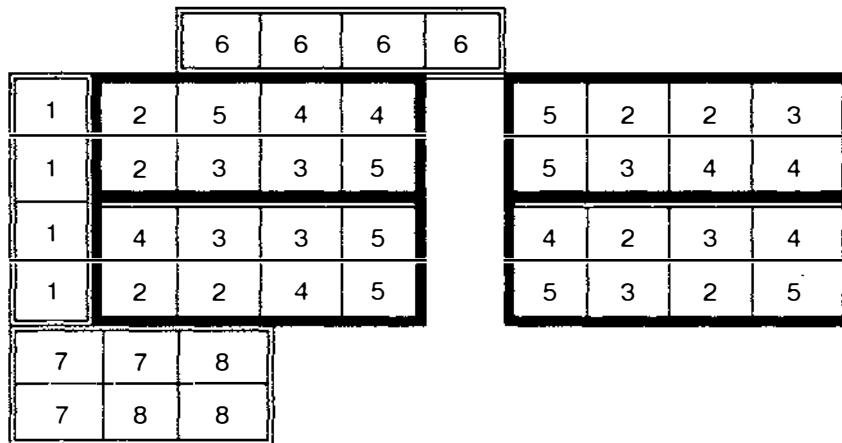


Photograph 4.8: Commercial extraction of aggregate adjacent to the Rangitikei trial site. The sandy overburden has been removed and a hydraulic excavator is removing the first cut of aggregate.

The **100C** and the **undisturbed fill** treatments were opportunistic inclusions to the trial. The four 1 m deep sand plots lay along the western side of the trial and were part of a commercially restored area abutting the trial (Figure 4.10 and 4.11). The four unripped fill replicates were included because commercial restoration did not completely surround the fill trial and left an area of undisturbed fill adjacent to the trial.

The Rangitikei trial contained several control treatments. Undisturbed Rangitikei soil in pasture was renovated by spraying with herbicide, simulating cultivation to 0.20 m and sown as for the main trial. This treatment (**Control**) provided a bench mark measure of pre-mining soil productivity with which production of all other treatments could be compared (Figure 4.10). In the same area, plots of undisturbed, unsprayed original pasture were included as an indication of the original pasture production (**Undisturbed**). This is a common, but false, control as comparison of newly seeded areas with mature, established areas of different species and cultivars is invalid. Fill treatments were another type of control, another benchmark to identify whether modifying the existing fill is an inexpensive alternative to replacing the original soil. The ripped fill (**Fill**) treatment simulated disturbing the surface 0.10 to 0.15 m of the fill which was probably the maximum practical depth able to be ripped which avoided machinery damage from striking large buried concrete or metal objects (Figure 4.11). The herbicide-sprayed, over-sown fill treatment was the cheapest reclamation treatment.

Figure 4.10: Design of the Rangitikei trial showing the location of individual soil replacement treatments.



#### Key to Treatments

No.	Code	Explanation of treatment
1	<b>100c</b>	1 m sand on fill
2	<b>40C</b>	0.40 m sand on fill
3	<b>10A+30C</b>	0.10 m of Rangitikei "topsoil" on 0.30 m of sand on fill
4	<b>10A</b>	0.10 m of Rangitikei "topsoil" on fill
5	<b>Fill</b>	fill material ripped to 0.20 m depth
6	<b>Undist. fill</b>	unripped fill material
7	<b>Undisturbed</b>	Rangitikei soil with original pasture and undisturbed soil profile
8	<b>Control</b>	Rangitikei soil cultivated to 0.15-0.20 m depth

NOTE Thick lines indicate blocks of replicates. Single lines indicate individual plots.

#### Construction of the Rangitikei trial

The Rangitikei trial site and topsoil borrow area were sprayed with a concentrated, translocating herbicide to kill all annual and perennial plants. A wheeled loader smoothed the rutted fill surface and removed the top 0.10 m which contained a 0.01 to 0.03 m deep incipient organic horizon and would have been a source of considerable variation. The Rangitikei trial was constructed during the first three weeks of December 1988. Plots 3.1 m wide and 4.1 m long were delineated using 0.15 m high untreated macrocarpa retaining boards. Rangitikei topsoil was obtained by scraping the top 0.10 m of Rangitikei soil from the borrow area with a light "Bobcat" digger. This topsoil included dead grasses. The delayed spraying of the borrow area meant pasture grasses were not fully decomposed by the time the soil was stripped (Photograph 4.9). Overburden stripped from the mined area with a hydraulic excavator and dumped beside the trial site was used as C horizon material.

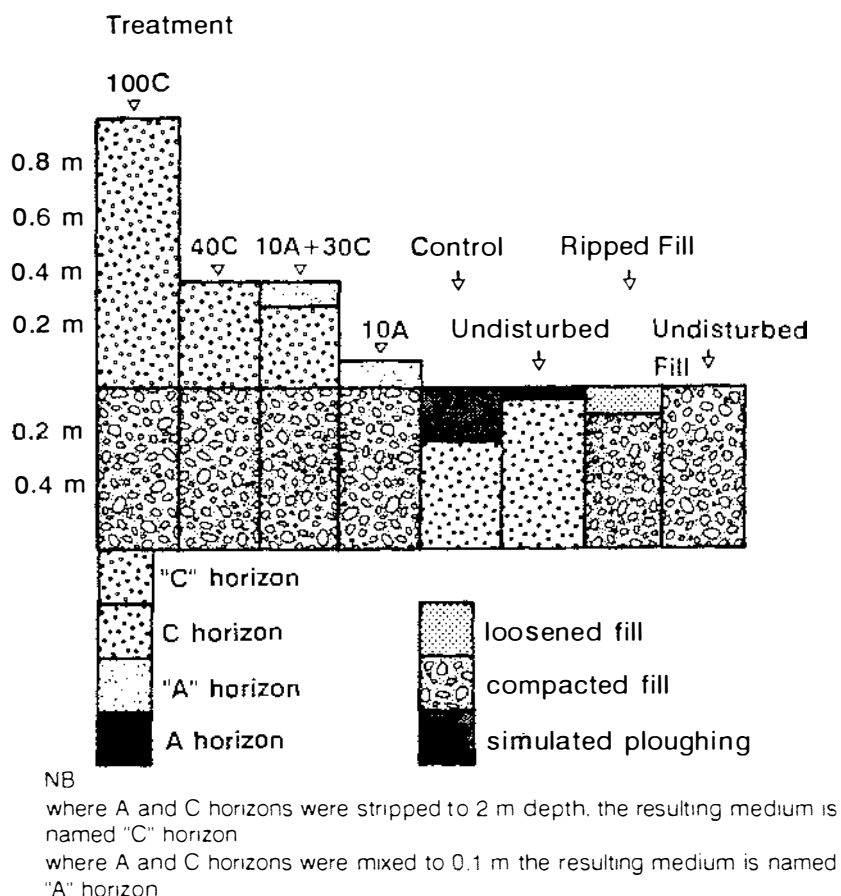
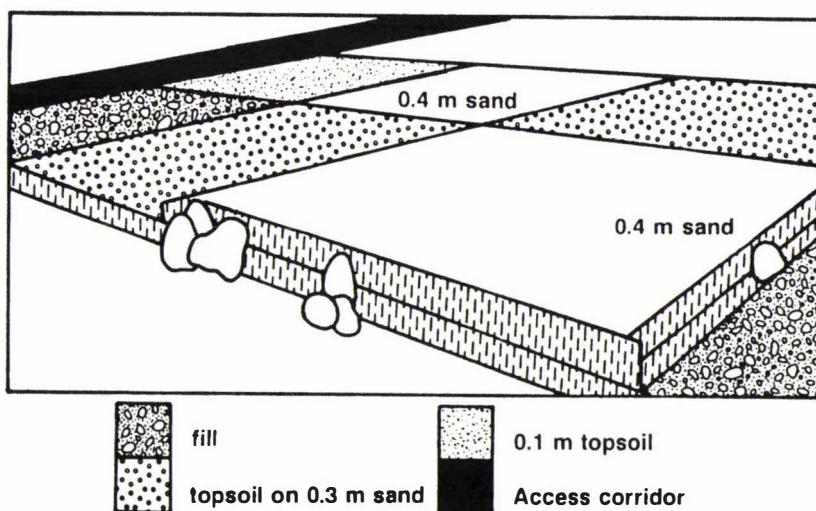


Figure 4.11: Schematic cross-section of soil replacement treatments at the Rangitikei trial site showing composition of the rooting media and total depths of applied soil.

The "Bobcat" digger was used to fill plots with topsoil or Rangitikei C horizon sands. Fill treatments were disrupted to 0.1 to 0.15 m using the "Bobcat". Where the fill was too dense to excavate fill was imported from an excavation at the edge of the trial site. After levelling, the plots were sown with a 50:50 mixture of barley and oats at  $115 \text{ kg ha}^{-1}$  and fertilised with super phosphate (0:10:0:8) at a rate of  $35 \text{ kg P ha}^{-1}$ . Barley and oats was planted as a cover crop to ensure surface stabilisation of sands and silts, which were easily eroded by the wind, and to aid the later establishment of ryegrass/clover pasture. This technique was used by Waipipi Ironsands (Connolly *et al.*, 1981) and Western Australian mining sites where reclaimed media are susceptible to wind or water erosion. In early autumn the grains were harvested by cutting stems 0.10 to 0.15 m above the ground surface and removed from the plots. The plots were scarified using rakes and a ryegrass/clover pasture was broadcast in May 1989 (see Table 4.3).

Pasture establishment was extremely poor and seedlings from the cover crop germinated along with many weed seeds on the topsoiled crops. The trial site was sprayed with glyphosate in July, resown and fertilised. The trial was fenced with a steel standard three strand electric fence which was initially powered with a battery unit and later connected to the farm electricity supply.





Photograph 4.9: The Rangitikei trial after completion of plot construction. A key to the treatments is presented below the photograph.

#### 4.3.3 Design and construction of the Ashhurst trial

Ashhurst trial replacement treatments mirrored Ohakea trial treatments (Chapter 4.3.1) with A and B horizons mixed to a depth of 0.70 m (**ABmix**), A and B horizons replaced in order (**AonB**) and A horizon placed directly on C horizon gravels (**Aonly**) (Figure 4.12). As in the Ohakea trial soil replacement treatments were unbalanced, with no compacted undisturbed or compacted control treatments. Following the Ohakea trial false control plots (**Undisturbed**) were placed at both

Table 4.3: Pasture species and sowing rates used to seed the Rangitikei and Ashhurst trials.

Pasture species	Kg ha <sup>-1</sup>
<i>Lolium perenne</i> var Ellet/ Ruanui (Ryegrass)	23
<i>Trifolium repens</i> var Pitau or Huia (White clover)	3.1
Total	26.1

western and eastern ends of the trial. These were replicates of a treatment where neither pasture nor soil was disturbed, a 'false' control as without resowing at the same time as the rest of the trial with the same species cultivars, pasture growth comparisons are not valid. Replicates were sited at the ends of the trial as contractors were unable to construct plots without severely compacting the surface horizons of adjacent plots. This surface compaction was ameliorated during excavation of all treatments except for the 'false' control.

Figure 4.12: Design of the Ashhurst trial showing the location of individual soil replacement treatments.

U	6	2	C	3	1	C	6	1	5	3	U
U	3	6	5	C	4	C	2	6	3	4	U

#### Key to Treatments

<u>No.</u>	<u>Code</u>	<u>Explanation</u>
1	<b>Aonly</b>	A horizon replaced on C horizon (compacted)
2	<b>AonB</b>	A horizon replaced on B horizon (compacted)
3	<b>ABmix</b>	A and B horizons mixed (compacted)
4	<b>Aonly</b>	A horizon replaced on C horizon
5	<b>AonB</b>	A horizon replaced on B horizon
6	<b>ABmix</b>	A and B horizons mixed
C	<b>Control</b>	Soil cultivated to 0.20 m depth
U	<b>Undisturbed</b>	Original pasture unsprayed and soil undisturbed

NOTE: Thick lines define blocks of treatments  
Single lines define individual plots



Photograph 4.10: Construction of the Ashhurst trial: the trial has been sprayed with herbicide, pegged out and treatments identified with fluorescent paint.

Ashhurst trial construction was preceded by spraying of the site with translocatable, non residual glyphosate herbicide (Photograph 4.10). The trial was constructed by a tractor-mounted backactor. Each plot was 5 m long and 3 m wide, with 0.5 m between plots. Decreased soil density and packing, resulting from excavation, raised the plot surfaces above the undisturbed ground surface and prevented surface water flow over the plots. Blue lupin seed was broadcast to provide initial cover, nitrogen and organic matter to the low water holding capacity soil. After two months, at flowering, the lupins were mown to 0.05 m. Half the plots were evenly compacted by removing the upper 0.15 to 0.20 m of the soil profile and passing a vibrating roller about 4 times over each part of the plot. The upper horizon was then replaced and lupin mulch incorporated. After levelling of the surface, plots were hand raked and broadcast sown with 23 kg ha<sup>-1</sup> "Ellet" perennial ryegrass (*Lolium perenne*) and 3 kg ha<sup>-1</sup> "Pitau" white clover (*Trifolium repens*). Two weeks after pasture germination, superphosphate fertiliser (0:10:0:8) was broadcast over the trial at a rate of 30 kg P ha<sup>-1</sup>. An eight wire post and batten fence, with electric wires on the sixth and top wires, was constructed around the trial to prevent grazing by stock.



## Chapter Five: Soil Replacement

### 5.1 Introduction

Topsoil, the uppermost, organic-enriched layer of a soil (Sims *et al.*, 1984), generally has physical, chemical and biological properties that promote plant establishment and growth. In reclamation these properties vary in importance depending on the environment, underlying substrate and post mining land use. Separate stripping and replacement of overburden, subsoil and topsoil is a standard procedure in most opencast mining operations, and is often a statutory requirement. Many authors highlight its importance (Coppin and Bradshaw, 1982; McRae, 1982; Mackintosh and Hoffman, 1985; Redente and Hargis, 1985; Ramsay, 1986; Alberta Environment, 1987; Michalski *et al.*, 1987; Hilditch *et al.*, 1988). Applying soil to recontoured surfaces during reclamation, however, is the single most costly part of land reclamation (Barth and Martin, 1984), as separately stripping topsoil and subsoil requires more machine-hours than removing all soil or overburden layers together. From ecological and economic standpoints therefore, quantification of minimum soil depths and topsoil requirements necessary to meet post mining land use objectives is highly desirable.

Section 5.1 is divided into two parts. Firstly, factors influencing the effects of topsoil mixing and optimum soil depth are examined, including the post mining use of land, and characteristics of soil, overburden and waste materials. Secondly, qualities of topsoil that make it a valuable resource for many reclamation situations are discussed, along with some of the undesirable consequences sometimes associated with introducing topsoil to a site.

Most authors do not distinguish between soil depth and total rooting depth when identifying soil depth requirements, thus most of recommended soil depths quoted assume that the rooting mass is restricted to the applied volume of soil. In this chapter "topsoil" is defined as soil A horizon. The engineering definition of topsoil as all solum material that will sustain plant growth (Hargis and Redente, 1984) is not used in this thesis. "Subsoil" is defined as all soil material below the A horizon and above unweathered material, for example rock. "Soil" includes topsoil and subsoil down to the unweathered soil parent material. Soil depth assumes no rooting impediments within the soil layer, i.e. the soil has no physical or chemical barriers so that soil depth equals the total rooting depth <sup>available to</sup> plants growing in the soil. The unweathered material and by-products of mining, such as tailings, are grouped together for the purposes of this chapter as "spoil". The term "rooting media" includes both soil and overburden, i.e. all possible plant root substrates.

## 5.2 Factors influencing the effects of topsoil mixing and optimum soil depth

### 5.2.1 Post-mining land use

The response of plant species to increasing depth of soil varies between species (Power *et al.*, 1981), as each plant has a natural optimum rooting depth. For example, plants adapted to undisturbed sites usually require a deeper soil (Van Kekerix and Kay, 1986) than those adapted to disturbed or shallow sites. Shallow rooted species such as grasses can produce a sustainable land covering with soil depths as thin as 0.1 to 0.2 m (Werth, 1980; Coppin and Bradshaw, 1982; Samuel, 1991) and do not benefit from excessive soil depths (Oddie *et al.*, 1989) when water and nutrient supply is non-limiting. For example, McGinnies and Nicholas (1980) found maximum grass yields in a glass house experiment occurred with a soil depth of 0.45 m. Deep rooting plants, for example tree species, require a greater depth of soil. The minimum soil depth that provides a stable anchorage for trees is stated as 0.5 m by Bradshaw (1989) and Hilditch *et al.* (1988), and 0.33 m by McLellan *et al.* (1979). Mackintosh and Hoffman (1985) recommended a minimum total soil depth of 1.2 m for production of stone fruits (peach, apricot and cherry species) where the water table is at the soil/overburden interface as stone fruit are intolerant of anaerobic soil conditions.

Soil may not be needed for optimum plant production where spoil has no adverse properties and rooting depth is unrestricted (Barth and Martin, 1984; Gregg *et al.*, 1990). Redente and Hargis (1985) found that root biomass was the same regardless of soil depth where the overburden material had no adverse characteristics. Sencindiver *et al.* (1989) also found that topsoil depth did not affect plant establishment or growth, and attributed the result to an underlying spoil which did not restrict root growth. Conversely, spoil underlying topsoil that prevents root exploitation increases the depth of topsoil required for plant establishment and growth. For example, where grass was established on solid rock floors Coppin and Bradshaw (1982) advocated placement of 0.5 to 1.0 m of soil, while satisfactory grass growth was achieved with as little as 0.1 to 0.2 m of soil on broken rock floors which allowed root penetration.

Species for arable agricultural or horticultural production generally require greater soil depths than species planted for amenity or erosion control (Coppin and Bradshaw, 1982; McRae, 1983; Sims *et al.*, 1984; McRae, 1986; Hemstock, 1991; Samuel, 1991). In arable cropping the top 0.15 to 0.25 m of the soil profile is disturbed by tillage machinery. Minimum soil depths of 0.25 m are therefore required to prevent soil dilution or contamination with underlying media (Coppin and Bradshaw, 1982; McRae, 1985). McRae (1983; 1985; 1986) and Mackintosh and Mozuraitis (1982) recommend a minimum total soil depth overlying the water table of 1 m for optimum arable crop production. Where subsurface drainage is required, soil depths must be great enough to cover the pipe with at least 0.2 m of undisturbed soil to limit sedimentation of drain pipes (Samuel, 1991). Restoration of full crop productivity generally requires greater soil depths

(Sims *et al.*, 1984). RMC (1987), a British aggregate mining company, advise a minimum 0.5 m soil depth for grassland with at least 1 m, and preferably 1.2 m, of soil to enable unimpeded root growth and the satisfactory installation of a drainage scheme.

#### 5.2.2 Properties of overburden, spoil and subsoil

Characteristics of overburden, spoil and subsoil determine the thickness of covering soil required for plant establishment and growth (Coppin and Bradshaw, 1982; Barth and Martin, 1984; Halvorson *et al.*, 1986; Hilditch *et al.*, 1988; Bradshaw, 1989; Samuel, 1991). Where subsoil or spoil is covered with topsoil the qualities of the underlying media become more important in the long term (Australian Mining Industry Council, 1989), promoting sustainability of plant growth by increasing the buffering capacity of the rooting medium. Physical and chemical characteristics of a rooting medium which are important for plant growth are its capacity to supply oxygen, plant-available water and nutrients, and allow root penetration (Coppin and Bradshaw, 1982) together with pH, sodicity and salinity. The influence of these characteristics on establishment and growth of vegetation is, however, modified by the requirements of individual species and cultivars. For example, some Welsh cultivars of *Agrostis tenuis* are tolerant of high concentrations of heavy metals. Site effects such as climate and management, for example fertiliser application and stocking rates, are also modifying factors.

Greater severity of adverse properties generally increases the depth of soil required for optimum plant growth (Hargis and Redente, 1984; Hilditch *et al.*, 1988; Bradshaw, 1989). Five soil depth experiments in the Northern Great Plains area of the United States showed that the optimum soil depth for maximum yields of individual species under similar precipitation was dependant on spoil type. Optimum soil depth ranged from 0 m for soil-like spoil to 0.5 m for non-toxic spoil and 0.71 m for sodic spoil. Root penetration into spoils was limited to 0.1 m or less in all but the soil-like spoil (Barth and Martin, 1984).

Many spoils from aggregate mines have a favourable soil forming potential with a loamy or sandy texture and lack only nutrients and living organic matter (Buckley, 1978; Coppin and Bradshaw, 1982). In such spoils, although topsoil increases seed germination and seedling growth, buildup of organic matter in nil-soil treatments results in a reduction in the advantage of topsoiled treatments over time (Pinchak *et al.*, 1985). In some cases overburden can be a better medium for plant growth than soil, especially if the chemical fertility of the soil is low (Sims *et al.*, 1984) or the physical properties are poor, such as in compacted clay or saline soils. This is recognised in North Dakota legislation, which requires reclaimed soil depth to be determined by spoil quality. However, a minimum soil thickness of 0.6 m is required when reclaiming prime agricultural land (Friedlander, 1989).

### *Texture and physical properties*

Soil and spoil particle size distribution influences physical properties such as structure, water retention, hydraulic conductivity and bearing capacity (Ramsay, 1986). Processing wastes from mining may have a very limited range of particle sizes (Bradshaw, 1981), for example the china clay industry produces coarse sand wastes (Johnson and Bradshaw, 1979; Marrs, 1989) whereas aggregate washing concentrates silt and clay<sup>into</sup> tailings.

Soils and overburdens may also have a limited range of aggregate sizes, for example McSweeney and Jansen (1984) described how transportation of specific soils on a conveyer belt resulted in smoothed and rounded aggregates with agglomerative, typically 30 mm thick skins of fine particles. These aggregates formed an open structure that favoured root penetration. Coarse wastes are often poorly compacted with high hydraulic conductivity (Marrs, 1989) and low capacity to store plant-available water while silty-textured media generally retain greater amounts of plant available water (Johnson and Bradshaw, 1979; Halvorson *et al.*, 1986). Fine textured media may also have low bearing capacities and tend to form massive structures with few macropores when disturbed (McSweeney and Jansen, 1984).

The texture or particle size distribution of a medium also influences its ability to retain plant nutrients. Coarse textured media tend to have low cation exchange capacities (Marrs, 1989) and contain low levels of most macro and micro nutrients (Regier, 1976 *cited by* Sims *et al.*, 1984). Low nutrient retention is exacerbated by high leaching rates typical of coarse textured media (Buckley, 1978; Samuel, 1991). In contrast, fine textured media frequently have higher cation exchange capacities due to elevated clay contents.

The creation of profiles comprising adjacent layers of markedly different textural properties may enable manipulation of plant available water and plant rooting patterns. Replacement of a coarse textured topsoil over a fine textured medium may result in a perched water table and formation of an anaerobic layer at the base of the topsoil during periods of high soil moisture, limiting the extension of plant roots. In areas of low rainfall, however, this strategy may increase plant available water by preventing percolation of water out of the root zone.

A perched water table may also be formed when a fine textured topsoil is placed over a coarse textured medium, as water will not penetrate the coarse textured layer until the fine textured soil is close to saturation. In extreme situations the drier underlying material may prevent extension of plant roots into the material (Van Kekerix and Kay, 1986). In high rainfall climates, for example in the West Coast of the South Island, replacement of topsoils on coarse-textured tailings in place of imperfectly draining subsoils has been beneficial. In this situation the increased hydraulic conductivity outweighed the reduction of plant-available water (Ross and Mew, 1990; Mew and Ross, 1991).

Where soil has lower plant available water or water holding capacity than the underlying spoil, shallow soil depths may increase the ability of roots to extract moisture from the underlying spoil (Sims *et al.*, 1984). Conversely, where plants are dependant on the soil for water because underlying layers have low water holding capacities, soil depths must be greater. In an experiment where wheat yield was limited by plant available water Halvorson *et al.* (1986) found maximum production was obtained by at least 0.7 m of topsoil on loamy sand spoil, but only 0.46 m of topsoil on clay loam spoil.

Surface sealing, or crusting, and microtopographical characteristics of plant rooting media may affect seed germination and seedling establishment. Surface seals are often associated with fine particles and dispersed soils. Surface seals can form when rain drops hit the soil surface, breaking soil aggregates into finer particles which form a thin layer with low hydraulic conductivity. Sodic or sodium-enriched soils are susceptible to dispersion of clay particles through deflocculation and may also display crusting and surface cracking (Hargis and Redente, 1984; Oddie *et al.*, 1989). Dispersion, like compaction, reduces pore sizes and hydraulic conductivity (Merrill *et al.* 1985; Oddie *et al.* 1989) and increases soil susceptibility to erosion. Russell and Takyi (1979) found that beneficial effects of topsoiling were offset by surface crusting and erosion. Establishment rates of grasses and legumes were greater on raw shale spoil as the rough shale surface contained more favourable microsites. Mihajlovich and Russell (1980) conducted a similar experiment in subalpine areas of Alberta, Canada, comparing topsoiled and non-topsoiled raw coal overburden. They hypothesised that the rough coal overburden surface provided sheltered microsites for seed germination to explain the observation that differences in plant cover between treatments were large in the first season but had decreased by the second growing season.

#### *Stone content*

Stoniness is a common problem associated with shallow soils and soils overlying sand and gravel deposits. Stones are introduced to surface horizons when quarry wastes or overburden containing stones are mixed with soil and when soil horizons are naturally stony (Street, 1985). Stones hinder cultivation and seedbed preparation and may damage farm equipment on land reclaimed to arable agriculture (Mackintosh and Mozuraitis, 1982; Mackintosh and Hoffman, 1985; Samuel, 1991). As the stone content of a medium increases the soil volume containing plant available water and nutrients decreases (Mackintosh and Mozuraitis, 1982; Samuel, 1991), reducing the nutrient and water buffering capacity of the medium. Additionally, surface stones can pose safety hazards for recreational uses such as contact sports (Samuel, 1991) where players slide on the ground surface.



### *Chemical properties*

The less chemically favourable an underlying medium for plant growth, the greater the yield response to increased depths of soil (Merrill *et al.* 1985). Topsoil depth can greatly influence productivity and longevity of vegetation established on sodic reclaimed lands by providing a root zone with favourable chemical and physical properties (Schuman *et al.* 1985; Leskiw, 1989). Saline media most often contain the salts of calcium, magnesium and sodium as chlorides and sulphides. High salt concentrations limit plant growth by inducing cation imbalances and osmotic stress (Hargis and Redente, 1984), reducing plant uptake of water and nutrients (Merrill *et al.*, 1985). Soil thickness requirements for saline and sodic materials must allow for upward salt migration and subsidence of reclaimed areas (Leskiw, 1989). The Northern Great Plains area of the United States and Canada contains large reserves of coal commonly covered by sodic subsoils and overburden (Leskiw, 1989) and most of the research into optimum depths of topsoil has been carried out in this region.

Mined areas revegetated without topsoil may produce forage of adequate volume but poor nutritional quality for livestock (Schuman *et al.*, 1980 *cited by* Schuman and Power, 1981). For example, Ross *et al.* (1982) found that the nitrogen (protein) content of clovers and grasses was depressed on treatments stripped of topsoil. Nitrogen and phosphorus are the most common deficiencies in reclaimed soils (Crook, 1992). Potential rooting media therefore, should be tested for macro-elements and micro-elements and pH to determine possible element deficiency and toxicity. In New Zealand Connolly *et al.* (1981) reported possible a copper deficiency in pasture reclaimed after iron sand mining.

#### 5.2.3 Properties of topsoil

Organic matter is the key component of topsoil (Mackintosh and Mozuraitis, 1982). Organic matter influences many soil properties, including colour and deactivation of agricultural chemicals. Topsoil is the 'living' component of a soil horizon in which plant nutrients, particularly nitrogen, have accumulated (Roberts *et al.*, 1988; Bradshaw, 1989) and in which the majority of plant roots, seeds, soil fauna and micro organisms are present. Topsoil is recognised as a valuable resource which generally aids plant germination, establishment and growth, nutrient cycling and erosion resistance (Bradshaw, 1989). Reclamation practices have been developed to conserve and protect topsoil from degradation, for example, replacement of topsoil in strips and rolling reclamation, where topsoil is directly transferred to an areas that is to be reclaimed without stockpiling (Australian Mining Industry Council, 1989).

If topsoil is not present the biological system will generally take a longer time to establish (Australian Mining Industry Council, 1989). Topsoil will ultimately develop with the breakdown of inorganic media and the accumulation of organic matter under suitable environmental

conditions (Johnson and Bradshaw, 1979; Sims *et al.*, 1984) and management strategies (Indorante *et al.*, 1981). In ideal conditions, however, topsoil may develop quickly (Sencindiver and Daniels, 1990). Mason *et al.* (1992), for example, reported rapid soil development in tailings and oxidised waste rock under ryegrass/clover pasture that was fertilised annually to maintain high levels of plant-available nutrients. Under this management, total soil carbon levels increased from approximately 0.04% to 1.8% in 7 years. Indorante *et al.* (1981) reviewed 8 Illinois sites which showed 0.10 m topsoil development in surface mine spoils under grasses and legumes in 30 years, with the depth of structure development ranging from 25 mm in 5 year old spoil to 360 mm in a 55 year old spoil. Sencindiver and Daniels (1990) report development of distinct A horizons 50 to 60 mm thick within three years.

#### *Chemical and biological fertility*

Soil chemical fertility and biological fertility are closely linked. Soil chemical fertility is related to the percentage of organic matter, rate of mineralisation, soil cation exchange capacity and level of activity of vesicular-arbuscular (VA) mycorrhizae and the macro and micro organisms in the soil. Climatic factors, such as rainfall (which influences weathering and leaching rates), temperature, soil stability and oxygen supply, also influence soil fertility (Younger, 1989). High organic matter contents increase the ability of a media to retain (Buckley, 1978; Putwain and Gilham, 1988) and supply plant nutrients (Coppin and Bradshaw, 1982; Mackintosh and Mozuraitis, 1982; Sims *et al.*, 1984; Hargis and Redente, 1984; Reganold, 1989; Samuel, 1991). Mineralisation of organic matter releases plant available nutrients, increases the cation exchange capacity (i.e. increasing the number of positively charged sites where cations such as potassium, magnesium, calcium and sodium are held) and supplies food for earthworms and invertebrates which then excrete plant available nutrients. This organically-bound nitrogen is not as prone to leaching as inorganic fertilisers (Berry, 1983). The influence of organic matter levels on soil properties may be highly modified by soil texture which influences many soil properties such as structure, water holding capacity and drainage (Ramsay, 1986). The benefits of organic matter may be larger and easier to measure on sandy textured soils with low initial levels of organic matter, i.e. less than 2%, and low cation exchange capacities (Johnston, 1986).

Reclaimed surfaces devoid of topsoil and organic matter are generally deficient in major plant nutrients (Buckley, 1978). Where a mineral media is naturally or artificially colonised most nutrients are contained in plants and nitrogen is supplied from biological fixation by legumes, fertilisation or amendments such as sewage sludge or manure (Coppin and Bradshaw, 1982; Marrs, 1989). Initially, decomposition and mineralisation of organic matter at reclaimed sites is slow because high carbon to nitrogen ratios reduce micro organism activity (Bradshaw, 1981). Additionally, non-topsoiled sites often have very <sup>low</sup> micro organism numbers and activity. As topsoil develops most nutrients are retained by soil organic matter. This acts as a reservoir for plant



nutrients, such as nitrogen, phosphorus and sulphur, which are required in large quantities for plant growth (Coppin and Bradshaw, 1982). Nitrogen is a significant constituent of plant proteins, nucleic acids, porphyrins and alkaloids (Schnitzer, 1991) and is required in larger amounts than any other mineral nutrient for healthy plant growth (Marrs, 1989). In production systems where nitrogen fixing plants are absent nearly all nitrogen in soil is closely associated with soil organic matter (Coppin and Bradshaw, 1982; Schnitzer, 1991). This nitrogen is released as ammonium or nitrate by mineralisation or decomposition by micro organisms and utilised by plants (Bradshaw, 1981; Van Kekerix and Kay, 1986). Studies on natural and artificial colonisation of sand waste from kaolin mining in the United Kingdom show that nitrogen accumulation and build up is the most important factor in soil and vegetation development (Coppin and Bradshaw, 1982). However, the nutrient storage and supply qualities of topsoil may be a disadvantage for establishment of trees on reclaimed areas as nitrogen availability may increase growth of competitive herbaceous vegetation (Schoenholtz and Burger, 1984; Crook, 1992).

As with nitrogen, the amount of plant available phosphate is influenced by mineralisation of organic matter. Between 20% and 80% of total soil phosphate in surface soils may be in organic forms as esters of phosphoric acid, inositol hexa phosphate and pentakis phosphate (Schnitzer 1991). The balance of phosphate is held in the soil mineral component so, unlike nitrogen, phosphate is present in both topsoil and subsoil, although a large amount of this phosphate is in insoluble forms and unavailable to plants (Bradshaw, 1984a).

#### *Physical fertility*

The physical properties of rooting media often limit the productivity of reclaimed areas (Johnson and Bradshaw, 1979; Sims *et al.* 1984). Organic matter, soil fauna and soil flora associated with topsoil aid the development and maintenance of favourable soil physical properties through decreasing bulk density and surface crusting (Coppin and Bradshaw, 1982; Gregg *et al.* 1992) and increasing aggregate stability, macro porosity and soil water holding capacity. Lowered soil bulk density and crusting reduce soil resistance to root and seed penetration (Hargis and Redente, 1984)(Chapter 6.2). Because organic residues accumulate at the surface, most benefits are associated with topsoil (Tisdall and Oades, 1982). Johnston (1986) postulated that organic matter may act as a buffer between sand particles and allow them to move more freely in relation to penetrating roots on lighter textured soils. Conversely, organic matter makes a soil more 'elastic', lending resilience to compactive forces (Van Kekerix and Kay, 1986) and increasing the soil bearing strength (Mackintosh and Mozuraitis, 1982; Samuel, 1991).

Topsoil generally has a favourable structure for seedling establishment and plant growth (Jansen and Dancer, 1981 *cited by* Daniels *et al.*, 1991; Sims *et al.*, 1984). This may be attributed directly to organic matter (Sears *et al.*, 1965; Coppin and Bradshaw, 1982; Mackintosh and Mozuraitis,

1982; Samuel, 1991) and indirectly to microbial activity. Johnston (1986) and Greene and Wilson, 1989) reported an improvement in physical structure of disturbed soils (decreased bulk density and increased macroporosity) after a grass ley. The improvement was associated with an increased organic carbon content. The improvement was most evident in the surface 0.20m of the profile. Organic amendments such as mulches and composts also improve soil structure (Insam, 1989). Organic matter stabilises aggregates against slaking by binding or cementing soil particles (Tisdall and Oades, 1982; Reganold, 1989; Sullivan, 1990), thus making them less vulnerable to breakdown and erosion. Some soil particles are also cemented or glued together by transient polysaccharides (Tisdall and Oades, 1982). Additionally, partially decomposed organic residues can prevent soil particles or crumbs from coalescing (Johnston, 1986), thus maintaining or increasing soil macroporosity (Van Kekerix and Kay, 1986). Increasing macroporosity increases infiltration and drainage of soils (Coppin and Bradshaw, 1982; Hargis and Redente, 1984), thus reducing surface water run off (Reganold, 1989). In a North Dakota study 0.05 m of topsoil over sodic spoils reduced run off by 47% (Power *et al.*, 1974 cited by Schuman and Power, 1981).

Enhanced organic matter concentrations and associated retention of topsoil enhances soil water holding capacity (Richardson and Dicker, 1972; Buckley, 1978; Elliott and Veness, 1985; Reganold, 1989; Ross and Mew, 1991). Even small increases in water holding capacity may maintain crop growth between periods of rainfall (Johnston, 1986). However, (Sims *et al.*, 1984; Halvorson *et al.*, 1986) found topsoil will only improve yields where alternative materials are "more drought prone", i.e. had a lower readily available water holding capacity.

#### *Presence of soil organisms*

Although soil micro organisms may arrive on a reclaimed site through the air on wind-blown soil, aerial spores and sown seeds (Richardson and Dicker, 1972) vital biomass is low in areas stripped of subsoils and raw mine wastes compared to surface soil (Johnson and Bradshaw, 1979; Ross and Cairns, 1982; Kiss *et al.*, 1989; Harris and Birch, 1989; Williamson and Johnson, 1990; Scullion, 1991). Earthworm numbers may also be dramatically reduced, in the short term, by soil stripping and replacement (Ross and Widdowson, 1987; Hart *et al.*, 1989; Scullion, 1991).

Soil fauna and flora enhance the potential for natural regeneration and reduce the time for establishment of self sustaining communities (Hargis and Redente, 1984; Michalski *et al.*, 1987; Scullion, 1991). An active soil biomass, comprising earthworms and other mesofauna, bacteria, actinomycetes, viruses and fungi (Richardson and Dicker, 1972), is essential to long term fertility of reclaimed soils (Williamson and Johnson, 1991). The importance of soil micro organisms is reflected in the use of measures of microbial activity or biomass as indicators of reclamation success (Hart *et al.*, 1989; Harris and Birch, 1990; Zak *et al.*, 1990; Scullion, 1992)

Replacing topsoil onto mined areas helps provide an inoculum of this biomass, in particular supplying mycorrhizal fungi (Jasper *et al.*, 1989; Ross and Mew, 1991) which are concentrated in the top 0.05 m of a soil (Nichols *et al.*, 1991). Scullion (1992) reports that re-establishment of earthworm populations is entirely dependant on an inoculum. Topsoil replacement may, however, also introduce undesirable micro organisms (Van Kekerix and Kay, 1986). For example, in Western Australia the fungal root pathogen *Phytophthora cinnamoni*, which can cause the death of jarrah (*Eucalyptus marginata*) and many other understorey species, can be spread in moist soil during reclamation operations (Elliott and Wake, 1991). Conversely, organic matter promotes soil microbial activity (Insam 1988), although biochemical properties decline more with soil depth than organic matter content (Ross *et al.*, 1982).

Soil micro organisms are particularly beneficial in nutrient poor conditions (Marrs, 1989; Williamson and Johnson, 1991) as they decompose soil organic matter and release plant-available nutrients, especially nitrogen (Richardson and Dicker, 1972; Younger, 1989; Bradshaw, 1981). Soil micro organisms therefore indirectly increase plant growth (Sims *et al.*, 1984). Symbiotic and free living microbes such as *Rhizobium*, *Clostridium* and *Azotobacter* are active in biological fixation, converting atmospheric nitrogen into forms available for plant uptake (Hargis and Redente, 1984). Mycorrhizal symbiotic fungi extend plant root scavenging ability. VA mycorrhizae, for example, symbiotically enhance plant uptake of ions that are immobile or diffuse slowly, such as phosphorus (Younger, 1989; Coppin and Bradshaw, 1982). In the absence of symbiotic mycorrhizae some species, for example *Acacia spp* exhibit much-reduced growth (Jasper *et al.*, 1989).

Soil flora and fauna increase soil aggregate stability, aeration and hydraulic conductivity. Springtail (Collembola) and mite (*Acarina*) invertebrate groups aerate the soil by burrowing and decomposing organic matter, producing fine particles on which micro-flora act (Hutson, 1972; Majer, 1983). Millepedes have been used in reclamation of a Kenyan quarry to break down leaf litter (Baumer *et al.*, 1990). Soil particles are physically bound by sticky fungal hyphae such as VA mycorrhizal hyphae (Molope, 1987), plant roots (Tisdall and Oades, 1982) and polysaccharides associated with soil microbes (Reganold, 1989; Williamson and Johnson, 1991; Haigh, 1992). Enzymes in the gut of earthworms partially breakdown organic matter and mix humified material into the soil, increasing soil water holding capacity, and forming water stable aggregates. Earthworm casts contain increased amounts of soluble and plant available nitrogen, phosphorus and potassium. Earthworms themselves, with an average life of one year, may significantly contribute to the available soil nitrogen pool, as they comprise approximately 72% protein (Edwards and Lofty, 1977). Ross and Cairns (1982) found that earthworms contributed to the restoration of pasture productivity after topsoil mining by stimulating biochemical activity and nutrient cycling (Chapter 3.3.1).

### *Presence of seeds and propagules*

Topsoil is a store of both desirable and undesirable seeds and propagules (Coppin and Bradshaw, 1982; Davidson, 1984b; Van Kekerix and Kay, 1986; Wade and Thompson, 1990) which may enhance or hamper revegetation efforts respectively (McRae, 1982; 1983; Hargis and Redente, 1984). Profuse weed growth is a major problem on much restored land (McRae, 1982).

Weed species are more common on topsoiled compared to non-topsoiled reclaimed areas (Sims *et al.*, 1984; Samuel, 1991). Where land is reclaimed to commercial forestry, agricultural or horticultural uses undesirable species introduced in topsoil compete with crops for water, nutrients and light resulting in reduced crop quality and yield (Samuel, 1991). In some cases weed introduction may offset the advantages of topsoiling (Sims *et al.*, 1984) and topsoils are discarded to avoid weeds that are difficult to control or noxious (Scheltus, 1990).

Soil replacement, revegetation and post reclamation management techniques have been developed to reduce weed competition. Pasture seeding rates approximately double those of normal agricultural renovation rates have been used successfully to reduce weed ingressions (Richardson and Dicker, 1972; McRae, 1982). Intensive grazing management of pastures and herbicide spraying are also used to control weed establishment (Vyle and Downing, 1972; McRae, 1982; Scheltus, 1990; Ross and Mew, 1991). Although a dense herbaceous cover is essential to control erosion, weeds can seriously inhibit the establishment of tree seedlings (Philo *et al.*, 1983; Davidson, 1984b; Samuel, 1991) and some exotic foresters have advocated planting trees in bare alluvial gold tailings to reduce weed competition (Ross and Mew, 1991). Davidson (1984a) advocated replacing topsoil in strips to gain the benefits of topsoiling, but reduce competition of adventitious weeds, by planting tree seedlings in the untopsoiled strips.

Topsoil is widely recognised as a valuable resource where land is reclaimed to indigenous vegetation as topsoil contains seeds and propagules which may enhance establishment of natural vegetation communities (Michalski *et al.*, 1987; Wade and Thompson, 1990). In Australian soils, which typically have shallow organic horizons, the 0 to 50 mm soil layer contains most of the seed in a soil profile (Australian Mining Industry Council, 1987; 1989; Jefferies *et al.*, 1991). Conservation and stripping of topsoil in two layers (0 to 50 mm and 50 mm to the base of the A horizon) is a technique used in reclamation of native sand dune, shrub land and forest ecosystems after mineral sands and bauxite mining in Australia (Brooks, 1989; Jefferies *et al.*, 1991; Nichols *et al.*, 1991) and reclamation of heath land after clay extraction in southern England (Putwain and Gilham, 1988). Research by Partridge (1989) indicates appreciable amounts of viable seeds are stored in New Zealand forest soils at depths up to 125mm, with the composition of species generally similar in both upper (0 to 25mm) and lower (26 to 125 mm) soil layers.

## Climate

The optimum thickness of replaced soil at a specific site is influenced by the plant available water holding capacity (AWHC) of the rooting media and the amount and distribution of effective precipitation (Hargis and Redente, 1984; Redente and Hargis, 1985), which is the balance between rainfall and evapotranspiration (Figure 5.1). For example, Tresler (1974, *cited by* Hargis and Redente, 1984) advocated 0.7 to 1.1 m soil depth for native grass production in low precipitation regimes and a minimum depth of 1.0 m in higher rainfall areas for deeper rooted crops. The optimum thickness of a plant rooting medium for maximum plant production increases with increasing effective precipitation to the point where the medium stores enough water for plant use during periods of water deficit (Hargis and Redente, 1984) (Figure 5.1). After this point, optimum medium thickness decreases (*cet. par.*) as the available soil water store is replenished before exhaustion by the plant.

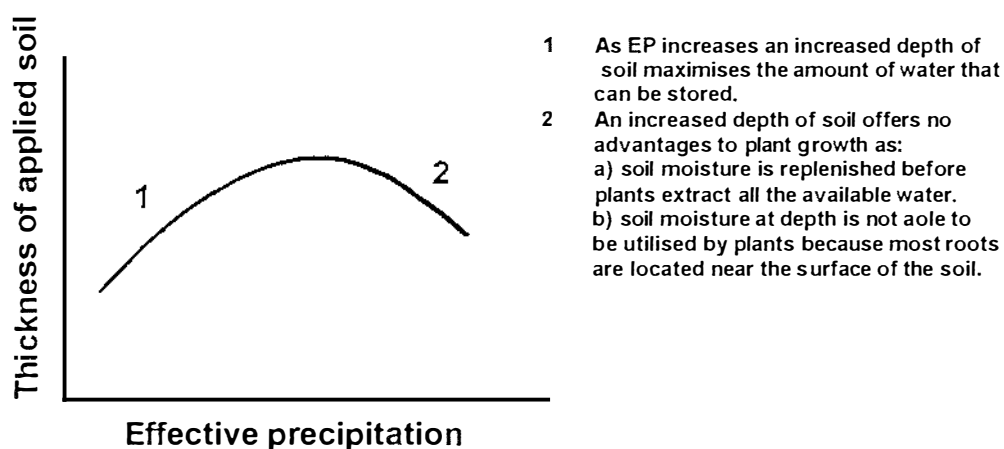


Figure 5.1: Schematic relationship between optimum soil depth and effective precipitation (EP) where  $EP = (\text{rainfall} + \text{irrigation}) - (\text{deep percolation} + \text{evapotranspiration})$ .

Sandy or coarse textured media generally have lower AWHC, consequently greater media depth is required. In areas where moisture usually limits crop growth, media with higher AWHC, resulting from either a finer soil texture or deeper topsoil, are more productive (Merrill *et al.*, 1985; Halvorson *et al.*, 1986; Jenkin *et al.*, 1986). Johnston (1986) recorded increased growth from shallow rooted crops when the AWHC of topsoil was increased.

### 5.3 Effects of mixing topsoil with other media (topsoil dilution)

Dilution of topsoil usually reduces the potential productivity of the mixed medium (Bradshaw, 1989) because topsoil is generally more chemically fertile than subsoil or overburden (Schuman



and Power, 1981; Hargis and Redente, 1984; Van Keulen and Kay, 1986). Mixing dilutes nutrients, organic matter and micro organisms, delays establishment of nutrient cycling and increases the time taken to develop a soil profile (Roe, 1987). Any disturbance of soil also disrupts microbial communities, for example fungal hyphae, and physically damages macro-organisms. Diluting topsoil may improve the quality of subsurface horizons but the mixture is generally less productive than when topsoil is placed separately on subsurface materials (Hargis and Redente, 1984; Michalski *et al.*, 1987). Mixing may cause a deterioration in chemical or textural characteristics (Hargis and Redente, 1984; Elliott and Veness, 1985) or cause contamination of surface layers (Ministry of Agriculture Fisheries and Food, 1982). For example mixing topsoil with a subsoil layer containing a phosphate-retentive ash layer may decrease plant phosphorus availability. Additionally seeds and propagules may be buried too deeply for effective germination (Nichols *et al.*, 1991).

Mixing topsoil with subsoil or other media may be deliberate, for example as a soil management alternative where topsoil is in short supply or topsoil and subsoil differ drastically in texture (Hargis and Redente, 1984), or accidental, for example where shallow soil depths are cultivated (Schuman *et al.*, 1985). In most cases, however, reclamation techniques are adopted to minimise topsoil dilution by mixing with subsoil or spoil. At Eneabba in Western Australia, for example, tractor drawn tines are used to cultivate the 0.05 m deep topsoil layer rather than traditional deeper rotary cultivation or ploughing techniques (Jefferies *et al.*, 1991).

The effect of topsoil mixing depends on the characteristics of topsoil and potential mixing media. Where topsoil contains little or no organic matter, or media and topsoil differ little in chemical fertility or texture, mixing may have little effect on plant productivity potential. An increase in productivity of a mixed medium may be due to modification of adverse or deficient topsoil properties (Schuman and Power, 1981; Hargis and Redente, 1984). Sencindiver *et al.* (1989) found that mixing sandstone (pH of 7.5) and native topsoil (pH of 4.5) increased plant growth by reducing topsoil exchangeable acidity, raising soil pH, and supplying available magnesium to overcome a native topsoil deficiency. Additionally, blending increased the low water holding capacity, cation exchange capacity and erosivity of the sandstone (Sencindiver *et al.*, 1989). Similarly, Chichester (1983, *cited by* Hargis and Redente, 1984) improved the status of iron, magnesium and zinc in topsoil by mixing topsoil with a subsoil profile containing these elements. An increase in productivity of mixed topsoil media may also occur where topsoils are very shallow as a large amount of moderately fertile material may be more productive than a thin layer of fertile medium over an infertile medium (Schuman and Power, 1981; Hargis and Redente, 1984; RMC, 1987). A glasshouse trial by Takyi <sup>*et al.*</sup> (1977), for example, showed that peat distributed through sand was more productive than a 0.038 m layer of peat over sand. Problems associated with the dramatic textural contrast were eliminated in the mixed medium with roots distributed throughout the pot rather than concentrated in the peat layer. Mixing peat with topsoil or subsoil

has been advocated to improve the handling and structural properties of soils involved (RMC, 1987).

#### 5.4 Effects of replacing different depths of soil

Topsoiling has the potential to markedly increase plant production on reclaimed sites by:

- \* improving soil nutrient status directly by supplying macro and micro nutrients and indirectly by masking or buffering toxicities such as heavy metals and salinity;
- \* increasing soil cation exchange capacity and water holding capacity;
- \* improving soil structure and macroporosity and decreasing bulk density;
- \* increasing the diversity and number of soil flora and fauna and providing an inoculation of beneficial mycorrhizae;
- \* modifying soil temperature fluctuations.

Optimum topsoil depths are site specific: dependant on the quality of topsoil and underlying media (Merrill *et al.*, 1985; Halvorson *et al.*, 1986), the amount of topsoil available, type of vegetation and post mining land use (Schuman and Power, 1981; Barth and Martin, 1984; Sims *et al.*, 1984) and climate (Power *et al.*, 1981). The most important climatic factor is the distribution and amount of precipitation over evapotranspiration (Sims *et al.*, 1984). Where topsoils are of poor quality, topsoil replacement may have no advantage or a negative impact on plant productivity. Such soils include saline, poorly draining or toxic topsoils, or those with a severe nutrient imbalance, for example serpentine soils (Leskiw, 1989). Similarly, where subsoil or spoil are chemically and physically fertile, plant establishment and growth maybe unaffected by topsoil depth (Sencindiver *et al.*, 1989).

Most research on soil depth has been concentrated in the Northern Great Plains region of the United States and Canada where overburden of strip coal mines (Schuman and Power, 1981) is high in clay and sodium (Merrill *et al.*, 1985) and root penetration into the overburden is limited. In the Northern Great Plains and in other situations where overburden or subsoils are a poor rooting environment, crop yields increase with increasing thickness of replaced topsoil and subsoil (Merrill *et al.*, 1985; Pinchak *et al.*, 1985) to a point where water or nutrient supply is non-limiting or maximum rooting depth is reached. Where rooting is confined to soil, shallow rooted crops require shallower soil than deeper rooted crops (Oddie *et al.*, 1989). Increasing the depth of soil generally increases the effective volume from which plants can extract plant nutrients and soil water (Mackintosh and Mozuraitis, 1982; Merrill *et al.*, 1985) and increases the range of crops that can be grown.

The productive advantage of deeper topsoil decreases over time as underlying media are modified through weathering and biological activity (Schuman *et al.*, 1985; Pinchak *et al.*, 1985). An exception occurs when the underlying medium is sodic or saline as salts may move up into



the topsoil (Schuman *et al.*, 1985). When other management practices are used in combination with topsoiling (fertilisation, irrigation) the effect of topsoil separation or depth may be enhanced or reduced (Sims *et al.*, 1984). In many cases, for example, topsoil replacement may result in compaction which adversely affects plant establishment and survival (Davidson, 1984b; McSweeney and Jansen, 1984).

## 5.5 Methods

In this section the methods and types of measurements undertaken in this study which relate to soil replacement treatments discussed in Chapter Four are described. Measurements mainly comprised replicated soil physical measurements and pasture measurements from individual plots. Measurements used to characterise soil treatments, such as particle size analysis, were determined by bulking samples from individual plots into treatment groups. The reasons for selecting specific methods or measurements are related briefly where applicable and discussed in more detail in Chapter Seven.

### 5.5.1 Bulk density

In this thesis bulk density = dry bulk density unless otherwise specified. Bulk density is the parameter most widely used as an indicator of soil compaction (Gameda *et al.*, 1988) and is a value used for converting soil moisture content from volumetric to gravimetric and determining soil total porosity. Bulk density was chosen to characterise soil compaction instead of cone or proctor penetration resistance as some treatments involved horizons containing stones, fine gravels or concretions. Cone penetration measurements are affected when stones are hit and it is not always easy to determine when a stone has influenced a measurement. Additionally to allow comparison of penetration resistance data individual plots and treatments should be measured at the same water content. This would have been very difficult given the different profiles and water table heights of plots at the Ohakea trial. Establishment of curves relating water content to density and penetration resistance for each soil horizon in the laboratory using soil samples compacted by a standard technique would have necessitated measuring wet or dry field bulk density anyway and correlating bulk density with penetration resistance.

The majority of bulk density measurements were taken using the core method. Sharpened ends of stainless steel cylinders c.50 mm tall with a diameter of c.50 mm were hammered or pressed vertically into levelled benches at desired depths to a maximum of 0.35 m until the tops of the rings were approximately 5 mm below the benched surface. Two to four samples were taken at each depth. The use of thin-walled cores with 5 to 10 mm of intact soil attached to each end of the core facilitated taking undisturbed cores. Exumed cores were placed in plastic bags to minimise desiccation. In the laboratory the outside of the cores was cleaned and the soil surface cut flush with the core ends with a sharp knife, avoiding compression. Where soil was dislodged

from below the surface of the core, excess soil from around that core was repacked to approximately the natural density. Repacked volumes did not comprise more than 10% of the core volume. Cores were dried at 110 Celsius overnight and weighed immediately after removal from the oven. The length of each core was measured with a vernier calliper to 0.1 mm. As cores were manufactured from the same diameter pipe, core diameters were similar. Bulk density was calculated as the ratio of the oven-dried mass over the field volume of the soil sample.

$$\rho_b = m / v$$

where

- $\rho_b$  = bulk density
- $m$  = oven-dried soil mass
- $v$  = field (wet) volume of the soil sample

Bulk density was also measured from cores used for Haines water release curve determinations. These cores, 25 mm and 30 mm height and 50 mm diameter, enabled slightly stonier soils to be included in the survey, as smaller cores were more easily inserted to avoid stones. Where extremely stony horizons were encountered bulk density was determined using an excavation method. A cylindrical hole 0.12 m in diameter and 0.10 m tall was excavated and the contents from the hole were dried overnight at 110 Celsius and weighed. Cores taken from holes and those taken with cores will differ because stones generally have a higher particle density than soil (and greywacke does not decrease in mass on drying). This matter is addressed in [Section 7.4](#).

### 5.5.2 Particle density

An adaptation of the procedure <sup>used in the Department of Soil Science, Massey University</sup> for measurement of particle density was used, with a 0.1 litre volumetric flask used instead of a pycnometer (specific gravity flask). Air dry samples were passed through a 2 mm sieve. Approximately 0.025 kg of sample was weighed into a 0.150 l beaker to which 0.05 l of distilled water was added. The suspension was brought to a gentle boil for several minutes to evacuate all trapped air and cooled before pouring into a 0.1 litre volumetric flask which was filled to the mark with distilled water and weighed. Quadruplicate samples were taken to determine sample gravimetric water content ( $\omega$ ).

$$\rho_s = m / v$$

where

- $\rho_s$  = particle density
- $m$  = dry mass of soil sample
- $v$  = volume of soil particles only

### 5.5.3 Total porosity

Total porosity was calculated using bulk density and particle density values, following the formula:

$$TP = 1 - \rho_b/\rho_s$$

where

$$TP = \text{total porosity}$$

### 5.5.4 Soil water retention or pore size distribution

The size and volume of pores in a soil and the surface area of soil particles determine the water contained in that soil at any time, *cet. par.*, precipitation and irrigation aside. Water in soil is held by capillary and adsorption or hygroscopic forces. Capillarity is the force seen as a curved meniscus of a water surface in contact with glass and results from the surface tension of water and its contact angle with the solid particles. Adsorption occurs where hydration envelopes are formed over hydrophilic particle surfaces or water is adsorbed onto the soil colloids. Thus, the amount of water held in a soil by adsorption forces reflects the clay and humus content of a soil. Assuming cylindrical pores of even diameter along their length, a gradual application of increasing suction to a soil will result in the emptying of large pores followed by progressively smaller pores because small pores exert a greater capillary pressure than large diameter pores. At low suctions, 0 to 100 kPa (0 to 10.2 m head), capillary forces, *i.e.* soil structure and pore size, control the volume of water held in a soil. At high suctions, for example 1500 kPa (153 m head) and above, only very narrow pores retain water, the hydration envelope thickness decreases and the surface area of a soil determines the amount of soil water held.

Haines and pressure plate measurements were used to determine the size and total volume of soil pores for the soil replacement treatments. Results are depicted as water release curves which are graphs relating gravimetric or volumetric water content to matric potential or suction (Hillel 1971; McLaren and Cameron, 1990). In this experiment soil water retention curves were determined for each soil using 0.05, 0.1, 1, 3, and 15 bar suction measurements. The methods used are described in the following section. All methods assume that soil pores have a circular cross-section and aggregates are hydrophilic.

#### *Soil moisture content at 1500 kPa to 100 kPa suctions*

The method for determining soil water content at 1500 kPa suction followed guidelines in *Operating instructions for the Soilmoisture Equipment Corporation 1500 ceramic plate extractor*. Air dry soil samples were passed through a 0.002 m sieve and used to half-fill 50 mm diameter retaining rings (25 mm height) on 1500 kPa ceramic plates. Samples were levelled, covered with

plastic sheeting to reduce evaporation and placed in a shallow tank which was gradually filled with water up to 2 to 3 mm below the top of the cores. After 24 hours (for sandy media) to 48 hours (for clay media) the tank was drained using a syringe and pressure was applied using a "15 Bar Ceramic Plate Extractor" until readings from a burette, or water collected in a container, attached to the plate outflow tube indicated water extraction from the cores had ceased (between 4 and 14 days). Samples were removed as soon as possible after release of pressure, placed in capped dishes to minimise evaporative drying and weighed before being dried overnight at 105 to 110° Celsius.

Determinations of soil water content at 300 kPa and 100 kPa followed the technique outlined above, however, undisturbed cores 0.05 m diameter and 0.01 to 0.015 m height were used instead of dry sieved samples because at these suctions the structural properties of a soil influence the soil moisture retained in a soil. The top and bottom surfaces of each core were trimmed flush with a sharp knife, and the cores placed on 300 kPa ceramic plates to which 300 or 100 kPa suction was applied after core saturation in water for 24 to 48 hours.

#### *Soil moisture content at 5 and 10 kPa suctions*

Adjacent pairs and triplets of cores (diameter = 0.05 m, height = 0.025 or 0.030 m) were pressed or hammered into moist soil, removed with undisturbed clods attached to both core ends, and placed in plastic bags to prevent desiccation. In the laboratory cores were cleaned and a sharp knife used to cut the soil flush with each end of the core. The lower face was placed on a damp 0.055 m diameter circle of Whatman 42 extra slow filter paper which provided thorough contact between the soil core and ceramic plate and facilitated removal and replacement of cores. Cores were slowly wetted from below and saturated for 24 to 48 hours before 5 kPa (0.50 m head) suction was applied through the 30 kPa ceramic plate, using a bubbling tower apparatus. Loveday (1974) described and illustrated the principles of regulation of a vacuum applied to a suction plate using a bubbling tower. When equilibrium was reached the cores were weighed and returned to the plate. Water was applied to the filter paper at the base of the cores to ensure re-sealing to the plate, and the suction was increased to 10 kPa (1 m head). When equilibrium was reached (24 to 72 hours) cores were weighed, dried overnight at 110°C and gravimetric water contents determined. The difference in weight between cores at 5 and 10 kPa suction was equivalent to the soil pore volume drained.

#### *Cellulose acetate peels*

An experiment was carried out to determine whether cutting the upper surface of a core subjected to a base suction of 5 or 10 kPa caused significant smearing. Smearing can cause an under estimation of core macroporosity value as pores opening to the upper core surface atmosphere are closed over Greenwood (1989). This reduces or prevents pores being drained

of water. Drainage of water from a pore is determined by the narrowest cross section of that pore and a pore drains at an artificially greater suction when the upper end is smeared. Smearing the surface of the core in contact with the suction plate (lower surface) does not affect the macroporosity, but may slow down the drainage rate of the pore.

A total of 82 undisturbed cores (diameter = 50 mm, height = 25 or 30 mm) were taken at different depths in the soil profile from Ohakea and Rangitikei trial sites. The upper surface of each core was either cut flush with a sharp knife or covered with a viscous solution of cellulose acetate and acetone, following the method described by Greenwood (1939). Peeling the set cellulose layer from the core removed a thin layer of soil and prevented surface smearing. All cores were placed under 5 and 10 kPa suction as described in the previous section. Results from this experiment are detailed in Appendix 5.6.

#### *Plant stress days*

Plant stress days were used to identify which dry matter harvests corresponded to periods when pasture was most stressed. Stress days were considered important as research in Taranaki and near Wellington which correlated ryegrass leaf extension rates and tensiometer measurements indicated ryegrass leaf extension abruptly decreased when the water deficit reached a critical level. In the Judgeford silt loam this critical level equated to a water deficit of 160 mm in the top 1 m (a soil water potential of -10 kPa in the subsoil and -50 kPa in topsoil) (Parfitt *et al.*, 1981). Calculation of stress days facilitated a correlation between pasture production from individual treatments at harvests with similar numbers of stress days preceding them. It was thought calculation of stress days would allow testing of the hypothesis that pasture production from individual soil replacement treatments was dependant on soil moisture conditions.

Plant stress days were calculated for each soil replacement treatment and determined from cumulatively adding the daily precipitation balance to the total water holding capacity of a soil profile to 0.35 m depth. A plant stress day occurred when no water was available for plant growth in the soil profile. A daily water balance was calculated by subtracting evapotranspiration ( $E_r$ ) from precipitation measured at Palmerston North D.S.I.R. climate station.  $E_r$  was estimated using the Priestly and Taylor (1972) equation which uses hours of sunshine, maximum and minimum air temperatures, date and latitude, as described by Snow (1992). The Priestly and Taylor (1972) estimate of  $E_r$  has been shown to work for well watered pasture in the Manawatu region (Scotter *et al.*, 1979; Green *et al.*, 1984), so the use of a more complicated equation such as the Penman equation, which requires extra inputs was not justified (Green *et al.*, 1984). Soil treatment water holding capacity was calculated from measurements of soil moisture contents of cores at 1500 kPa and 0.5 kPa (approximating field capacity) using the formula:

$$\text{TAWHC} = (\theta_{\text{FC}} - \theta_{\text{PWP}}) \cdot z$$

TAWHC	= total available water holding capacity
$\theta_{\text{FC}}$	= soil moisture content at field capacity
$\theta_{\text{PWP}}$	= soil moisture content at permanent wilting point
z	= rooting depth, or depth over which TAWHC is calculated

#### *Field soil moisture content*

Soil moisture was measured using Soilmoisture Equipment Corporation IRAMS soil moisture analyzers (Time Domain Reflectometers or TDRs). A TDR measures the integral of the soil moisture content by pulsing an electric current through the length of stainless steel wave guides or probes. Wallis (1991) reviewed literature on TDR measurement and discussed the positive and negative attributes of TDRs, gravimetric, and neutron probe methods of soil moisture measurement in detail. Wallis concluded that TDR's allowed rapid, non-destructive, accurate sampling with no soil calibration requirement and could be used to 0.1 m from the soil surface. Air gaps are the major causes of error associated with soil moisture measurements (Topp and Davis, 1985). Air gaps reduce the conductivity of the electric pulse to the soil, hence inducing an artificially low soil moisture measurement, and may be caused by soil shrinking and swelling and when probes wobble as they are inserted (Baker and Lascano, 1989).

At the Ohakea site, pairs of steel probes were permanently inserted into the centre of each plot to depths of 0.20, 0.40 and 0.60 m. The probes were marked with white tags and pasture between and around the probes maintained in the same condition as the rest of the plot by hand shearing around the probes at the same time as plots were harvested.

#### 5.5.5 Pasture quantity and quality

Four methods were used to measure pasture characteristics: pasture dry matter production; pasture composition; root mass and root length.

##### *Dry matter production*

Harvesting dry matter is a standard measurement of the agricultural or horticultural productivity of reclaimed land. Plant production is a favoured measure of reclamation success because plants integrate chemical, biological, and physical characteristics of aerial and soil environments over time and space (Letey 1985). Dry matter production may not, however, give an indication of land versatility, especially where a resilient crop such as ryegrass is grown. Additionally, plant productivity may not be an accurate predictor of reclamation success nor sustainability of production. For example arable crop yields equal to those of undisturbed crops may be attained

in the first year after reclamation but to the long term detriment of the soil as ploughing and harvesting may cause compaction and loss of organic matter. Total dry matter production ignores the rate of tissue turnover in a sward resulting from formation of new tissue and decomposition of older tissue. Tissue turnover is a measure of the rate of buildup of soil organic matter. Dry matter production was measured despite these drawbacks as it is a widely used, standard method which facilitates comparison of results with similar experiments. Additionally mowing is a relatively fast measurement considering that trials must be mown anyway to simulate grazing and maintain pasture quality.

Pasture dry matter production was measured by removing 4 or 5 0.5 m<sup>2</sup> quadrats from each plot (17 to 21% of each plot) with electric shears. Hand shearing, although labour intensive, is more accurate than another common pasture production measurement method in which a lawn mower catcher is weighed before and after cutting a specified area of plot, particularly when plots have different clover contents. Clover species generally have higher moisture contents than grass species and tend to splatter when mown rather than be thrown into the catcher. Thus plots with high clover contents can have artificially low measured yields. After quadrats were cut the remainder of the plots was mown with rotary lawnmowers which mulched the residues into the plot surfaces. Where large amounts of dry matter remained, plots were mown twice, first at a high setting with herbage removal and secondly at a lower setting leaving residue on the plots. Approximately 50% of the residue was returned or mulched into the surface of the plot, depending on pasture height and moisture content. The height setting of rotary mowers was lower than that of the hand-shorn quadrats. Swards were harvested when they had reached an average height of 0.15 to 0.20 m as greater errors were associated with harvesting short swards because residues from the previous harvest could represent a substantial part of the herbage mass. Additionally longer swards were more even.

#### *Pasture composition*

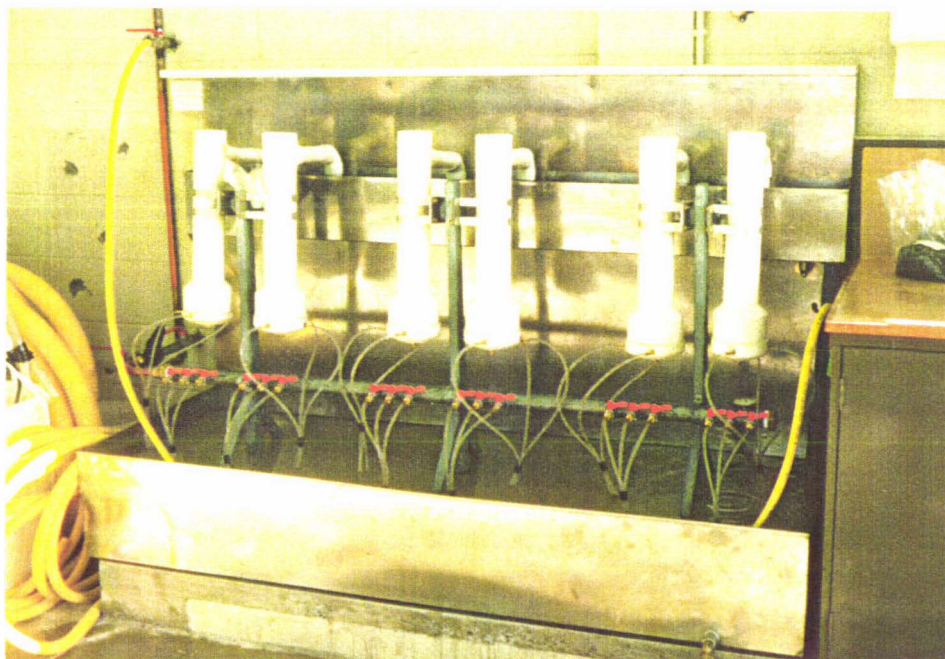
Pasture composition was measured because it is an indication of pasture quality and a part of most studies of the effect of management on herbage production. All herbage dissections were carried out on one bulked sample formed from 4 equal fresh weight subsamples. Subsampling was achieved by thoroughly teasing out and mixing the herbage, dividing it into half, and half again before analysing a portion of the remainder which varied according to the length of herbage and visually estimated variation of the sample. Samples were stored in a refrigerator until dissected in paper bags which minimised degradation of the plant material. Dissection categories were determined by the information required, for example the first harvest of the Rangitikei trial was separated into cereals (barley and oats) and weeds. In a short study of commercially reclaimed land at the Rangitikei site, herbage samples were divided into flowering and non flowering grass tillers, rushes and daisies. Most other pasture samples were separated into clovers, grasses and weeds.



### *Root length*

Measurement of root length and root mass was used to compare root growth between and within soil profiles. All measurements made on roots tend to have a high coefficient of variation (Troughton 1957; Matthew, 1992). Root length was the primary rooting characteristic measured as it is a more stable variable than root mass which changes with the length of time root samples are stored as roots are metabolised. Root length enables more appropriate inferences on plant root water and mineral uptake, while mass : length ratios indicate root distribution. Root length has been measured since 1966 when the line intersect method was developed and has been increasingly adopted as the preferred measure in root studies.

Roots of grasses are concentrated near the soil surface. Troughton (1957) stated that 50% of the rooting of a temperate grassland generally in the upper 0.10 m and 75% in the upper 0.30 m while Matthew (1992), reviewing pasture rooting literature, found that that typically 60 to 80% of the total root mass was in the surface 0.15 m of soil. In this study samples were taken from 0.005 to 0.05 m, 0.1 to 0.15 m, 0.20 to 0.25 m and 0.30 to 0.35 m.



Photograph 5.1:

The root washing machine designed by Matthew (1992), Agronomy Department, Massey University which was used to separate roots from soil.

The number of samples taken at each site was limited by the slowness of excavating soil samples by hand as the presence of stones precluded a use of a tractor powered stainless steel corer which is the method adopted in most field studies. At the Rangitikei site two cores ( $d=0.10$  m) were removed from plot at each depth (total volume  $0.0013\text{ m}^3$ ). Where horizons were extremely stony, for example the fill horizons, the outline of the corer was marked and the soil and stones removed piecemeal by hand and crowbar. At Ohakea sites  $0.20$  by  $0.20$  by  $0.05$  m samples were excavated (sample volume  $0.002\text{ m}^3$ ). Samples were placed into sealed plastic bags and refrigerated for up to four weeks.

In the lab, samples were weighed, thoroughly mixed, halved and a sub sample of approx  $1.1$  to  $1.2$  l taken for root washing. An additional sample of approximately  $0.2$  l was taken to determine gravimetric water content. Roots were separated from the soil samples using a "hydropneumatic elutriation system" or root washing machine which was redesigned at Massey University as described by Matthew (1992)(Photograph 5.1). Roots were washed in a manifold by three water jets, the pressures of which were adjusted to provide an agitation and flow rate which floated roots into a wire mesh basket. Small fragments of soil were carried out of the manifold and collected with the root sample, necessitating re-washing by hand using a very fine sieve. No attempt was made to distinguish between live and dead roots or roots of different species. Roots were stored in 90% ethanol solution, which prevented microbial decomposition for at least four months.

Root length was calculated from washed roots using a Comair Root Length Scanner, which determines the total length of scanned roots by counting the intersections between the roots on a set of randomly placed and orientated lines. The root scanner was used as specified in the instruction manual. A line fitting equation was used to adjust raw root length data of samples with over  $50$  m of roots to compensate for increased numbers of overlapping roots. The total root length for any one subsample was less than  $120$  m. Each root sample took approximately  $1.5$  to  $2.5$  hours to sample, wash, scan, and weigh.

#### *Root mass*

After root samples had been scanned for root length, they were dried for  $12$  to  $24$  hours at  $70$  C and weighed. Thirty samples were subsequently ashed in a muffle furnace at  $700$  C for  $4$  to  $6$  hours as recommended by Troughton (1957) to determine the proportion of organic matter in the root weight, i.e. to enable correction of root mass for adhering soil. Results of this experiment comprise Appendix 6.5.

*Turnover of plant tissue in pasture swards*

Pastures are dynamic systems in which the rate of formation of new tissue and senescence/decomposition of older tissue change with season and environmental conditions. Measurement of these changes is more sensitive than gross measurements of pasture dry matter production by mowing. Changes in leaf extension rates, for example, often give the earliest indication that plants are under stress (Chu and McPherson, 1977).

Table 5.1: A sample record card for recording the growth characteristics of ryegrass. The location of a tag is given by the distance along a tape and angle from the tape. Leaf type was either m (mown) or u (unmown).

Plot, Rep	Location of tag cm, °	Ryegrass leaf		
		Length (mm)	Type	Stage
1 , a	12, 120	50	m	mature
1 , a	"	25	u	juvenile
1 , b	30, 45	43	m	mature

NB A new line is started for each leaf on a tiller.

In 1991 Dr Alan Younger (University of Newcastle) measured rates of change of the predominantly clover/ryegrass sward at the Rangitikei trial using measurements of set tagged ryegrass tillers and clover stolons on 5 occasions at 3 to 4 day intervals over a three week period. Results were compared from two soil replacement treatments: 0.40 m C horizon and 0.10 m A horizon replaced on 0.30 m C horizon. Randomly selected defoliated tillers and stolons were marked along two 1 m transects in each of four replicate plots using yellow plastic rings. Table 5.1 is part of a sheet used to record ryegrass leaf extension (length), whether a leaf had been mown (type) and the age grouping of a leaf, i.e. juvenile, mature, reproductive or dead leaf (stage). Tiller measurements included the length of the lamina of all leaves which allowed calculation of leaf extension rates. Clover leaf area and stolon length was also measured. These measurements were used to estimate rates of growth, senescence and net production of ryegrass and clover by multiplying individual plant values by population density estimates. Length measurements were transformed to a weight basis using results from concurrent samples of plant material (Bircham and Hodgson, 1983). Population density estimates were based on the number of tillers of ryegrass and other grasses, the number of clover shoots and the number of other plant species in 0.04 m diameter plugs which were taken from each plot at the time of the first and last measurements.

### 5.5.6 Total carbon content

Total organic carbon can be accurately and precisely measured using the LECO induction furnace. The total organic carbon content of a soil reflects the organic matter content of a soil, however, the relationship between the two varies from soil to soil and with depth in a profile so that any constant factor used to relate them selected is an approximation at best. In this report, therefore, only total carbon contents are used.

A total of 6 soil cores were taken from 0 to 0.075 m depth and 0.075 to 0.15 m depth diagonally across each plot. Subsoil cores were taken from below 0.30 m in treatments which contained subsoil. Cores were air-dried and passed through a 2 mm diameter sieve before removal of a c. 0.05 kg subsample. Subsamples were finely ground to break-up all aggregates and stored at 60 °C until required for analysis. An adaptation of the standard method

for use of the LECO induction furnace for total carbon analysis of soils was used. The LECO measures CO<sub>2</sub> evolved from completely burning soil at c. 1650 °C. Two 40% carbon glucose standards were run after every 10 soil samples, with low and high carbon content samples measured in separate groups to keep approximately the same amount of CO<sub>2</sub> flowing through the bulb. To meet a limited budget but minimise error every alternate sample and samples with unexpectedly high or low carbon contents were duplicated.

### 5.5.7 Particle size analysis

Particle size analysis of soils was measured using a standard pipette analysis for clay, silt and sand adapted from Day (1965) and Gie and Bauder (1986). Soil cores for the particle analysis were collected from 4 to 8 plots with 4 cores removed from each plot. Damp soil aggregates were separated into their constituent particles using chemical dispersion (hydrogen peroxide and Calgon dispersant) and mechanical dispersion (centrifuges and vitamisers). Particles were separated by sieving and sedimentation according to size limits into clay (<2 microns diameter), silt (2 to 50 microns diameter) and sand particles (50 to 2000 microns diameter).

The root washing machine caused heavy particles from each 1.1 to 1.2 litre sample to remain in the manifold while silt, clay and grass roots were removed. The particles remaining in the manifold were tipped into a 0.001 m diameter sieve and collected for each soil depth and plot. Later these coarse fragments were sieved through 0.002 m and 0.01 m sieves and their mass recorded.

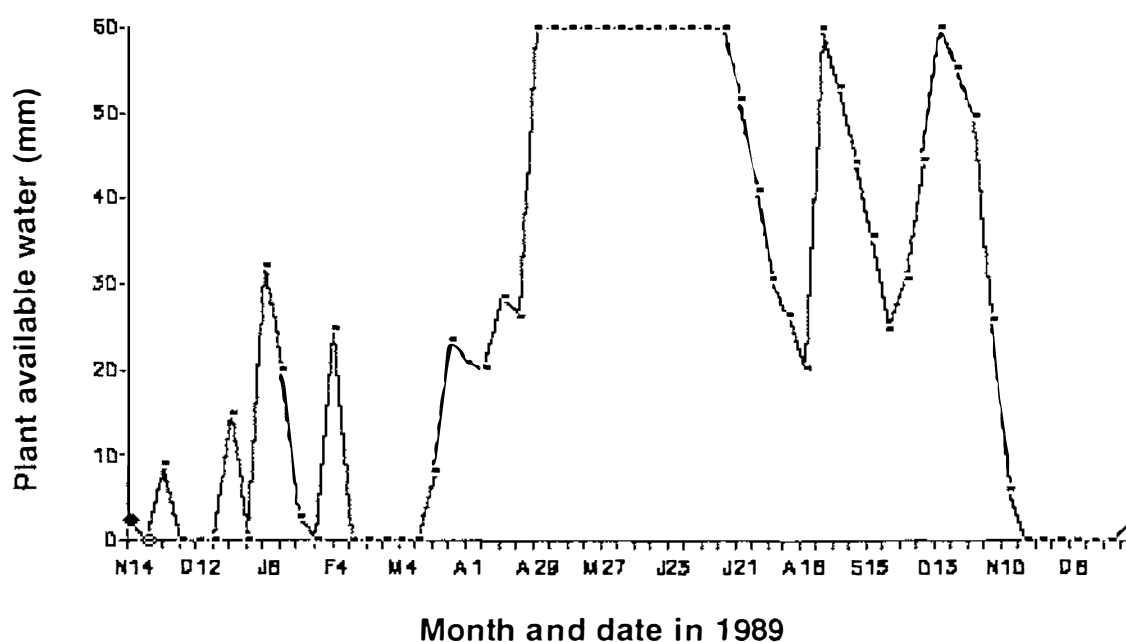
## 5.6 Growing conditions over the period of the Ohakea and Rangitikei field trials.

### 5.6.1 Summer 1988-89

Summer of 1988-89 was droughty with plant available moisture exhausted for 10 of 17 weeks between November 14 and March 11 in a hypothetical soil with total plant available moisture (PAM) of 60 mm in the surface 0.35 m. Within this period February was an extremely dry month with nil plant available moisture for 4 consecutive weeks out of 5, based on weekly totals of evapotranspiration and rainfall (Graph 5.1).

### 5.6.2 Autumn-Winter 1989

The autumn and early winter of 1989 was very wet. Soil moisture levels were at or above field capacity (in the hypothetical soil with 60 mm PAM) between April 29 and July 14, a period of 14 continuous weeks. During this period soil oxygen levels may have been limiting to plant growth (anaerobic), particularly in treatments with impeded drainage or comprising large clods. Soil moisture conditions were favourable for plant growth during late winter and spring 1989 with moderate levels of PAM from July 14 to November 18 and only 2 of 17 weeks during which soil levels were at field capacity (Graphs 5.2 and 5.3).



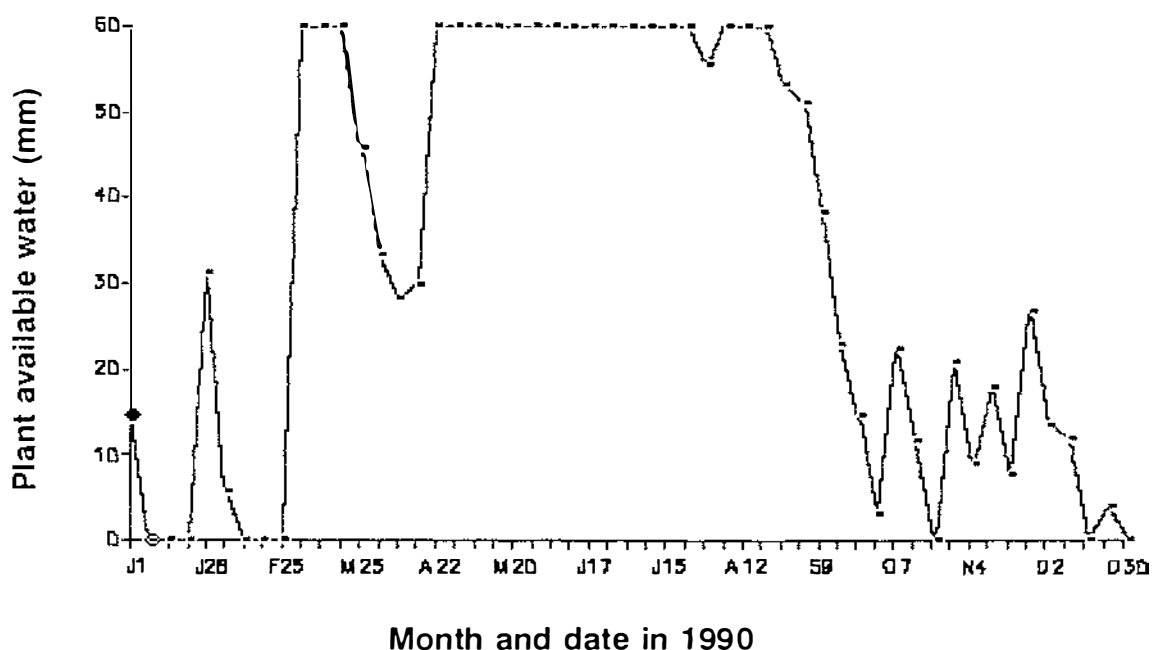
Graph 5.1: Weekly fluctuation of total plant available moisture (PAM) from November 14 1988 to December 30 1989 for a soil with 60 mm PAM in the surface 0.35 m of soil. Climatological data from AgResearch (DSIR), Palmerston North.

## 5.6.3 Summer 1989-90

Soil moisture levels in the summer of 1989-90 were lower than those of 1988-89 but the period of moisture deficit was shorter; extending from November 18 1989 to February 25 1990. No soil moisture was available for plant growth for six consecutive weeks from November 18 to December 22 1989. Shorter periods of zero plant available soil moisture continued intermittently to February 25 with the hypothetical soil containing zero plant available moisture for 6 of the first 9 weeks of 1990 (Graphs 5.2 and 5.3). When PAM is calculated on a daily, rather than weekly basis the 1989-90 summer is characterised by three distinct periods of 0 PAM: 18 consecutive days in mid to late November; 20 consecutive days in December; and 17 consecutive days in February-March.

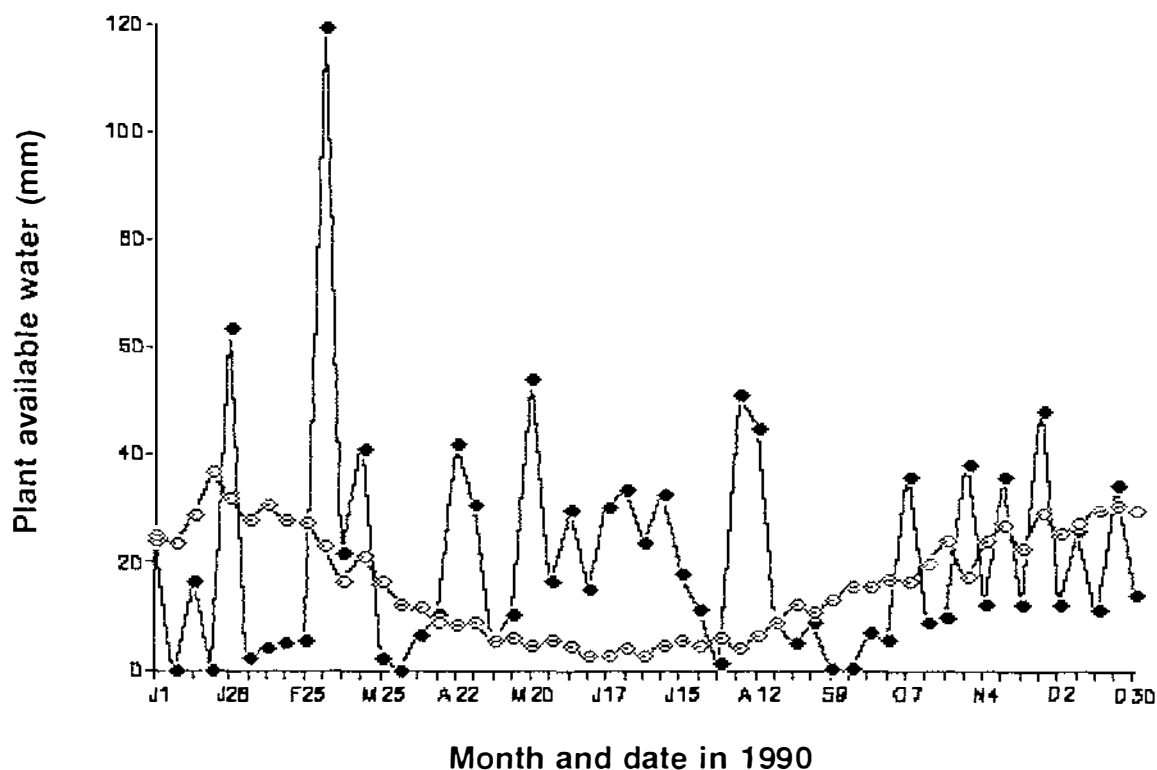
## 5.6.4 Autumn-Winter 1990

Favourable plant growth conditions, i.e. adequate availability of soil oxygen and soil moisture, were maintained from March 18 to April 29 1990, with soil moisture levels below field capacity and above zero in the hypothetical soil. The winter of 1990 was characterised by a lengthy



Graph 5.2: Weekly fluctuation of PAM during 1990 for a soil with 60 mm PAM in the surface 0.35 m of soil. Climatological data from AgResearch (DSIR), Palmerston North.

period of high soil moisture levels. A hypothetical soil with 60 mm PAW was at field capacity for 16 of 17 weeks from April 22 to August 19 (Graphs 5.2 and 5.3). During this period soil replacement treatments with low hydraulic conductivity may have experienced anaerobic conditions.



Graph 5.3: Total monthly precipitation (●), measured at AgResearch (DSIR), Palmerston North and calculated monthly total evapotranspiration ○ (mm) from January to December 1990. Note the extended period of low rainfall in February.

#### 5.6.5 Summer 1990-91

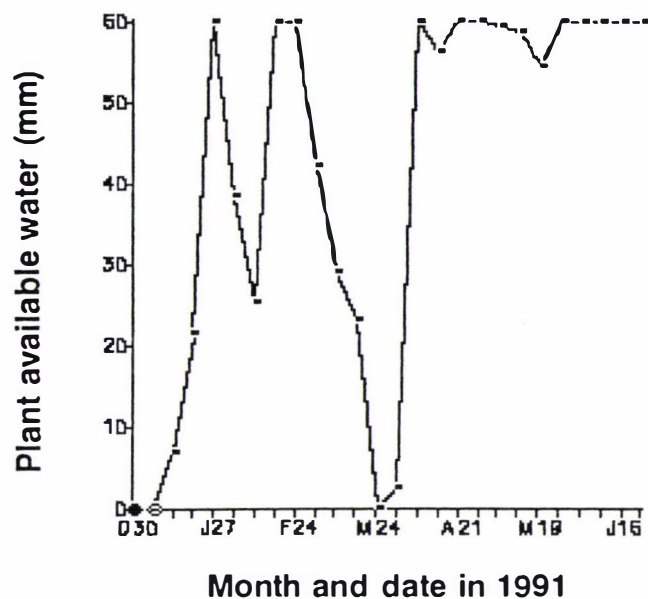
Summer of 1990-91 was relatively wet with only a short period when PAM levels were zero. There was only one week of zero plant available moisture in the hypothetical soil between the first week in September to the second week in December 16 1990 and again between the first week in January to the end of March 1991. During the second period soil moisture levels were high but below field capacity for 7 of the 10 weeks, indicating that most soil treatments would have had favourable conditions for plant growth (Graphs 5.3 and 5.4).



## 5.6.6 Autumn-Winter 1991

The autumn to mid-winter period in 1991 was predominantly wet. From 7 April to 23 June 1991 weekly soil moisture levels were consistently at or within 10% of field capacity, i.e. soil conditions would favour soil treatments with high hydraulic conductivity.

The Ohakea Trial was planted in April 1989 and the Rangitikei Trial planted in December 1988. Tables 5.2 and 5.3 are referred to throughout chapters 5 and 6 in sections which summarise results of pasture harvests and discuss these results.



Graph 5.4: Weekly fluctuation of PAM from December 30 1990 to June 23 1991 for a soil with 60 mm PAM in the surface 0.35 m. Climatological data from AgResearch (DSIR), Palmerston North.

Table 5.2: Rangitikei trial: harvest dates and number of days of moisture stress prior to each harvest for a hypothetical soil with 60 mm PAM in the surface 0.35 m.

<u>Harvest</u>	Date	Days of 0 plant available soil moisture	Days of soil moisture above field capacity
1	February 1989		
2	16 January 1990	45 (59% of days)	0
3	7 April 1990	34 (42% of days)	7 (9% of days)
4	8 August 1990	0	64 (53% of days)
5	27 September 1990	0	14 (28% of days)
6	8 November 1990	7 (16% of days)	0
7	12 December 1990	0	0
8	20 April 1991	27 (21% of days)	4
9	June 1991	0	28 (46% of days)

Table 5.3: Ohakea trial: harvest dates and probable days of moisture stress prior to each harvest for a hypothetical soil with 60 mm PAM in the surface 0.35 m.

<u>Harvest</u>	Date	Days of 0 plant available soil moisture	Days of soil moisture at or above field capacity
1	5 September 1989	0	68
2	6 October 1989	0	0
3	9 November 1989	0	6
4	22 December 1989	35	0
5	22 March 1990	7	44
6	6 May 1990	0	4
7	4 August 1990	0	55
8	14 September 1990	0	17
9	28 October 1990	6	0
10	6 December 1990	1	0
11	18 January 1991	18	0
12	15 February 1991	0	1
13	12 March 1991	0	1
14	10 June 1991	9 (late March)	22

## 5.7 Rangitikei trial soil replacement treatments

In section 5.7 the effects of different soil replacement strategies on soil and plant characteristics are presented. Results of soil physical measurements are presented within each section that describes the soil replacement strategy and are followed by results of pasture production. Results from all three trials are presented and discussed in concluding sections of the chapter. Descriptions and abbreviations for each of the soil replacement treatments were presented in Chapter Four, Figures 4.6 and 4.7 (Ohakea trial), Figures 4.10 and 4.11 (Rangitikei trial) and Figure 4.12 (Ashhurst trial). A summary of the soil replacement treatments used in the Rangitikei trial is given in Table 5.4.

### 5.7.1 Reporting of statistics

The probability of an event happening, or one variable being related to another variable, is used to indicate how frequently a particular outcome will occur or how certain the link between two variables is. For example compaction may cause a decrease in pasture production 80% of the time in a particular environment. The probability of an event occurring is tested in terms of a Null hypothesis. The Null hypothesis for any experiment is the hypothesis that the measured result is due entirely to the random chance or extraneous error associated with the experiment; i.e. that there is no effect or real difference between treatments. In the compaction example above, the result in terms of the Null hypothesis is that the effects of compaction are due entirely to chance 20% of the time; i.e. the probability of the Null hypothesis being true is 0.20.

All the tables in chapters 5 and 6 which contain probability values are presented in terms of the Null hypothesis. Therefore the nearer a probability value is to 1.00 the greater the chance that any differences between treatments are due entirely to chance or natural variation, rather than "real" differences between the treatments. Conversely, the closer a probability to 0 the greater the certainty that any differences between treatments are "real", i.e. due to experimental treatments. A probability of 0.10 (10%) has been selected as the cut-off value at which a difference is significant.

Throughout this chapter common words and phrases are used to report statistics associated with results. Within this paragraph these words and phrases are bolded. A **significant** result, where treatment A is **lower** or **less than** (conversely **higher** or **greater than**) treatment B, is one where the probability that differences between treatment means are due entirely to chance (i.e. the null hypothesis holds) has a value of less than or equal to 10% ( $p < 0.10$ ), or the specified probability. **Highly significant** results have a probability of the null hypothesis being true of less than or equal to 1% ( $p < 0.01$ ) while **similar** results have treatment means which are **not** significantly different at  $p < 0.10$ ; i.e. the probability that differences are due entirely to random chance. Results that show a **trend** are not significantly different from each other at  $p < 0.10$ ; however, a number of measurements taken over time or at increasing depths have a similar pattern and the

highlighting of a trend or **consistent** result draws attention to this. Smaller variances within the replicates of a single treatment may have resulted in significant results, thus the identification of a trend can indicate that further experimentation using different measurement techniques, more replicate plots or more samples may have been warranted.

Table 5.4: Descriptions and zones of probability used to relate the statistical significance of results in chapters Five and Six.

Description	Example	Probability
Not significant	A is similar to B	$p > 0.10$
Significant	A is greater than B	$p \leq 0.10$
Highly significant	A is greater than B	$p \leq 0.05$

Throughout Chapters Five and Six, tests of statistical significance, primarily Duncan's Test, were carried out at both 5% and 10% probability levels. A Duncan's test assigns treatments that are significantly different at the nominated level (usually 10%) with different letters. An explanation of Duncan's test is given in Appendix 5.1. Ascribing significance to a 10% probability balanced the scientific and practical aims of the trials, i.e. if field trials showed that in 9 of 10 harvests low compaction treatments produced more pasture dry matter than high compaction treatments, reclamation practitioners should be encouraged to adopt practices that minimise compaction. Depending on the benefits of a technique, industry may adopt a technique that showed benefits in only 60% or 80% of cases. Additionally, 10% was chosen as the cut-off for significance due to the low number of replicates or sample volume and inherent variability of some of the measurements associated with field trials. The results of Duncan's statistical tests are reported frequently throughout Chapters Five and Six as the test allows a visual appraisal of the significance and order of treatments.

#### 5.7.2 The effect of soil depth

The Rangitikei Trial was harvested from February 1989 to June 1991 on dates specified in Table 5.2. The numbers in Table 5.2 are used throughout Chapters Five and Six in reference to Rangitikei harvest dates. The given harvest date is the day a harvest began as in most cases harvesting took 2 days. In this section the effect of increasing depth of soil of both topsoiled and nil-topsoil treatments on pasture dry matter production and species composition is presented.

*Topsoiled treatments*

Table 5.5: Rangitikei trial. Description, symbol and total depth of spread sandy loam ("sandy materials" in text) of each soil replacement treatment.

Replacement treatment	Total depth of applied sandy loam (m)	Description
Fill	0	nil soil applied on fill
10A	0.1	0.1 m topsoil on fill
10A+30C	0.4	0.1 m topsoil on 0.3 m C horizon on fill
40C	0.4	0.4 m C horizon on fill
100C	1.0	1.0 m C horizon on fill
Control	c.1.5	A horizon mixed to 0.2 m on c.1.3 m undisturbed C horizon

Dry matter production of barley and oats from topsoiled treatments at the Rangitikei trial (harvest one) displayed a classical response to increased soil depth where rooting is restricted to the volume of soil spread and water or/and nutrients is limiting. The major factor limiting growth was probably the amount of moisture in the soil available to the plants, as extended periods of moisture deficit occurred during the growing period (Graph 5.1). Additionally, the trial was fertilised with urea and superphosphate so that nutrients were unlikely to be limiting. Pasture yield increased with increasing soil depth. The c.1.5 m deep control treatment produced significantly more above-ground dry matter, comprising barley, oats and weeds, than the 0.40 m treatment which in turn produced significantly more than the 0.10 m deep treatment. Photographs of the barley and oat crops on nil soil and 0.10 m topsoil treatments show the dramatic difference in colour and proportion of weeds in the two treatments (Photographs 5.2 and 5.4).

The control treatment significantly outproduced the fill treatment in 5 of the 8 pasture harvests (Table 5.6). The two harvests in which the control treatment produced significantly less than the fill treatment was probably due to the control plots being disproportionately affected by a hormonal herbicide which was sprayed by the land-owner to control weeds nearby. The control plots were located in a paddock adjacent to the main trial area and therefore received a higher concentration of herbicide than plots in the main trial area which were in a protected, sunken area (Chapter 4.3). The 10A+30C treatment produced significantly more dry matter than the fill treatment in one third of the harvests and the same as the fill treatment in more than half the harvests. Pasture production from the 0.40 m deep (10A+30C) and 0.10 m deep (10A) treatments was similar in all but one pasture harvest. The 10A treatment significantly

Table 5.6: Rangitikei trial. Dry matter production ( $\text{kg ha}^{-1}$ ) from different total depths of sandy materials covered with a 0.1 m depth of sandy loam topsoil. Letters on the RHS of each column are Duncan's Test results at  $p=0.01$  (Appendix 5.1). \* = the fill treatment is a nil soil treatment i.e. no sandy materials were applied.

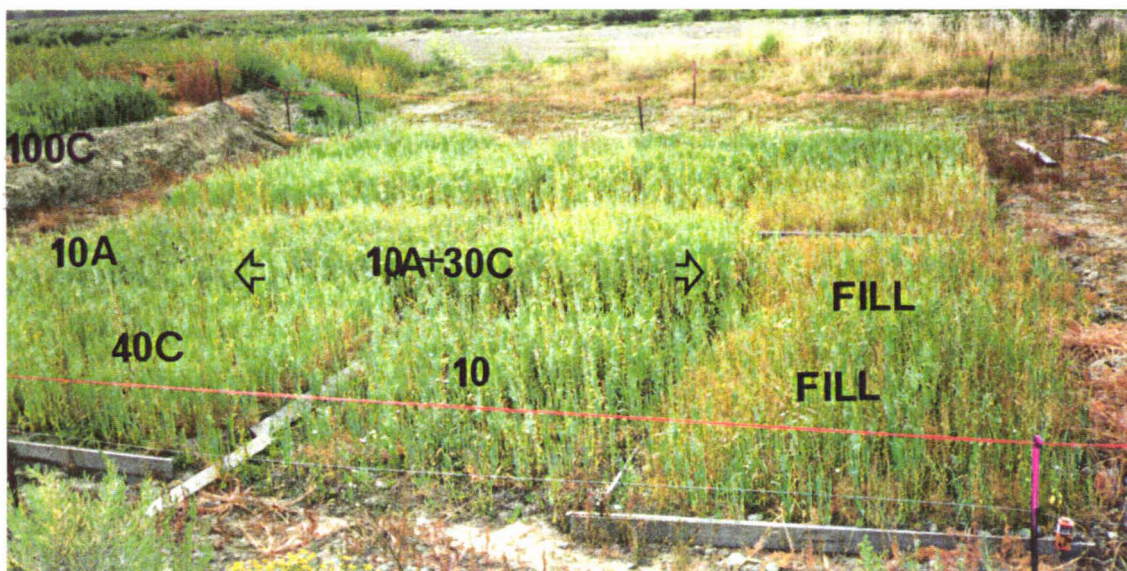
Soil Treatment	Dry matter production ( $\text{kg ha}^{-1}$ )				
	1	2	3	4	5
Control	184±7 a	3250±1770 a	3030±300 a	1220±120 a	1660±240 a
10A+30C	143±16 b	900±230 b	210±110 b	1160±210 a	1550±140 ab
10A	81±16 c	1250±350 b	270±140 b	1190±370 a	1570±160 ab
Fill*	92±21 c	1070±500 b	230±190 b	1080±170 a	1460±90 b
Significance	0.0001	0.003	0.0001	0.66	0.40
Soil Treatment	6	7	8	9	
Control	290±70 c	1130±230 c	1340±110 b	440±30 a	
10A+30C	1480±370 b	1760±220 a	1850±100 a	340±100 b	
10A	1910±250 a	1670±360 a	1710±260 a	310±130 b	
Fill	2240±750 a	1460±310 b	1430±350 b	300±50 b	
Significance	0.001	0.001	0.001	0.06	

outproduced the nil soil (fill) treatment in only two of the eight harvests of pasture (Table 5.6).

In summary, increasing the depth of soil over compacted fill from 0 to c. 1.5 m was generally associated with increased productivity of both barley and oats and pasture. Spreading topsoil on the fill only resulted in increased yields of pasture in harvests 7 and 8. Additionally, there was no increase in pasture production related to an increase in depth of the replaced soil from 0.1 to 0.4 m (Table 5.6).

Herbage dissections of five harvests from both topsoiled treatments contained the same percentage of weeds by dry mass. In two harvests the control treatment contained significantly more weeds than the nil soil (fill) treatment (Appendices 5.2.1 and 5.2.2).

Measurements of total root length at the end of the trial showed no significant differences between treatments due to the large error associated with the measurements (Appendix 5.2.3). The nil soil (fill) treatment had the most variation in both root mass and root length at depths of 0.10 to 0.30 m, reflecting the variability of the medium. Trends in results, which may have been significant given a different sampling regime (Chapter 7.4.3), were that the nil soil treatment had



Photograph 5.2: Rangitikei trial. The barley and oats crop immediately prior to harvest. Note the variation in the colour and density of the crop in different treatments. An explanation of the treatment codes is in Table 5.4.

the greatest root length in the surface 0 to 50 mm depth and the control treatment had the shortest root length and lowest root mass at sampled depths between 0 and 0.25 m. Root mass results showed the 10A+30C and control to have a smaller mass of roots than the 10A treatment at 0.20-0.25 m depth, indicating that, contrary to expectations, roots had exploited the surface 0.15 m of the underlying fill (Appendix 5.2.3).

#### *Nil-topsoil treatments*

The crop of barley and oats from non-topsoiled treatments at the Rangitikei trial also showed the classical response to increasing soil depth, as described for topsoiled treatments in the previous section. Significant increases in above-ground dry matter corresponded with increasing total soil depths from 0 to 0.40 to 1.0 m (Table 5.7). Photographs of the barley and oats crop growing in nil, 0.40 m deep and 1.0 m deep replaced soil show the variation in colour, crop density and proportion of weeds in each treatment (Photographs 5.2, 5.3 and 5.4).

Pasture dry matter production did not show a clear response to increasing depths of non-topsoiled soil. Similar production was recorded from the 1.0, 0.40 m and nil soil treatments in 6 of the 8 harvests, however, the nil-soil treatment consistently produced less than the 100C treatment. The c.1.5 m deep control treatment generally produced more than the nil soil treatment, although the differences were significant in only 2 of the 8 harvests. However, herbicide spray damage (described earlier) caused a sudden, dramatic decrease in production of clover in the control treatment from harvest 6 to harvest 8 (Appendices 5.2.4 and 5.2.5). The percentage of clover in the control treatment decreased from 58% in harvest 4 to 13% in harvest 8. This large decrease did not occur in other soil replacement treatments and therefore was



Table 5.7: Rangitikei trial. Dry matter production ( $\text{kg ha}^{-1}$ ) from four nil-topsoil treatments with different depths of sandy loam. Duncan's Test letters at  $p=0.10$  are given on the RHS of each column of figures.

Treatment	Dry matter production ( $\text{kg ha}^{-1}$ )				
	1	2	3	4	5
Control	184±7 a	3250±1770 a	3030±300 a	1220±120 a	1660±240 a
100C	169±14 b	1400±150 b	310±40 b	1270±80 a	1420±120 b
40C	142±13 c	800±370 b	170±100 b	1060±200 a	1510±150 ab
Fill	92±21 d	1070±500 b	230±190 b	1080±170 a	1460±90 b
Significance	0.0001	0.003	0.0001	0.12	0.24

Treatment	6	7	8	9
Control	290±70 b	1130±230 c	1340±110 b	440±30 a
100C	1820±220 a	1850±210 a	1590±280 a	470±120 a
40C	2130±260 a	1710±220 a	1580±210 a	230±100 b
Fill	2240±750 a	1460±310 b	1430±350 ab	300±50 b
Significance	0.0001	0.0003	0.40	0.009

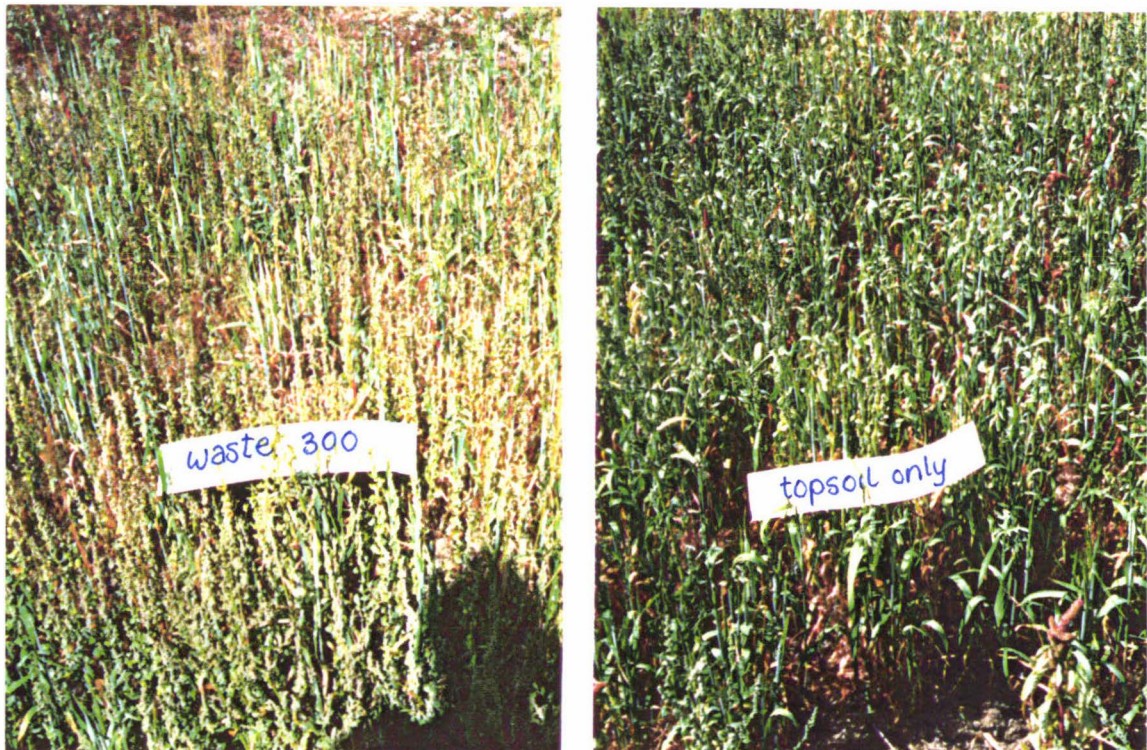
probably linked with the large decrease in dry matter production resulting from the herbicide.

Herbage dissections of five harvests recorded similar pasture compositions in both 100C and 40C treatment plots. Pasture in the nil soil treatment comprised a higher percentage of grass than both the 100C and 40C treatments in three harvests. All three treatments, however, contained similar % of weeds by mass. The 40C and 100C treatments contained significantly more clover than the nil soil treatment and control treatments in 3 of the 4 dissections (Appendices 5.2.4 and 5.2.5).

Measurements of total root length at the end of the trial showed few significant differences between treatments due to the large error associated with the measurements (Appendix 5.2.6). The surface 0 to 50 mm of the fill treatment contained a greater length and mass of roots than the surface 0 to 50 mm of treatments comprising sandy materials. Additionally, the 40C treatment had a greater root length and root mass at 0.10 to 0.15 m depth than both the 100C and control treatments. A trend was the low mass and length and mass of roots in the control and 100C treatments, compared to the 40C and fill treatments indicating that, contrary to expectations, roots had exploited the top 0.25 m fill to a greater extent than the 0.4 and 1.0 m deep sandy treatments (Appendix 5.2.6).



Photograph 5.3: Barley and oats crop growing on two nil-topsoil treatment plots: a "40C", 0.4 m of sandy medium (LHS) and a 100C treatment, 1.0 m of sandy C horizon (RHS). The crop in the 100C plot is noticeable darker green and bushier than the crop in the 40C plot.



Photograph 5.4: Barley and oats crop growing on a "fill" (nil-topsoil) plot of loosened fill (LHS) and a "10A" topsoiled plot (RHS). The fill plot has a high proportion of weeds and barley plants with yellow lower leaves.



### 5.7.3 The effect of mixing horizons and replacing topsoil

In this section some effects of mixing topsoil with soil from other horizons, or separately stripping and replacing soil horizons in their natural order are reported.

#### *Properties of soils*

The particle density of the Rangitikei fine sandy loam was not altered by mixing topsoil and the underlying C horizon. This was because particle densities of the A and C horizon were similar (Appendix 5.3.1), in part due to the low organic matter content of the very young A horizon.

Different soil replacement strategies resulted in rooting media with markedly different total soil carbon contents. Increasing dilution of A horizon material with underlying C horizon material lowered total organic carbon contents (Table 5.8). Mixing the top 0.10 m of the soil profile, for example, resulted in a mean carbon content of 1.74% while mixing the top 0.18 to 0.22 m of the profile resulted in a carbon content of 1.57%.

Table 5.8: Rangitikei trial. Total organic carbon content of soil replacement treatments. Specific soil replacement treatments from which samples were taken are in brackets under "type of medium". Significance = 0.0001.

Type of medium	N	Total % carbon	Duncan's Test (10%)
		Mean and std. dev.	
A horizon (10A)	5	1.74 ± 0.06	a
A horizon (control)	3	1.57 ± 0.10	b
C horizon	6	1.18 ± 0.09	c
Fill	6	1.85 ± 0.15	a

The moisture content of the treatment media at 1500 k Pa suction (permanent wilting point) differed significantly (Appendix 5.3.2) with the fill material having the highest water content (8.0%) due to its higher clay content. Note, however that the figure is determined from sieved, <2 mm diameter, fill samples so that the *in situ* moisture content would be lower. Soil from the Rangitikei C horizon had a significantly lower water content at 1500 k Pa suction than soil from the A horizon which contained more organic matter (Table 5.8 and Appendix 5.3.2).

Cores taken from topsoiled and nil-topsoil treatments had similar porosities at 0, 0.10 and 0.20 m depths at 5 k Pa suction, equivalent to having a water table at a depth of 0.50 m below the soil surface (Appendix 5.3.3). At 10 k Pa suction the topsoiled treatment had a higher porosity than the nil topsoil treatment at both the soil surface and 0.10 m depth (Appendix 5.3.4).

Table 5.9 : Rangitikei trial. Gravimetric moisture content (% by mass) of water held in soil pores of soil replacement treatments at 10 k Pa suction. N = number of cores taken.

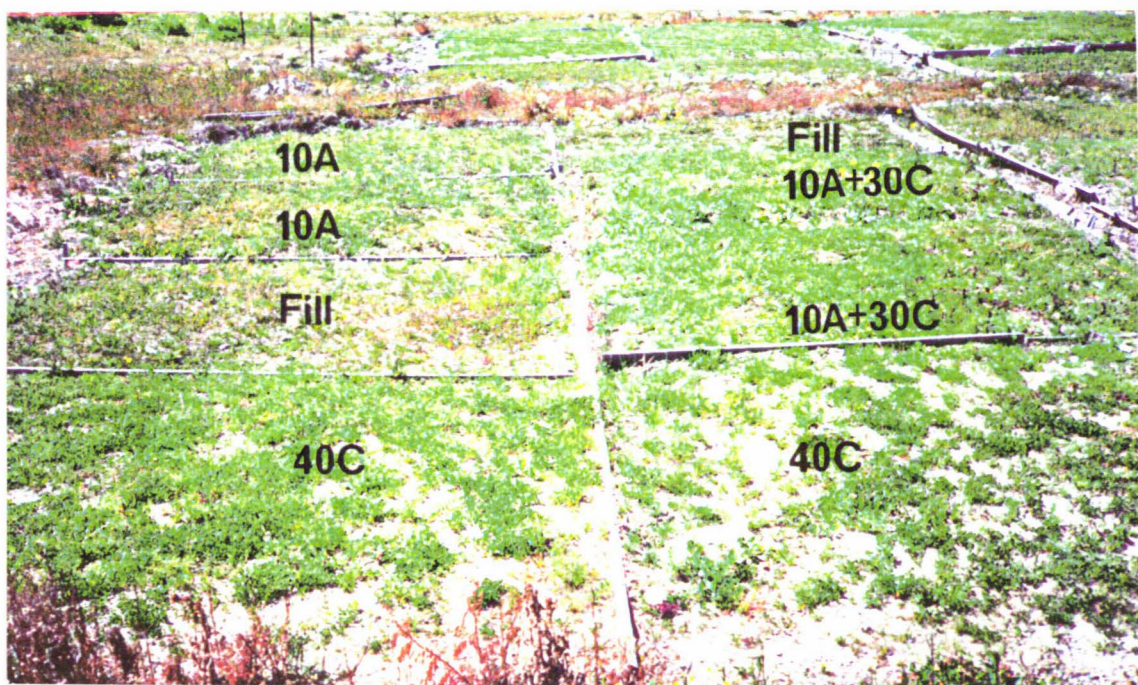
Treatment	Soil depth (m)			
	0	0.1	0.2	0.30
Undisturbed	31.7±0.6 ab	23.0±1.0 b	20.7±0.6 b	20.0±1.0 b
Control	37.0±0.2 a	21.0±1.4 b	20.5±0.7 b	18.0±0.2 b
10A+30C	36.0±1.0 a	27.0±3.6 a	25.3±1.2 a	28.0±1.4 a
40C	32.0±3.0 ab	26.5±0.7 a	23.0±5.7 ab	27.5±0.7 a
100C	30.3±1.3 b	26.3±2.9 a	23.5±0.6 ab	25.5±3.1 a
10A	32.3±6.2 ab	28.3±1.5 a	na	na
Probability	0.08	0.01	0.20	0.02
N	20	17	14	13

Macroporosity, determined from the mass of water retained at 10 k Pa suction, was lower at 0.1, 0.2 and 0.3 m depth in the control and undisturbed treatments than the reclaimed treatments. Macroporosity at the soil surface (0 to 0.05 m depth) was higher in the control and topsoiled treatments than the 100 C treatment (Table 5.4). The high number of roots in the undisturbed soil treatment may have limited full contact between soil cores and the ceramic plates, resulting in the surprisingly low macroporosity of the undisturbed treatment.

Both topsoiled and nil-topsoil treatments had similar water-filled porosities at 0.5 k Pa suction at depths of 0 to 0.2 m. However, at 10 k Pa suction topsoiled treatments retained significantly greater moisture than nil-topsoil treatments in the 0 to 0.1 m deep layer (topsoil horizon)(Appendix 5.3.5).

#### *Pasture dry matter production*

Two treatments with a total depth of 0.40 m of sandy media over fill were examined to determine the effect of replacing topsoil when reclaiming a Recent sandy soil. The topsoiled treatment is coded 10A+30C and the nil-topsoil treatment coded 40C (as specified in Table 5.5). Dry matter production from the topsoiled and nil topsoil treatments were similar in harvests 1 to 5, although the nil topsoil treatment plots took longer to establish a complete vegetative cover. The nil topsoil treatment consistently produced less dry matter than the topsoiled (10A+30C) treatment in the first four pasture harvests with visual differences obvious in the first two harvests in two of the four treatment blocks (comprising four replicates)(Photograph 5.5). Variation in production in the other two blocks masked this difference. In harvest 6 the nil-topsoil treatment produced



Photograph 5.5: Rangitikei trial. Pasture on soil replacement treatments showing poorer establishment and clover-dominated sward on the nil topsoil treatment compared to the topsoiled treatments.

more dry matter than the topsoiled treatment, however this result was reversed in the final two harvests (Table 5.10).

Table 5.10: Rangitikei trial. Dry matter production ( $\text{kg ha}^{-1}$ ) from treatments in which topsoil was replaced (10A+30C) or mixed with 1.5 to 2 m of C horizon (40C). Duncan's Test letters are significantly different at  $P = 0.10$ .

Soil Treatment	Dry matter production ( $\text{kg ha}^{-1}$ )				
	1*	2	3	4	5
Control	180±7 a	3250±1170 a	2030±300	2220±120	2660±240
40C	140±13 b	2000±370	170±90 b	2060±200	2510±150
10A+30C	140±16 b	2000±230	210±110 b	2160±210	2550±140
Significance	0.01	0.01	0.001	0.35	0.40
Soil Treatment	6	7	8	9	
Control	290±70	2130±230	2340±110	440±50 a	
40C	2130±260	2710±280	2580±210	230±100 c	
10A+30C	2480±3870	2730±200	2850±100	340±100 b	
Significance	0.001	0.001	0.01	0.04	

The nil topsoil treatment contained more clover, by dry weight, than the topsoiled and control treatments in 3 of the 4 dissected harvests. Although the percent of grass was consistently higher in the topsoiled treatment, significant differences were only evident in one harvest (Appendix 5.3.6). There was a higher proportion of weeds in the control treatment than either 0.40 m deep soil replacement treatments in 4 of the 5 dissected harvests. Additionally, the percentage of weeds in the topsoiled treatment was consistently higher than in the nil topsoil treatment in four of the five harvests although this trend was only significant in the final dissection (Appendices 5.3.6 and 5.3.7). Results indicate that the number of viable seeds and propagules contained in the stripped topsoil was not a significant factor controlling the % dry matter of weed species. The percentage of weeds decreased over time as pasture became more dense and harvesting removed weeds with upright growth forms (Appendix 5.3.7).

#### 5.7.4 Effect of stripping soil on stone content of soil

When the Rangitikei soil C horizon was stripped, some of the underlying gravels (the aggregate resource) were mixed with the C horizon sands. However, although the stripped C horizon displayed a trend of a higher stone content than unstripped soil at every sample depth, there was no significant increase in stone content of the C horizon sands.

The percentage of stones greater than 5 mm diameter in the fill material varied with depth (Table 5.11) and location of the plot on the trial site, as was expected from the diverse constituents of the fill.

Table 5.11: Rangitikei trial. Volume of stones (%) in undisturbed, stripped and fill media at four depths (m).

Medium	% of stones by volume at specified soil depth (m)			
	0	0.1	0.2	0.3
Undisturbed (control)	0 ± 0	0.1 ± 0.2	0.2 ± 0.3	0 ± 0.1
Stripped horizon (40C)	0.6 ± 0.8	0.6 ± 0.6	0.34 ± 0.4	0.2 ± 0.3
Fill	14 ± 13	45 ± 19	48 ± 14	30 ± 17

#### 5.8 Ohakea trial soil replacement treatments

The Ohakea trial was planted on 7 April 1989 and harvested from September 1989 to June 1991 on dates specified in Table 5.2, Section 5.6. The results of both different depths of soil and soil mixing are presented together, as all the soil replacement treatments were statistically analysed together. To determine the effect of different soil replacement treatments on soil physical



properties and pasture production characteristics, only the low-compaction soil replacement treatments, comprising five of the eight Ohakea treatments, were analysed (Appendix 5.4.1).

#### 5.8.1 Properties of soils

Mixing A and B soil horizons resulted in a media with soil physical properties similar to those of the undiluted B horizon; the same mean particle density was measured for both B horizon and AB mixed media (Appendix 5.4.2). Similarly, the gravimetric soil moisture content at 1500 k Pa suction, often called the permanent wilting point, of mixed AB horizons was similar to that of the undiluted B horizon and significantly less than that of the A horizon (Appendix 5.4.3).

Different soil replacement strategies resulted in rooting media with significantly different total soil carbon contents. Dilution of A horizon material with approximately 0.50 m of underlying B horizon material lowered the mean total soil organic carbon content from 3.75% to 1.87%. Mixing the A horizon to 0.20 m (simulating ploughing) also diluted soil organic carbon content in the surface 0.075 m by an mean 0.58%. This indicates that an organic matter profile had re-established since the ploughing of the paddock less than five years prior to establishment of the trial (Appendix 5.4.4).

Cores excavated from all plots at 0, 0.10, 0.20 and 0.30 m depths showed that most soil replacement treatments had similar bulk densities and macroporosities at these depths (see Appendix 5.4.5 and 5.4.6). The surface of the undisturbed soil treatment was less dense than the surface of the AonB treatment. Soil macroporosity of both control and original treatments was higher than both the AonB and AB mix treatments at 0.10 m depth.

#### 5.8.2 The effect of soil depth on production of above-ground dry matter and pasture composition

During the first five harvests, or establishment period, the Aonly treatment was consistently the poorest performing of all the soil replacement treatments (Appendix 5.4.7). Over the life of the trial the Aonly treatment produced the lowest mass of pasture dry matter or a mass not significantly different from the poorest performing treatment in 12 of the 14 harvests. The control treatment produced more dry matter than the Aonly treatment in 8 of the 14 harvests. Conversely, during the four weeks following seedling germination visual assessments showed that seedlings in Aonly plots germinated earlier and grew taller than seedlings in other treatments.

Herbage dissections performed on two harvests showed that the Aonly treatment contained a higher percentage of clover than the AonB treatment in both harvests. Additionally, in the second dissection the Aonly treatment contained a lower percentage of grasses and weeds than the AonB treatment (Appendix 5.4.8). Although closure (the three categories summed must



equal 100%) indicates that if one category is significantly higher, one or both of the other categories must be significantly less, variability in the latter categories can mean that differences are not significant.

#### 5.8.3 The effect of topsoil replacement on production of above-ground dry matter and pasture composition

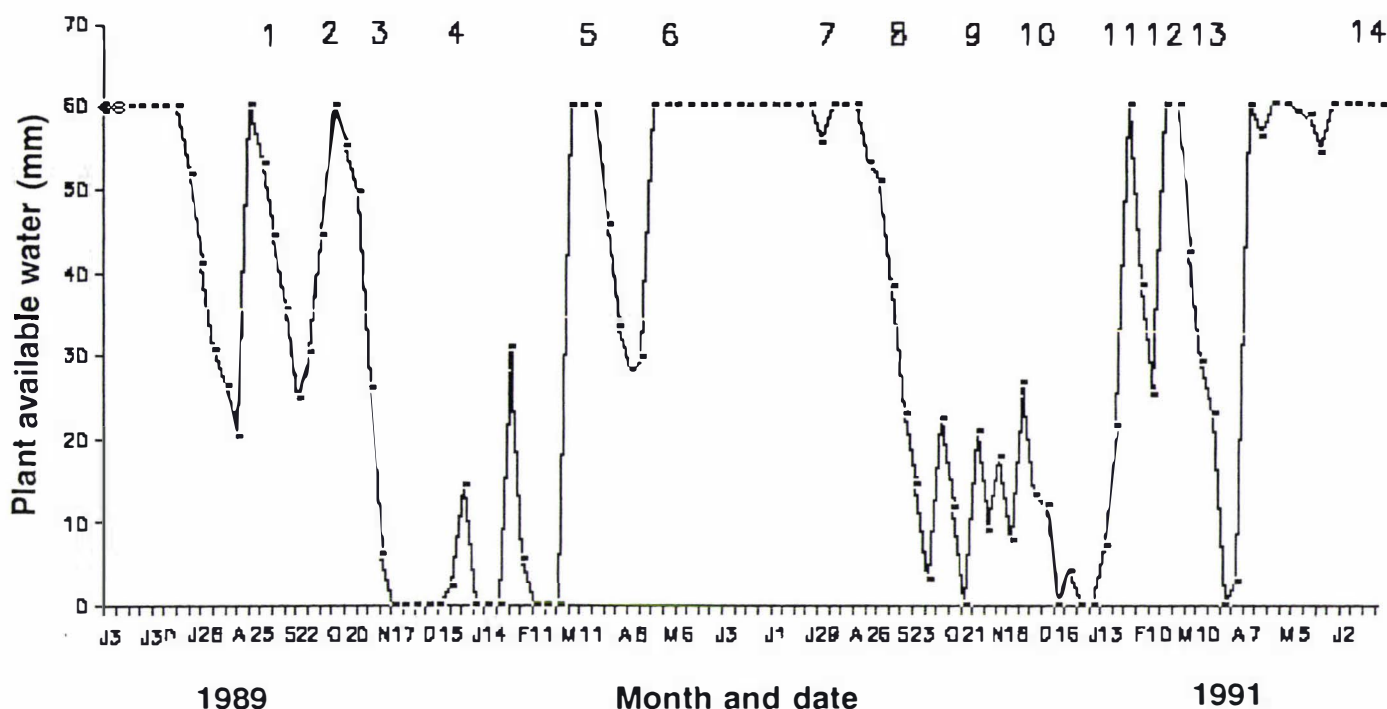
The effect of topsoil replacement was investigated by comparing characteristics of ABmix and AonB treatments. In the first two harvests the ABmix treatment produced significantly less dry matter than the AonB treatment, however, in three quarters of the harvests (9 of 14 harvests) production from both AonB and ABmix treatments was similar (Appendix 5.4.7). With the exception of harvest two, the five harvests in which the AonB significantly outproduced the ABmix treatment (harvests 1,2,7,8 and 14) followed extended wet periods when soil moisture levels were at or above field capacity (Table 5.2 and Graphs 5.1 and 5.5). The control treatment produced more dry matter than the ABmix treatment in 5 of 14 treatments. These results indicate that mixing soil horizons of an Ohakea soil results in decreased production of pasture dry matter in the short term, especially during the establishment period.

Herbage dissection of the first two harvests found that the AonB treatment had higher percentage of weeds in both harvests than the ABmix treatment. This result reflects that the original A horizon contained a greater number of weed propagules than the B horizon material (Appendix 5.4.8).

The effect of radically disturbing the soil profile of Ohakea soils was investigated by comparing treatments where the soil profile was stripped to 0.7 m (AonB and ABmix) with the control treatment in which only the top 0.20 m of the profile was disturbed. The control (simulated ploughing) treatment was consistently among the highest producing treatments. It was one of the top two producing treatments in 13 of 14 harvests (excluding the undisturbed treatment)(Appendix 5.4.7). However, the control treatment produced the same or less dry matter than the AonB treatment for 13 of 14 treatments. This indicates that, provided the soil horizons are replaced in order, pasture productivity will not be significantly decreased.

#### 5.8.4 Characteristics of pasture roots

Root mass and root length results were characterised by large standard deviations due to the small number of replicates and wide variation between treatment replicates. All soil replacement treatments had similar root masses. The AB mix treatment showed a trend of lower root masses in the surface, 0.20 and 0.30 m depths than the other soil replacement treatments (Appendix 5.4.9).



Graph 5.5: Ohakea trial. Plant available soil moisture (mm) and times of harvests for a soil with 60 mm total plant available soil moisture in the surface 0.35 m. Climatological data from AgResearch (DSIR), Palmerston North.

Results of root length measurements were less subject to wide variation. Root lengths of all treatments at 0 to 0.05 m and 0.10 m soil depths were statistically similar. At 0.2 m depth the control and Aonly treatments had significantly greater total root length than the ABmix and undisturbed treatments (Appendix 5.4.10). The undisturbed treatment was characterised by shorter roots at 0.30 m depth (although not significantly) than the control treatment. This may indicate that bulk densities in the topsoil of the control treatment were limiting root proliferation.

#### 5.8.5 Concentrations of nutrients in soil and pasture

Total soil nitrogen (N) and phosphorus (P) levels were similar for all Ohakea soil replacement treatments (Table 5.11) in August 1989, indicating that soil fertility levels of these plant macronutrients were unlikely to be contributing to differences in pasture dry matter production at this time.

In October 1989 clover and grass samples dissected from each plot were analysed for total nitrogen and phosphorus. There was no difference in levels of total nitrogen or total phosphorus in ryegrass between soil replacement treatments (Appendix 5.4.12). Total nitrogen and phosphorus contents in clover differed between some treatments. In some soil replacement treatments total nitrogen levels in clover were greater in the undisturbed soil treatment than the other soil replacement treatments. Additionally, total nitrogen levels in clover were lower in AonB



Photograph 5.6: Ohakea trial. Pasture on ABmix (LHS) and AonB (RHS) soil replacement treatments prior to the first harvest. Pasture on the AB mix plot is more sparse. White tags mark the position of permanent TDR probes.

Table 5.12: Ohakea trial. Soil nutrient concentration ( $\text{g/m}^3$ ) means and standard deviations on 17 August 1989. Duncan's Test letters are on the right hand side of each column.

Soil Replacement Treatment	N	Soil nutrient concentration ( $\text{g/m}^3$ )	
		Nitrogen	Phosphorus
AB mixed	4	$35.9 \pm 9.2$ a	$270 \pm 34$ a
A only	4	$31.6 \pm 3.4$ a	$268 \pm 26$ a
Undisturbed	4	$38.0 \pm 2.3$ a	$283 \pm 14$ a
Control	4	$31.6 \pm 7.6$ a	$250 \pm 31$ a

treatment than in the ABmix treatment and clover total phosphorus levels were lower in the AonB treatment than the Aonly treatment (Appendix 5.4.1†).

### 5.9 Ashhurst trial soil replacement treatments

The Ashhurst trial was harvested on nine occasions from April 1989 to September 1990 (Table 5.13). The harvest dates shown in Table 5.13 are used throughout Chapters Five and Six in reference to Ashhurst harvest numbers. Results of mixing soil horizons and replacement of

topsoil at the Ashhurst trial are presented together due to the small number of analyses and consistency of the results.

Although mixing A and B horizons resulted in a significant reduction in the amount of moisture held in the soil at both 1500 k Pa (when plants permanently wilt) and 100 k Pa (assessed as the point when plants become stressed), the effect on the plant available moisture between these levels was not large (Table 5.14).

Table 5.13: Dates on which the Ashhurst trial was harvested.

Harvest	Date of harvest	Harvest	Date of harvest
1	14 April 1989	6	5 December 1989
2	26 May 1989	7	20 March 1990
3	5 July 1989	8	May 1990
4	23 September 1989	9	20 September 1990
5	4 November 1989		

Table 5.14: Ashhurst trial. Percentage of water retained in soil pores of A horizon and diluted A horizon at applied suctions of 1500 and 100 k Pa. The number of samples used in each analysis is in brackets on the RHS of each column.

Media	% soil moisture at applied suction (k Pa)	
	1500	100
A horizon	35.4 ± 5.1 (4)	23.2 ± 3.5 (5)
A and B horizons mixed	25.4 ± 2.3 (4)	16.2 ± 0.8 (3)

Mixing Ashhurst soil A and B horizons did not deleteriously affect pasture dry matter production. The control treatment outproduced both soil replacement treatments in only one harvest and there was no significant difference between the ABmix and AonB treatments in any harvest. Similarly, there was no effect on production attributable to increased depth of Ashhurst soil with similar dry matter production generally recorded from both Aonly and AonB treatments. In Harvest 8 the AonB and control treatments outproduced the Aonly treatment. Herbage production of the control treatment was generally the same as other soil depth treatments and significantly greater than the shallowest treatment in two of the nine harvests (Table 5.15).

Table 5.15: Ashhurst trial. Pasture production (kg ha<sup>-1</sup>) from soil replacement treatments. A key to the treatments is in Figure 4.13. Duncan's test at p=0.10 letters are on the RHS of each column.

Soil Treatment	Dry matter production (kg ha <sup>-1</sup> )				
	1	2	3	4	5
Undisturbed	1560±210 a	1760±100 a	1130±210 a	1560±450 b	1940±270 a
Control	1730±520 a	1420±240 b	970±80 a	2145±310 a	2170±300 a
ABmix	1290±350 a	1380±250 b	1010±130 a	1710±310 b	2365±300 a
AonB	1200±70 a	1410±350 b	1020±60 a	1810±70 b	2140±180 a
Aonly	1530±870 a	1220±220 b	910±30 a	1940±290 b	1830±500 a
Significance	.59	.03	.66	.16	.68

Soil Treatment	6	7	8	9
	Undisturbed	2150±150 a	2330±570 a	2310±710 a
Control	1580±460 a	3330±620 a	2690±540 a	460±70 a
ABmix	1910±530 a	2930±600 a	1760±410 ab	490±90 a
AonB	1860±420 a	3060±630 a	2370±130 a	400±90 a
Aonly	1790±740 a	2550±500 a	1100±150 b	420±170 a
Significance	.89	.50	.15	.96

NOTE 16 plots are used in each harvest analysis with n=32, 48 or 64 depending on the number of samples cut from each plot.

When individual soil replacement treatments were placed in order of productivity for each harvest (Appendix 5.5) the Control treatment and undisturbed treatment were seen as one of the two most productive treatments in 6 of the 9 and 5 of the 9 harvests respectively. The shallow, Aonly treatment was consistently one of the two lowest producing treatments (7 of the 9 harvests).

Volumetric moisture content, as measured by time domain reflectometry, was correlated with yield from each harvest to see if the two harvests in which the control treatment outproduced the Aonly treatment were correlated with moisture contents. The correlation analysis identified a significant positive correlation (at a significance level of 0.10) in three harvests.

These were not the same harvests in which significant differences in pasture production occurred (Appendix 5.5.2) so that, although differences in soil moisture content and pasture production occurred at the same time in individual plots, there was no significant effect determined for pasture production between treatments.



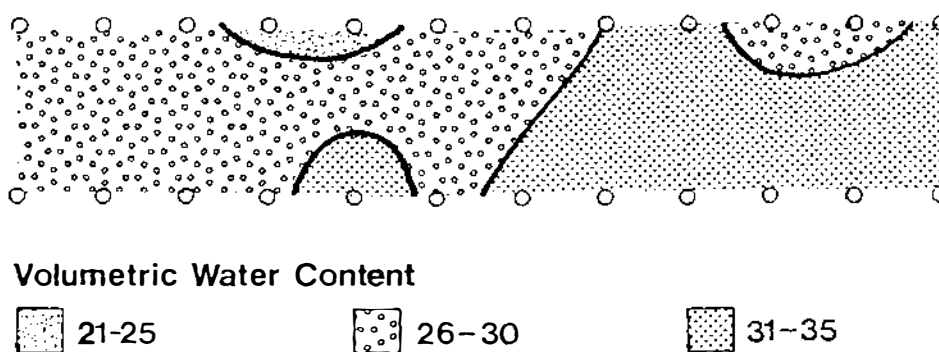


Figure 5.2: Ashhurst trial. Volumetric water content of soil in each plot measured with a TDR using 150 mm probes (mean of 4 measurements per plot). Changes in soil moisture content reflect changes in soil texture across the trial site.

In all harvests variation between plots of one treatment was high, as shown by large standard deviations (Table 5.15). Variation of soil texture within the trial site may have contributed to the variation in dry matter production. Soils at the northern end of the trial were drier than those at the southern end of the trial and two bands of soils with 5 to 10% elevated volumetric soil moisture content ran across the trial block (Figure 5.2).

## 5.10 Discussion

### 5.10.1 Soil depth

#### *Rangitikei trial*

The barley and oats crop showed a dramatic response to increasing depth of soil. Significant increases in yield corresponded with each incremental increase in total soil depth for both topsoiled and nil-topsoil treatments. This result contrasted with the relationship between soil depth and production of pasture dry matter. In nil-topsoil plots there was no significant difference in production of pasture from 0, 0.40 and 1.0 m deep treatments in 6 of the 8 harvests. Additionally, pasture production from the third and subsequent harvests of both nil-topsoil and 0.1 m deep topsoiled plots was similar. Pasture production from nil-topsoil 0.40 and 1.0 m treatments was also similar for all eight harvests. These results indicate that the ripped fill medium, despite its widely variable constituents, is capable of producing quantities of pasture dry matter not significantly different to that produced by any depth of Rangitikei fine sandy loam C horizon.

It is improbable that the presence of topsoil conferred increased sensitivity of pasture to increases in soil depth, as production from topsoiled plots with total soil depths 0.10 and 0.40 m was similar for nearly all harvests of pasture. The barley and oats crop may have been more

sensitive to total depth of soil due to a larger root system and greater sensitivity to moisture deficits at critical times of their growth period. The responses were accentuated due to growth over a period of soil moisture deficits (summer) and non-limiting levels of major plant nutrients in the soil. Thus root exploration was restricted by proximity of the compacted fill material (although pasture roots were able to exploit it) in treatments with total depths of applied media of 0, 0.10 and 0.40 m.

The control treatment (c. 1.5 m deep) outproduced the nil-topsoil treatment in 5 of 9 harvests. The control plot was not a perfect comparison for determining the effect of increased soil depth of topsoiled plots as the "topsoil" had been diluted by mixing to a depth of 0.15 to 0.20. Additionally, the Rangitikei C horizon used to construct the 0.40 m deep treatments would have had different water retention characteristics, as the C horizon of the control treatment comprised laminar layers of sands and silts of contrasting textures, while no layering occurred in replaced soils. Laminar layers increase the amount of plant-available moisture, as reported by Webb (1989) for sandy layers in alluvial soils in Canterbury. I anticipate that a 1 m deep treatment with 0.1 m of topsoil spread on top would have been more productive than the control treatment, especially during pasture establishment, although water perched in the control would give greater long term production provided regular additions of fertiliser were maintained. A reclaimed soil profile with layers of compaction or adjacent media with contrasting textures could be enable maintenance of the original productivity.

Research in Taranaki, Wellington and Canterbury has shown that pasture can abstract large quantities of water from up to 1.8 m below the soil surface, where favourable rooting conditions are present (Webb, 1989) and that this moisture may be important in maintaining pasture growth during dry periods. I would predict, therefore, that greater applied depths of soil would benefit both production and survival of pasture during extended periods of moisture deficit. Additionally, a greater depth of applied soil will give greater trafficability during wet periods when water perches on top of the compacted fill. In summary, I would advise 0.30 to 0.40 m of free-draining material be placed on the fill to aid pasture survival and flexibility of management decisions.

Herbage composition of pasture was unaffected by soil depth. Herbage composition of topsoiled 0.10 and 0.40 m deep treatments were similar; likewise the composition of nil topsoil 0.40 and 1.0 m deep treatments was similar, as expected given the similar weed burden and similar proximity to sources of windblown seeds. Pasture of the fill (nil soil) treatment generally comprised a higher proportion of grass than both topsoiled treatments and nil-topsoil treatments covered with Rangitikei soil. The fill may provide an inhospitable environment for nodulation of clover, either chemically (through constituents in the clay fraction), or physically as the clover roots may not be as proficient at exploiting dense substrates.



*Ohakea trial*

The shallow Aonly treatment of the Ohakea trial produced significantly less pasture dry matter than the AonB treatment in 4 of the first 5 harvests. The Aonly treatment was also consistently the poorest performing treatment, or the same as the poorest performing treatment in 12 of the 14 harvests. However, during the first four weeks following seedling germination, seedlings in A only plots germinated earlier and grew taller than seedlings of other treatments. This precocious early performance and consistently poor later performance of was probably not only due to the shallow depth of soil. The A only treatment created shallow 0.5 m deep holes; the holes probably conferred cooler surface temperatures (decreasing water loss through evapotranspiration) and shelter from the wind. Both factors would have been advantageous to seedling establishment, which occurred at during a dry period. Two measurements taken in early spring showed that the water table was significantly shallower on the A only treatments by a mean 0.19 m. Additionally, on six of seven measurement dates soil volumetric moisture contents were higher in the Aonly treatment than the AonB treatment in the surface 0.15 m. Therefore, although the soil moisture and temperature conditions were probably conducive to early germination and growth of pasture seedlings, once roots had started to extend throughout the soil the restricted rooting depth, due to poor penetration into the gleyed lower B horizon, and periods of low aeration, due to the elevated moisture status, resulted in pasture growth being limited compared to the AonB and control treatments. The Aonly treatment only exceeded the production of the ABmixed and control treatments during periods of moisture deficit, when the increased soil moisture was advantageous to growth of pasture.

*Ashhurst trial*

There was no reduction in pasture production associated with Aonly plots at the Ashhurst trial. Given the thin topsoil, low percentage of clay and gravelly nature of the Ashhurst B horizon, removing the B horizon would not have significantly reduced the amount of moisture or nutrients available for plant growth. Additionally, the low bulk density of the soil means that the volume of soil able to be exploited by the roots for moisture and nutrients would not be decreased by removal of the B horizon.

In all three trials the effect of a reduction in rooting volume (Rangitikei trial) or reduction in capacity of the soil to store plant available moisture (Ohakea and Ashhurst trials) associated with replacing only 100 mm of topsoil (Rangitikei) or removal of the B horizon (Ohakea and Ashhurst) could potentially be offset by perched water tables. The low hydraulic conductivity of the fill and lower B horizon of the Rangitikei and Ohakea trials respectively, restricted drainage of water through the base of the soil profile. In the Ashhurst trial an abrupt change in texture from topsoil to coarse sandy gravels would also form a barrier to deep percolation of water.

### 5.10.2. Mixing horizons and replacing topsoil

#### *Rangitikei trial*

The higher total organic carbon content of the stripped Rangitikei topsoil influenced the water retention characteristics, so that topsoil comprised more water-filled pores than the subsoil (C horizon material) at 1500 and 10 k Pa suction. Although I expected topsoiled treatments to be more productive in the first harvests because of the more favourable moisture supply, both topsoiled and nil topsoil treatments produced similar yields in harvests 1 to 5. The difference in water holding capacity held in surface 0.15 m of profile between topsoiled and nil-topsoil treatments was calculated to be c.3 mm, or one day of evapotranspiration in spring. This was not great enough to result in significant differences in pasture production. The water holding capacities were calculated using values of moisture held at 1500 k Pa and 10 k Pa, assuming that values measured at 0-20 mm were consistent to 100 mm, and values measured at 100-120 mm were consistent to 150 mm depth, i.e.:

$$10A+30C \text{ (topsoiled)} = (.360-.064)*0.10 + (.270-.064)*0.05 = 40 \text{ mm}$$

$$40C \text{ (nil topsoiled)} = (.340-.057)*0.10 + (.238-.057)*0.05 = 37 \text{ mm}$$

The nil-topsoil treatments showed a trend of marginally lower productivity in each of the first five harvests. The visibly sparser vegetation on the nil topsoil plots must have experienced less competition, allowing compensatory growth leading to larger individual plants.

The proportion of weeds in topsoiled treatments was consistently higher, but not significantly higher, than in nil-topsoil treatments in the first four harvests. The proportion of weeds in a sward is a function of the number of viable weed propagules in the soil and the competitiveness of other species. The result indicates that only a small number of weed propagules was present in the topsoil (which was in pasture) and/or the environment was unfavourable to establishment of weed seedlings. The proportion of weeds in the sward decreased over time as weeds were mown out and the pasture developed a dense sward which shaded the soil surface. This suppresses the germination and establishment of weed seeds. The percentage of clover was higher and percentage of grass lower, in the nil topsoil treatment in 3 of 4 dissected pasture harvests. This may indicate that the nitrogen status of C horizon was lower than that of the topsoiled treatment, i.e. that fertiliser applications were not frequent enough, given the high leaching potential of the sand.

#### *Ohakea trial*

In three quarters of the harvests of the pasture production from ABmix and AonB treatments was similar. Significant pasture excesses were produced by the AonB treatment in early to late spring. Pasture surpluses from June to mid September (4 of 5 harvests where significant differences occurred) have a higher value because pasture growth through this period greatly

influences the carrying capacity of a farm and the timing of calving and lambing. Pasture is of reduced value if the number of days that it can be grazed without damage to the soil are few. Throughout the trial period the Abmix treatment was less firm, thus more susceptible to physical damage than other treatments. In a commercial reclamation, where pasture is grazed by animals, utilisation of pasture grown on the Abmix treatment would have <sup>been</sup> restricted. This further reduces the value of pasture produced by the Abmix treatment.

Mixing Ohakea A and B horizons together resulted in a medium with half the total organic carbon content of an undiluted A horizon. The lower organic carbon content and trend of lower root mass in the surface 0 to 50 mm soil depth also reduce the resilience of Abmix treatments to pugging. Soil physical properties of the Abmix medium were similar to those of an undiluted B horizon.

I had expected the Ohakea AonB treatment to produce more pasture than the control treatment as the AonB treatment should have more favourable physical conditions for root extension in the AonB treatment below 0.25 m. Complete disruption of the B horizons would have increased the hydraulic conductivity (drainage and aeration) and lowered soil bulk density. However the AonB treatment and control produced similar masses of pasture in 12 of the 14 harvests, with no seasonal pattern or overall trend in production between the two treatments.

#### *Ashhurst trial*

Mixing the A and B horizons of an Ashhurst soil did not deleteriously affect dry matter production of pasture. The Ashhurst soil was similar to the Rangitikei soil; both soils have low levels of topsoil organic matter and subsoils are free-draining with no major impediments to root extension. Thus "loss" of the A horizon by dilution with the underlying horizon has no marked effect on pasture production, however the increase in stone content of the surface horizon will increase wear on tillage implements, and may thus prevent annual cropping of such soils.

### **5.11 Conclusion**

Increased depth of sandy media sourced from a Rangitikei fine sandy loam on compacted fill material resulted in increased production of barley and oats grown during a period with frequent moisture deficits. However, replacing sandy material on compacted fill was not advantageous to production of ryegrass and clover pasture for most harvests as pasture roots were able to exploit the fill material for water. Depressed yields of pasture was associated with placement of 0.20 m of topsoil on a gleyed, dense lower B horizon following removal of 0.5 m of B horizon from the Ohakea soil. Significant reductions in yield probably reflected the lower aeration and increased concentration of plant toxins, including soluble metal ions and gases, in addition to a reduced volume of soil available for root exploitation. When the same soil replacement

treatment was applied to a free-draining, stony Ashhurst soil, yield of pasture was unaffected. This result reflects the lack of impediment to root extension in the Ashhurst subsoil.

The implications of these findings to the depth of replaced soil which is required on reclaimed sites to maximise pasture production are:

- i) Replace sandy media on fill sites. To maintain pasture productivity no sand need be applied, however the pasture produced may not be able to be utilised due to the low hydraulic conductivity of the fill material which increases susceptibility of the "soil" to damage from traffic and animals.
- ii) Replace A and upper B horizons of Ohakea soil. Remove the lower B horizon entirely, if practical.
- iii) Replace only the topsoil of an Ashhurst soil.

Dilution of topsoil resulted in levels of total soil organic carbon and particle densities being lowered to levels similar to unmixed subsoil. Diluting topsoil by mixing it with subsoil had no long-term detrimental effects on any of the three soils trialed. The separate stripping and replacement of topsoil aided establishment of pasture on Ohakea soils (a statistically significant result) and Rangitikei soils, although the latter result was not statistically proven. This effect was most likely due to greater amounts of plant-available moisture, warmer temperatures and possibly minimal toxicity of the Ohakea topsoil. Topsoil replacement may have aided pasture establishment by decreasing surface crusting and a providing a higher number of sheltered microclimates.

The implications of these findings to the soil replacement strategy which is required on reclaimed sites to maximise pasture production are:

- i) Separately strip and replace Ohakea horizons in order to maximise the speed of pasture establishment, management flexibility and production of valuable late winter-early spring pasture.
- ii) No advantage is gained from separately stripping Ashhurst soils

## Chapter Six Compaction and Soil Water

### 6.1 Introduction

Reclamation after surface mining has often resulted in compacted and poorly drained soils and major alterations of drainage patterns. Concern about soil compaction is a fairly recent phenomenon in the mining industry (Swiegard, 1990), however, the adverse effects of compaction have long been recognised as a widespread problem on arable land (McKibben, 1971; Gupta and Allmaras, 1987; Swiegard, 1990). The most widespread and serious consequence of compaction is restricted root growth (Hakansson *et al.*, 1988, Widdowson and McQueen, 1990) which may reduce plant yield and persistence (Figure 6.1). Compaction of subsoils is particularly serious since it can last for long periods as natural amelioration of subsoil compaction is limited (Gameda *et al.*, 1985).

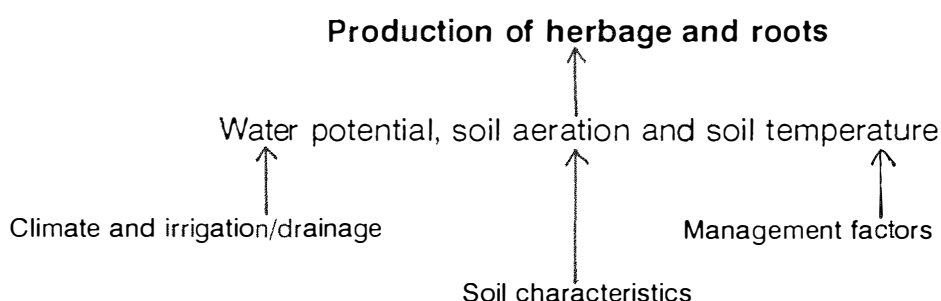


Figure 6.1: Soil physical factors which affect production of plant roots and herbage.

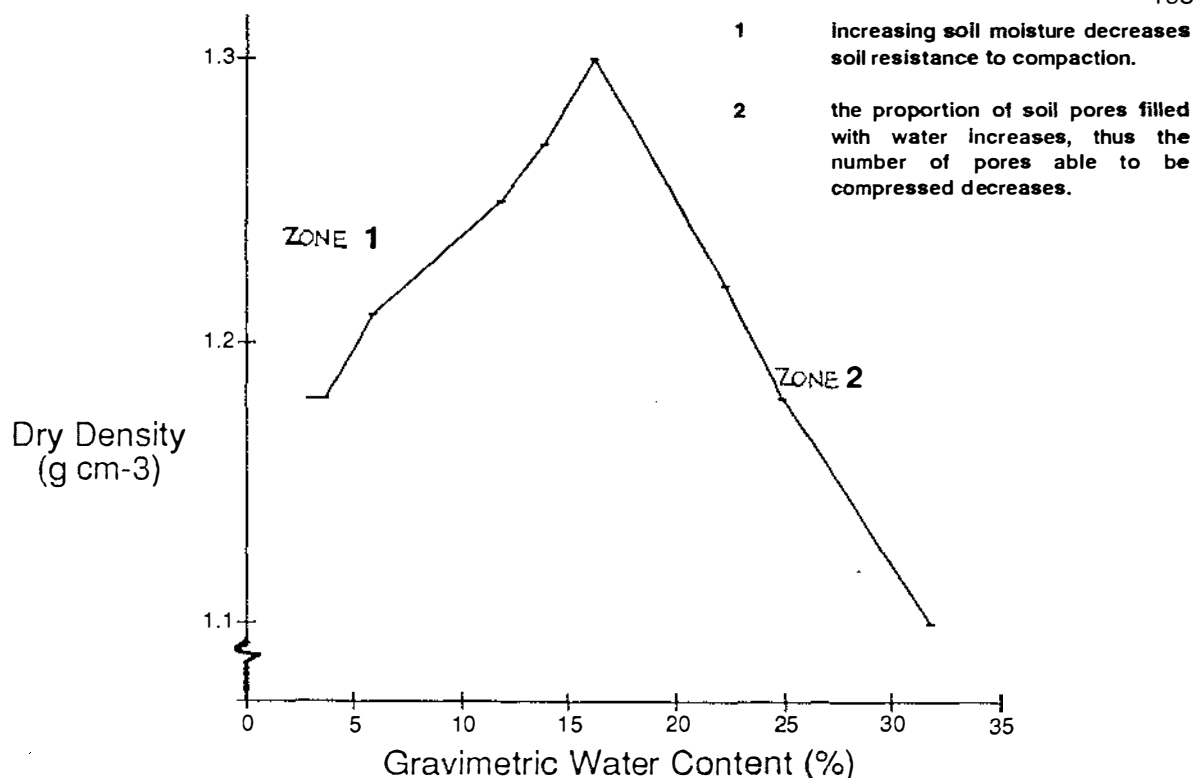
Compaction and drainage status are often inter-related, as compacted layers impede water flow into and through the profile of restored soils, and poorly-drained soils generally have increased sensitivity to compaction. Additionally, many effects of soil compaction are similar to those associated with poor internal drainage as both may influence the moisture content, or water potential, of soil, albeit by different mechanisms. Compaction primarily influences soil moisture status through changing the size, number and continuity of soil pores while drainage directly lowers the moisture content of soil. In this review the mechanisms of these impacts are outlined. Soil water potential is the dominant factor influencing plant growth, both by itself and through influencing soil mechanical resistance, temperature and soil oxygen concentration and diffusion rate. The influence of compaction and drainage on the above factors, their interrelationships, and positive and negative effects on plant germination, growth, and crop yield are presented in this review.

## 6.2 Literature review of compaction with an emphasis on reclaimed soils.

Compaction in reclaimed soils is usually present as horizontal laminations or discrete compact layers at several depths in the soil profile (McRae, 1983; Evans *et al.*, 1986; Moran *et al.*, 1989) created by movement of soils with scrapers and other heavy machinery (Buckley, 1978; Younger, 1989). Haigh (1992) reported that particles formed from breakdown of exposed mine-stones filled up surface pores with fine particles, resulting in an increase in bulk density. Compaction is also commonly associated with soil moving or cultivating machinery and post reclamation land management. Surface crusts or seals on some soils are formed by a layer of fine particles created from breakdown of aggregates by raindrops or chemical dispersion. Rainfall may also wash dispersed clay just below the soil surface to form a high density, low permeability layer. Compaction of reclaimed soils is exacerbated by dilution or loss of soil organic matter and the use of raw mineral media (Raghavan *et al.*, 1990).

Compaction can be defined as a reduction in the total volume of a given mass of soil (Harris, 1971; McKibben, 1971; Raghavan *et al.*, 1990). Compaction takes place when external pressures are greater than soil bearing capacity and shear strength (Gameda *et al.*, 1985). The effect of a defined compactive force on soil changes with soil moisture content (Graph 6.1). Generally a soil displays decreased resistance to an applied stress with increased moisture content (Hakansson *et al.*, 1988) (Graph 6.1), i.e. dry soil is more resistant to compaction than moist soil (McRae, 1989). Akram and Kemper (1979), for example, showed that applying a compactive force of 0.346 M Pa to sandy loams and finer textured soils at field capacity reduced water infiltration rates to less than 1% of values obtained after these soils have been compacted when air dry. As the soil moisture content increases, the resistance of soil pores to shear forces decreases, leading to destruction of pores (Graph 6.1, Zone 1). Large pores are generally less resistant to shear forces than small pores. As the moisture content of the soil increases further, the pore volume available to be compacted is reduced because water is incompressible and soil bulk density decreases (Graph 6.1, Zone 2). When a soil is saturated no air pores are present to compress, thus no more air can escape from the soil and compaction stops (Hakansson *et al.*, 1988). Compactive forces do damage saturated soils, however (Koolen 1987), as at high moisture contents deep wheel penetration or rutting and sideways displacement of soil occurs (Raghavan *et al.*, 1990).

The response of a defined volume of soil to a compactive force is influenced by soil texture (Koolen, 1987; Sweigard, 1990). Finer textured soils display maximum compaction at higher moisture contents than coarse soils and this effect is exacerbated as fine textured soils tend to have higher moisture holding capacities (Raghavan *et al.*, 1990). The effects of compaction are greater in silty soils than sandy soils (Slowinska-Jurkiewicz and Domzal, 1991). Gupta and Allmaras (1987) reported that the susceptibility of soils to compaction increased as soil clay content increased to 33% and then became constant. Similarly, Henderson *et al.* (1988) found that the presence of coarse sand or clay in a soil increased the maximum bulk density that could be achieved with a standard compactive effort. They hypothesised that soils with clay contents



Graph 6.1: Proctor compaction test for Rangitikei fine sandy loam. Increasing soil compaction (dry bulk density) is graphed against soil gravimetric water content to illustrate the main stages of compaction.

below 10% were less susceptible to compaction because they contained few particles small enough to fill voids between large particles.

The response of a defined volume of soil to a compactive force is also influenced by the mass of the compacting load and history of soil compaction (Sweigard, 1990). The first compaction of an uncompacted soil generally results in a much greater change in bulk density and porosity than subsequent compactions. Effects of compaction can be cumulative as increased moisture content can lead to increased soil damage and loss of free draining macropores in a perpetuating cycle (Gradwell, 1960).

The level of soil organic matter (carbon content) influences the response of soil to compactive forces (Hakansson *et al.*, 1988; Howard *et al.*, 1981 *cited by* Gameda *et al.*, 1985). Soane (1975) found that the maximum bulk density of a soil attained by the Proctor test was negatively correlated with the amount of readily oxidised organic matter in a soil ( $r^2=0.52$ ). Organic matter binds between particles and within aggregates (Soane, 1975). A high organic matter content restricts <sup>the</sup> decrease <sup>in</sup> soil volume upon compression and increases soil elasticity or resilience (Koolen, 1987). Organic matter is effective at reducing the effect of compaction in sandy soils (Koolen, 1987) and soils with high water contents (Soane, 1990). High organic matter contents increase the moisture content at which maximum compaction occurs (Ohu *et al.*, 1986 in



Raghavan *et al.*, 1990). The plastic and liquid limits of a soil are also closely linked with soil organic matter content (Soane, 1975; Soane, 1990).

### 6.2.1 Effect of compaction on soil physical properties

Compaction can be described in terms of changes in soil physical characteristics. Soil compaction primarily affects soil porosity and soil strength. Soil strength is commonly measured indirectly by dry bulk density and directly by penetration resistance or field assessment as part of describing a soil profile. Compaction increases soil bulk density by increasing the number of soil particles occupying a defined space (McQueen and Ross, 1982; Becher, 1985; Evans *et al.*, 1986; Widdowson and McQueen, 1990; Leslie, 1990). Soil strength is one of the few soil characteristics that directly influences plant growth (by limiting root extension). Changes in bulk density and pore size distribution indirectly affect plant growth by influencing relationships between soil moisture, aeration, mechanical resistance and temperature (Letey, 1985).

#### *Soil strength and soil density*

The strength (or mechanical resistance) of a specific soil at a specific moisture content usually increases with increasing soil bulk density (Chancellor, 1971; Greacen and Sands, 1980; McQueen and Ross, 1982; Asady and Smucker, 1989). Penetration resistance also increases with increasing compaction (Hammel, 1988). At all water contents, increased bulk density is related to increased penetration resistance (Henderson *et al.*, 1988). Soil structure can be changed by compression, particularly under wet conditions when soil aggregates are weaker. Compaction results in an increase in the percentage of large or coarse aggregates (McQueen, 1983; Bakken *et al.*, 1987; Dexter, 1988; Hakansson *et al.*, 1988) and formation of dense structural units in clay soils (Department of the Environment *et al.*, 1988). Severely compacted soil may become structureless with few pores and smooth ped faces (Raghavan *et al.*, 1990).

#### *Soil porosity*

One of the most important effects of compaction is reduction of the volume of soil macropores (Figure 6.2). This influences plant productivity by altering soil oxygenation and moisture storage characteristics. Compaction lowers soil total porosity (Harris 1971; Freitag 1971; McRae 1983; Evans *et al.*, 1986; Hakansson *et al.*, 1988) particularly lowering the number and volume of macropores (Figure 6.2) (Gradwell, 1960; Warkentin, 1971; Reeve *et al.*, 1973; Greacen and Sands, 1980; McQueen and Ross, 1982; Koolen, 1987). Macropore continuity is also reduced by compaction (Soane *et al.*, 1981; Asady and Smucker, 1989; Agrawal, 1991). Grable (1971) reported that continuity of surface vented macropores was likely to be broken when soil macroporosity was lowered to less than 10%. Reduced macroporosity decreases the rate of water infiltration into soils (Flocker, 1964; McQueen, 1983; Sims *et al.*, 1984; Van Es *et al.*, 1988; Hodgkinson, 1991) because large continuous pores are the primary drainage routes

in saturated soil (water flow in a circular pore is proportional to the cubed radius of the pore). The rate at which ponded water drains through soil, or saturated hydraulic conductivity, is lower in compacted soils (Becher, 1985; Department of the Environment *et al.*, 1988; Hammel, 1988; Agrawal, 1991). Increased water ponding on the soil surface due to low infiltration rates may elevate surface run off and erosion (Greacen and Sands, 1980; Ross and Widdowson, 1987; Voorhees, 1987; Hakansson *et al.*, 1988).

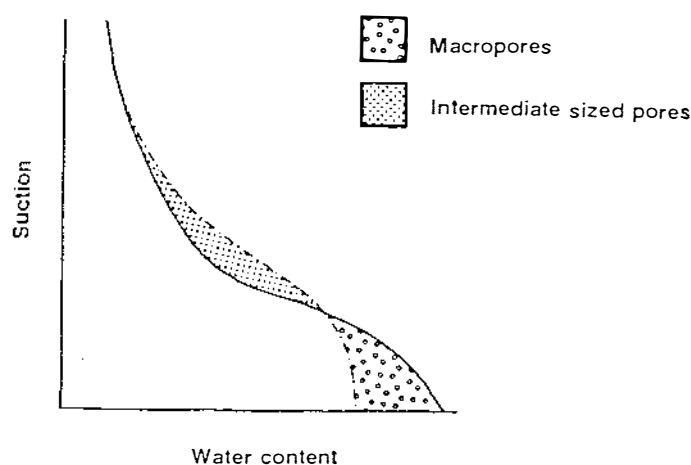


Figure 6.2 Schematic graph of the distribution of pore sizes of a soil before (—) and after (- -) application of a compactive force (from Hillel, 1971). The volume of large pores is smaller in a compacted soil.

The number of small pores less than  $0.2\mu\text{m}$  increases as large pores spaces are reduced or eliminated (Figure 6.2)(Warkentin, 1971; Becher, 1985; Asady and Smucker, 1989). Soane *et al.* (1981) reported, however, that small pore volume remained unchanged, while Potter *et al.* (1988) reported that the volume of pores between 4.5 and  $0.1\mu\text{m}$  radius was unchanged following compaction. These results may be due to compaction eliminating a number of small pores equivalent to the number of new micropores formed from collapse of macropores.

Compaction may increase or decrease unsaturated hydraulic conductivity depending on its impact on the number and continuity of micropores (Hakansson *et al.*, 1988) although unsaturated hydraulic conductivity is generally less affected by a decrease in total porosity than saturated hydraulic conductivity (Warkentin, 1971; Greacen and Sands, 1980). Laminar smearing, for example, disrupts pore continuity thus preventing water movement through the affected zone. Decreased hydraulic conductivity associated with compaction has resulted in impeded drainage and seasonal waterlogging (Ross and Widdowson, 1987; Department of the Environment *et al.*, 1988; Sweigard and Saperstein, 1991). In wet climates impeded drainage may induce saturated upper soil horizons which are more susceptible to damage by stock and machinery (Horne, 1985). In dry climates, however, impeded drainage associated with compaction is beneficial where it reduces losses of nitrogen fertiliser through leaching and losses of water from a soil profile by deep percolation (Agrawal, 1991). Where compaction results in

an increase in medium-sized pores, which govern the rate of water movement through soil in unsaturated conditions, soil drainage may be improved.

Altering the number and distribution of soil pores affects the water holding capacity of a soil. Plant available water is held in small pores drained at suctions between 0.5 to 1 and 1500 k Pa. Researchers have generally found that compaction of soil increases the amount of plant available water (Warkentin, 1971; Greacen and Sands, 1980; McQueen, 1983; Agrawal, 1991) through the formation of additional small pores. Where a compacted soil layer at depth impedes drainage, the volume of water filled pores in overlying soil is increased (Warkentin, 1971). Sheptukhov *et al.*, (1982, *cited by* Gameda *et al.*, 1985) reported that increasing soil bulk density increased the plant unavailable water stored in a soil, presumably through increasing the number of pores drained at suctions greater than 1500 k Pa. At high levels of soil compaction the reduction in total porosity may be greater than the increase in small pores (Greacen and Sands, 1980), thus reducing the volume of plant available water stored in a soil (Department of the Environment *et al.*, 1988; Hakansson *et al.*, 1988; Samuel, 1991). Gradwell (1968), for example, reported a 10% decrease in water holding capacity of topsoil following severe stock pugging.

Soil texture influences the impact of compaction on soil water holding capacity. Reeve *et al.*, (1973) compacted soils of varying textures with carbon contents of less than 5% and reported that soil water capacity in most inorganic (B and C) horizons decreased with increasing bulk density. Sandy or silty A horizons responded in a similar way. Conversely A horizons of loam and clay-textured soils increased water holding capacity with increased bulk density provided that the water holding capacity was less than total soil porosity as fine textured soils characteristically have a greater volume of fine pores.

The decrease in large air-filled pores associated with compaction of soil results in a reduction of soil aeration and air permeability (Trowse, 1971a)

Soil aeration and air permeability in compacted soils are also lowered by an increase in the number of saturated small pores (Grable, 1971; Asady and Smucker, 1989; Slowinska-Jurkiewicz and Domzal, 1991). Soil compaction decreased soil air oxygen content, increased soil air carbon dioxide content and increased the variability of soil oxygen concentrations. Additionally, Harris and Birch (1989) reported more anaerobic microsites were present in compacted soils.

Soil moisture and bulk density changes associated with compaction may influence the thermal properties of a soil (Willis and Rany, 1971). In wet periods soil moisture affects the thermal properties of a soil to a greater extent than bulk density. Low soil temperature fluctuations are associated with elevated soil moisture contents because water acts as a temperature buffer.

In dry soil thermal properties are dominated by bulk density. Willis and Raney (1971) reported that bulk density increases of 0.3 to 0.4 Mg m<sup>-3</sup> doubled thermal conductivity resulting in a greater variation of soil temperatures. Douglas and Campbell (1988) reported soils compacted at depths

of 0.05 and 0.10 m had lower spring temperatures (when soil moisture levels are usually high) and higher summer temperatures (when soil moisture levels are usually low).

### 6.2.2 Effect of compaction on soil biological properties

Many soil micro organisms are sensitive to changes in aeration and soil moisture levels (Soane *et al.*, 1980) which may be influenced by soil compaction and presence or absence of drainage. Prolonged periods of low aeration restrict oxygen transfer to microorganisms (Grable, 1971). Harris and Birch (1989) reported that, of the aerobic soil microorganisms, fungal activity was particularly depressed in compacted soils while Scullion (1992) reported that the re-establishment of aerobic bacteria in reclaimed soils was primarily determined by the physical properties of the soil. Voorhees *et al.* (1976, *cited by* Soane *et al.*, 1980) reported that soya bean nodule bacteria numbers were reduced by soil compaction and Ross *et al.* (1982) found that ripping reclaimed soils increased microbial biomass.

Springtails (*Collembola*) and mites (*Acarina*), the main groups of soil fauna beneficial to soil development, are particularly affected by soil compaction. Soil fauna are particularly affected by changes in aeration, but low soil moisture contents and high soil temperatures may also limit the survival of these groups.

Compaction may limit earthworm activity by physically impeding their movement. Earthworms are more sensitive to compaction under conditions of high water potential (7 k Pa suction) or poor drainage (Kretzschmar, 1991). Earthworm sensitivity varies between species with researchers reporting reduction in earthworm tunnelling at widely differing pressure. Kretzschmar (1991) found that earthworm cast production, a measure of burrowing activity, increased with increased compaction to 250 k Pa while levels of compaction greater than 250 k Pa limited burrowing activity. In contrast, Dexter (1978) found penetrometer resistance of 3000 k Pa had no effect on the rate of earthworm tunnelling. A highly compacted subsoil may limit worm populations by preventing worms escaping drought conditions through deep burrowing (Hutson, 1972).

### 6.2.3 Effect of compaction on plant growth

#### *Germination*

Compaction has been shown to depress seed germination and growth by lowering soil aeration and soil temperature (Soane *et al.*, 1980). A soil crust may physically impede seedling shoot penetration (Cannell, 1977) and indirectly limit growth by increasing the incidence of plant fungal diseases by promoting ponding of water on the soil surface and elevated soil moisture levels.

### *Direct effect of compaction on plant root systems*

High levels of soil compaction may directly affect plant rooting characteristics. Plant roots grow either by entering continuous pores larger than root diameter (Dexter, 1988) or forcing aside soil to create new pores (Cannell, 1977). Because compaction reduces both the continuity and size of soil pores, increased mechanical resistance to root penetration restricts root growth (Soane *et al.*, 1980; McRae, 1989; Simojoki *et al.*, 1991). Similarly, high bulk density restricts root growth (Dexter, 1986a; Hakansson *et al.*, 1988; Daniels *et al.*, 1991; Sweigard and Saperstein, 1991) and root functioning (Greacen and Sands, 1980; Evans *et al.*, 1986; Hammel, 1988; Asady and Smucker, 1989).

Mechanical impedance decreases rates of root elongation (Russell, 1973; Taylor, 1971; Gooderham and Fisher, 1975; Vepraskas, 1986) by decreasing the rate of cell division and cell length. The resulting shorter roots have increased diameters (Flocker, 1964) and are generally less branched than roots growing in uncompacted soils (Bengough and Mullins, 1990). High mechanical resistance associated with compacted soil changes the lateral rooting pattern of plants (Russell, 1971) causing concentrations of roots where favourable soil conditions are present. For example, where subsoils are compacted roots may be restricted to the topsoil with freely penetrating lateral roots reaching greater than normal lengths (Lipiec *et al.*, 1991; Bengough and Mullins 1990; Daniels *et al.*, 1991). Philo *et al.* (1982) reported that tree seedlings growing in compacted reclaimed soils with  $\rho_b = c. 1.5 \text{ Mg m}^{-3}$  in the surface 0.3 m had shallow, stunted taproots and poor development of lateral roots compared to trees growing in ripped soils ( $\rho_b = c. 1.0 \text{ Mg m}^{-3}$ ). Where compaction is extreme roots are deflected horizontally on top of the compacted layer (Buckley, 1978; Dexter, 1986a) or are confined to vertical fissures between dense structural units (Department of the Environment *et al.*, 1988). Naturally occurring compaction in yellow grey earths in New Zealand forces this pattern of rooting on trees. Rooting patterns may change with increasing soil moisture content as soil strength or root penetration resistance decreases (Letey, 1985).

### *Indirect effect of compaction on plant root systems*

Root growth may be affected by a decrease in soil aeration and oxygen diffusion rates characteristic of compacted and poorly drained soils. Trowse (1971c) found a strong correlation between root activity and rate of air permeability when soil water became deficient in oxygen. Low oxygen levels in rhizospheres of roots may slow cell creation in active tissue such as root tips which require oxygen for cell division (Trowse, 1971c) and result in sparse and slender roots (Gradwell, 1965). Where soil compaction or poor drainage induces anoxia the shortage of oxygen can prevent roots from absorbing water. In severe cases susceptible plants, for example corn, may dehydrate in a soil saturated with water (Bidwell, 1979). Ethylene gas accumulation in saturated soils is associated with low permeability of soil oxygen and high biological respiration rates. Impeded roots may also produce ethylene (Cannell, 1977) which causes an

increase in the formation of root hairs and lateral roots and decrease the ability of root systems to resist topsoil-resident pathogens.

A perched water table may induce poor anchorage of roots and lodging of plants. Finally, depressed soil temperatures sometimes associated with water-logged soils decrease plant physiological functions which are regulated or modified by soil temperature, for example, absorption of water and nutrients by roots (Trowse 1971b).

#### *Availability and uptake of nutrients by plants*

Most soil nutrients move in the soil solution by diffusion and mass transport. Plant nutrient availability may be influenced by increases in the volume of saturated pores and number of soil particles within a given volume. An increase in the number and volume of water saturated pores associated with compaction or inadequate drainage increases the rate at which nutrients move to the roots by these processes (Kemper *et al.*, 1971). Compaction increases the number of cations and anions (e.g. major plant nutrients  $\text{PO}_4^{=}$ ,  $\text{NO}_3^-$  and  $\text{K}^+$ ) in a defined volume of soil (Kemper *et al.*, 1971).

Plant nutrient uptake is affected by the distribution of roots through a soil profile and root activity. Uptake of immobile ions, such as phosphorus, is limited if root distribution is restricted while root uptake of mobile ions such as nitrogen is reduced to a lesser extent (Cannell, 1977). Where rooting density and elongation are restricted overall nutrient uptake is reduced despite the presence of more nutrients per unit volume of soil, (Greacen and Sands, 1980; Hakansson *et al.*, 1988).

An increase in anaerobic microsites in compacted and poorly drained soils increases denitrification activity causing increased losses of nitrogen (Bakken *et al.*, 1987; Hakansson *et al.*, 1988; Harris and Birch, 1989). Soil nitrate is denitrified to gaseous nitrous oxide and nitrogen by facultative anaerobic bacteria capable of using nitrate instead of oxygen as a hydrogen acceptor (Cannell, 1977) (Figure 6.3). Plant nitrogen uptake is depressed as a result of lower nitrogen concentrations (Douglas and Campbell, 1988; Widdowson and McQueen, 1990) however only nitrate present in the soil at the onset of anaerobic conditions will be lost through denitrification since no further nitrate is formed while anaerobic conditions persist (Cannell, 1977). Nitrogen mineralisation from soil organic matter is particularly sensitive to increases in compaction (Whisler *et al.*, cited by Kemper *et al.*, 1971).

#### *Yield and crop attributes*

Many studies have shown compaction can reduce the potential or actual yield of crops from cereals and forestry to pasture and tomatoes (Flocker, 1964; Stucky and Linsey, 1982; Evans *et al.*, 1986; Bakken *et al.*, 1987; Ross and Widdowson, 1987; Leslie, 1990; Soane, 1990; Sweigard and Saperstein, 1991). Henderson *et al.* (1988) reviewed Western Australian research that

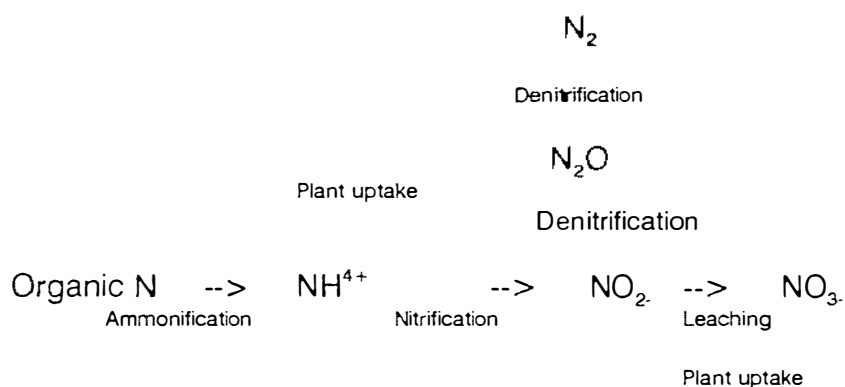


Figure 6.3: Transformations of nitrogen in soil (from Cannell, 1980). Small letters represent the processes of transformation or loss of nitrogen from the soil.

showed soil compaction caused decreased yields on sandy soils and duplex (layered) soils with sandy A horizons. Compaction can lower the uniformity of crops, delay ripening or cause irregular ripening (Soane *et al.*, 1981). High compaction levels have been associated with reduced quality of crops (Soane *et al.*, 1981) through decreased digestible organic matter and crude protein levels (Douglas and Campbell, 1988).

The availability of water is often the critical variable affecting productivity of plants because, combined with physical properties, water availability affects rates of oxygen diffusion, mechanical resistance and water potential of soil (Letey, 1985). Crop yield is only affected by compaction when nutritional and water requirements of plants are not met (Evans *et al.*, 1986). Crop moisture requirements are determined by the balance of evapotranspiration with precipitation, the readily available water holding capacity of the soil and rooting depth of the crop. The latter factors may both be affected by compaction. Compaction generally increases crop vulnerability to nutrient and water stresses, (Asady and Smucker, 1989) however, the influence of compaction on plant growth differs according to the degree and type of compaction. For example, if compaction does not affect the total root system of a plant compensatory root growth may occur in zones with better physical properties and yield may not be affected.

In areas that experience climatic moisture deficits, a plant requirement for water greater than supply is a primary cause of reduced yields (Goderham and Fisher, 1975). Water extraction by roots is usually reduced in evenly compacted soils (Trowse, 1971b; Greacen and Sands, 1980; Hammel, 1988; Hakansson *et al.*, 1988) due to low root elongation rates limiting root proliferation within the volume of soil explored (Trowse, 1971b). Where subsoils are compacted extraction of subsoil water by roots is reduced and yield reduction due to compaction is usually more pronounced in periods of high moisture stress (Trowse, 1971b).

Moderate levels of compaction are not necessarily detrimental to crop growth (Raghavan *et al.*, 1990). Moderate compaction may improve seed germination and increase crop yields in seasons when growing season precipitation is less than the critical amount required by the crop (Voorhees, 1987; Hakansson *et al.*, 1988; Agrawal, 1991) (Figure 6.4). This situation occurs most



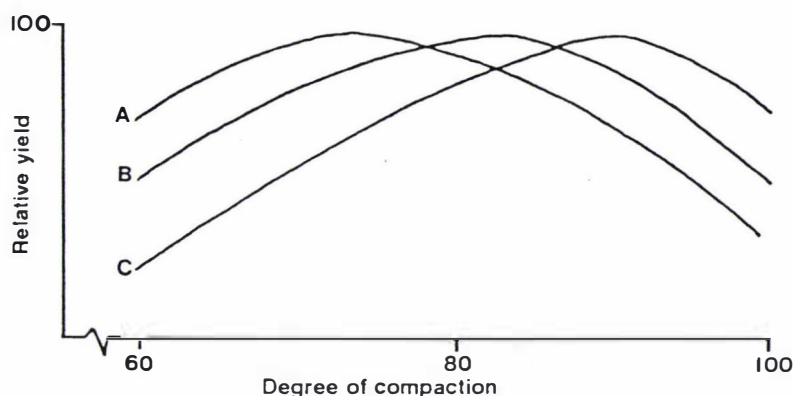


Figure 6.4: Schematic relationship between level of compaction, plant yield and weather in a (A) wet year, (B) normal year and (C) dry year (from Eriksson *et al.*, 1974 in Raghavan *et al.*, 1990).

commonly when the uncompacted (control) soil is coarse textured and friable.

Yield response to compaction varies between species (Crews, 1984) and cultivars, for example, Flocker *et al.* (1964) found potato yields and quality were affected while tomato yields were unchanged at the same level of compaction in the same soil. Raghavan *et al.* (1990) reported deep rooted species were less sensitive to compaction. Gradwell (1965) found that consistently large depressions in growth of ryegrass seedlings occurred only when elevated bulk density was accompanied by low soil aeration and low gas diffusion, i.e. very low oxygen levels (Gradwell 1965). Flocker (1964) reported that mechanical resistance was the dominant factor limiting cotton root development into subsoils with high bulk densities, while at moderate bulk densities oxygen and carbon dioxide concentrations limited root development.

#### *Pasture composition*

In pastures primarily comprising clover and perennial ryegrass species, compaction depresses clover growth and increases competitiveness of weed species (McDonald and Dolby, DSIR, unpublished data; Simcock, 1990). Additionally, poor drainage associated with compaction decreases pasture competitiveness (Horne, 1985). Both white clover and ryegrass species can tolerate saturated soil conditions with low oxygen contents for weeks when temperatures are low (Cannell, 1977). However, Green (1974, cited by Cannell, 1977) found the proportion of clover was lower in poorly drained treatments (possibly due to higher soil temperatures and/or clover growing more actively). White clover is more susceptible to trampling damage than ryegrass and displays slower spring growth due to an inability to grow at lower temperatures (Edmond, 1984 cited by Hamblin, 1985).

A New Zealand trial investigating reclamation of loess soils to ryegrass and clover pasture found clover contents in plots which were compacted (unripped) were half those of ripped soils in the

first year, but were no different in the second year of the trial (McDonald and Dolby, unpublished). This effect was unlikely to be influenced by differences in fertility as compacted soils are more likely to have low soil nitrogen levels through decreased mineralisation, increased leaching and increased denitrification. In another New Zealand study, weed species were found to contribute more than twice as much to pasture dry weight in a heavily compacted reclaimed soil than in less compacted soil (Simcock 1990).

Horne (1985) compared the botanical composition of drained and undrained mob stocked pasture. The effects of soil moisture content (drainage) and pugging damage on botanical composition were not separated. Both factors are closely linked, with saturated soil conditions increase susceptibility of soil to pugging (Gradwell 1960). Horne (1985) found the proportion of weeds was consistently higher in undrained treatments, and during seasons favourable for clover growth (late spring to mid summer) clover contents were significantly higher in drained plots. Horne concluded that a gradual deterioration of pasture quality was likely to occur in the undrained plots.

#### 6.2.4 Conclusion

The response of soil to compaction varies according to soil type and compaction history, soil moisture and organic matter content as well as the characteristics of the compactive force: magnitude, number of passes and length of time over which the force is applied. Compaction is most damaging when a large force is applied slowly and frequently to fine textured soil with a high moisture content and low organic matter content. The main effects of compaction are an increase in soil bulk density and penetration resistance and a decrease in total soil porosity and macroporosity.

The change in soil pore distribution and volume may directly and indirectly affect micro-organism activity, plant and root growth. Root growth and burrowing of soil macro-fauna may be limited through mechanical impedance and creation of massive soil structures. Soil compaction may indirectly affect plant root and soil organism activity through adversely altering the permeability and volume of air and water in the soil, soil temperature and nutrient availability. Many soil chemical activities may also be affected. The overall result of compaction on plant growth is retardation of root extension and rooting volume. These limit the volume of soil explored, thus decreasing nutrient and water availability. Compaction or poor drainage will only affect root growth and hence plant yield if it causes an environmental factor, most commonly oxygen, water or nutrients, to become limiting. Plant activity may only be limited during periods of peak nutrient or water demands, for example, during reproduction or maximum spring growth. The effect of compaction or drainage on plant yield depends on soil fertility, plant root distribution plant species, growth stage of the plant soil aeration and soil moisture.

## 6.3 Literature review of drainage with an emphasis on reclaimed soils

### 6.3.1 Introduction

Poorly managed reclamation following strip-mining has often resulted in poorly drained soils (Tomlinson, 1984) and major alteration of drainage patterns. In the United Kingdom poor drainage is one of the most common problems associated with restored land (RMC, 1987). The importance of installing artificial subsurface drainage in reclaimed land has been recognised in the United Kingdom aggregate (McRae, 1983; 1989; Department of the Environment *et al.*, 1988) and coal industries (Younger, 1989). Brooks (1989) highlighted the importance of establishing both surface and subsurface drainage patterns after mining of mineral sands in Australia, particularly for wetland reclamation where changes in water tables of as little as 0.15 m can critically affect drainage and vegetation patterns (Brooks, 1989).

### 6.3.2 Causes of poor drainage

In the United Kingdom, reclamation of fine textured and poorly structured soils commonly requires artificial drainage (RMC, 1987) as these soils have intrinsically poor hydraulic conductivity. Decreased soil structural stability and compaction associated with earth moving accentuates the requirement for drainage of reclaimed soils by decreasing soil hydraulic conductivity (permeability) (Hodgkinson, 1991). Poor drainage is caused by a combination of excess rainfall, low run off and low hydraulic conductivity and is exacerbated where soils have a low water holding capacity (Cox and McFarlane, 1990; Moffat and Roberts, 1989). Additionally, inadequate drainage is associated with lateral flow of water into hollows in a rolling topography or onto lower areas where changes in slope occur, for example between quarry walls and floor (Richardson and Wilson, 1986; Cox and McFarlane, 1990). Poor drainage is exacerbated by a high or fluctuating ground water table and high intensity rainfalls (Richardson and Wilson, 1986). Thus waterlogging is generally highly variable spatially and between years. Poor drainage is also associated with soils which comprise a freely draining topsoil over a impermeable or poorly draining subsoil (McFarlane and Wheaton, 1990).

### 6.3.3 Types of drainage and modes of action

Drainage systems may be located on the surface or subsurface. Surface drainage systems range from creation of small catchments and wetlands to retain storm water, to back-draining terraces or contour drains to break up long slopes and control erosive run off. Drains may also intercept surface water and transmit it off site (Brooks, 1989). Another type of drainage is the formation of large-scale ridge and hollow landforms (Moffat and Roberts, 1989). Conventional drainage involves the installation of clay or perforated plastic pipes covered with permeable backfill to drain a profile and transport water to a discharge point (RMC Group, 1987). Subsurface drainage may include mole drainage which comprises temporary drains formed from pulling a torpedo-shaped device through clay-rich soil horizons above and perpendicular to

conventional pipe drains. Mole drains increase the interception of water and the associated soil disturbance loosens surface horizons, thus promoting water movement into the drains (Hodgkinson, 1991; RMC Group, 1987).

Subsurface tile or plastic pipes lower the water table immediately above the drain to the depth of the drain (Figure 6.5), by removing free water from the soil and intercepting shallow moving and surface water to the depth of the drain (Cannell, 1977; Scotter, 1988). Drains only flow when the water table is at or above their depth. The height of a water table between drains depends on the structure and texture of the soil together with the depth and spacing of the drains (Bowler, 1980)(Figure 6.5). Lowering the water table increases tension's draining moisture down the profile, thus smaller diameter pores become air-filled (Cannell, 1977). The effectiveness of a drain, measured by the water content of the soil above the drain, depends on the hydraulic conductivity of the soil and backfill above the pipe, i.e. how fast water moves into soil profile and to the drain (Bowler, 1980; McRae, 1983; Howatson, 1986; Scotter, 1988; Stewart and Scullion, 1989). Additionally, the unstable structure of many reclaimed soils may reduce the performance of drains. Dispersion and translocation of weak aggregates may block drainage channels or fissures leading to the channels (Scullion and Mohammed, 1986). Drain size and gradient affect the capacity of the drain to remove excess water (Bowler, 1980; McRae 1983; Howatson 1986).

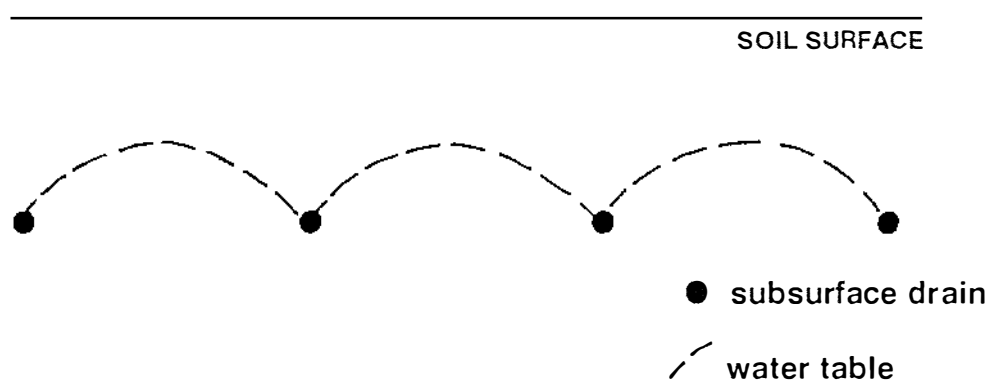


Figure 6.5: The effect of subsurface drains on depth to water table in a soil comprising horizons of equal hydraulic conductivity (after Bowler, 1980).

#### 6.3.4 Effects of drainage and waterlogging on soil

Draining a soil increases the volume of air-filled pores by draining the larger, water-filled soil pores. Soil pore distribution, however, is unaffected by drainage. Ripping or subsoiling soil with shallow compacted horizons underlain by freely draining horizons also results in lower soil water contents although ripping changes soil pore distribution by increasing soil macroporosity.

The effects of low aeration are identical, whether the result of poorly drained soils, in which macropores are occupied with water, or associated with compacted soils in which the number of macropores is reduced. Drainage only increases aeration in poorly drained soils, although soil disruption associated with drainage, particularly mole drainage, may help relieve compaction. Poorly drained soils develop low concentrations of oxygen and elevated concentrations of carbon dioxide because gases diffuse very slowly through water-filled pores (10,000 times more slowly than through air). Anaerobic conditions occur when the rate of consumption of oxygen of roots and soil organisms exceeds the rate at which oxygen diffuses into the soil. Drainage can prevent saturation of surface soil horizons and thus increase soil aeration, and reduce the high carbon dioxide levels associated with waterlogged soil (Evans *et al.*, 1986; Howatson, 1986).

Waterlogged soil has slower breakdown of organic matter and decreased availability of plant nutrients, especially nitrogen (Section 6.2). Decomposition of organic matter by bacteria which proliferate under anaerobic conditions may lead to production and increased concentrations of hydrogen sulphide, ethylene and toxic organic acids (Setter and Belford, 1990). Additionally, in anaerobic conditions the more soluble, reduced forms of iron ( $\text{Fe}^{2+}$ ) and manganese ( $\text{Mn}^{2+}$ ) are created. These microelements may be toxic to roots in high concentrations (Bowler, 1980; Setter and Belford, 1990).

Drainage may increase the rate of solute and particulate matter movement through soil, leading to increased leaching of plant available nutrients (Williams *et al.*, 1988). Williams *et al.* (1988) reported that very high rates of nitrogen could be leached through drains and sulphur losses were twice as much on drained compared to undrained areas.

Artificial drainage may decrease the water holding capacity of a soil (Cannell, 1977; Scotter, 1988) by lowering the amount of water held in the soil at field capacity and capillary rise of water into surface soil layers. Lowering the water table increases the suction (or head) at the soil surface, resulting in more pores being emptied of soil water. Scotter (1988) calculated that lowering the water table of a high macroporosity (Pukepuke) sand from 0.4 to 1.2 m reduced its readily available water holding capacity from 183 mm to 26 mm. The decrease in water holding capacity may be offset by increased rooting depths in drained pasture and is dependant on the depth of the water table and the pore size distribution of the soil. For example Scotter (1988) also calculated that lowering the water table of a poorly structured silt loam soil with low macroporosity resulted in only a small decrease in the readily available water holding capacity.

Drainage increases soil bearing strengths, measured by penetration resistance (Richardson, 1988), thus decreasing the potential for soil damage by animal pugging (Richardson and Wilson, 1986; Hamilton and Horne, 1988). Drainage may also reduce the depth and extent of soil compaction by machinery traffic (Cannell, 1977).

Drainage of soil water can modify the thermal properties of a soil, allowing it to warm up more quickly (Bergman, 1975 *cited by* Cannell, 1977; Bowler, 1980). This may be particularly important in spring, leading to earlier growth responses of pastures and crops (Bowler, 1980). Feddes (1972 *cited by* Cannell, 1977) reported that mean spring daily temperatures of a soil with a water table 0.45 m below the soil surface was 1-2°C lower than a soil with water table at 1.65 m. In the soil with the 1.65 m water table radish, spinach and broad bean seedling emergence was up to 10 days earlier than in the soil with a high water table.

### 6.3.5 Effects of drainage on soil management

Drainage generally increases management flexibility (Street, 1985) particularly as regards timing of stock and vehicle movement, choice of crop species, crop sowing and harvesting dates thus reducing risk. Climo (1984<sup>a; b</sup>) reported that drainage markedly increased the number of available grazing days of a silt loam in Manawatu. This is primarily due to a drier surface with increased resistance to wear and tear (Samuel, 1991). An increase in grazing days is particularly advantageous in areas pasture growth occurs in winter (Richardson and Wilson, 1986). Drainage may also increase utilisation of pasture in winter (Hamilton and Horne, 1988; Richardson, 1988) lower weed control costs (Samuel, 1991) and reduce run-off, thus minimising erosion. In Australia the mineral sands industry has drained areas before mining to facilitate stripping of topsoil. Drainage is also used to promote wetland establishment by preventing flooding until vegetation is of sufficient height to withstand inundation (Brooks, 1989).

### 6.3.6 Benefits of drainage to plant growth

The effect of drainage on plant yield varies with seasonal rainfall, crop species and severity of soil conditions before drainage. Drainage, like low compaction, is only advantageous if conditions before drainage imposed some limitation (Cannell, 1977). Many researchers have reported increased yield of crops growing on drained soils (Younger, 1989; Samuel, 1991). Research in Western Australia has shown pasture on severely waterlogged soils had poor growth during most of the year while pasture on mildly waterlogged soils had increased pasture growth during dry periods. Pasture on moderately waterlogged soils displayed increased pasture growth in late spring which partially or totally compensated for a reduction in growth in early spring (McFarlane and Wheaton, 1990).

Increased crop yields have been related to increased plant root development (Street, 1985), plant growth (Hodgkinson, 1989), utilisation of nutrients from greater soil depths (Horne, 1985) and improved sward quality (Samuel 1991). Younger (pers. comm., 1991) reported a 60-70% recovery of nitrogen in drained plots compared to 35-45% recovery in undrained plots. Evans *et al.* (1986) found that plant roots of plants growing in drained plots achieved earlier maximum rooting depths and greater subsoil root development. Additionally, roots in the drained plots extracted more water and nutrients from deeper in the soil profile, while the undrained site had the most water extracted from surface horizons (Evans *et al.*, 1986).

Many researchers have reported that crops growing in poorly drained or waterlogged soils exhibit reduced yields (Eden, 1986; Evans *et al.*, 1986) and quality (Climo *et al.*, 1988). Annual crops may be stunted and yellowed with depressed crude protein, K, Mg and Cl contents (Bowler, 1980). Yellowing and early senescence of older leaves occurs because plants translocate nitrogen to the younger leaves (Setter and Belford, 1990). Plants which are sensitive to waterlogged soils may have wilted (Eden, 1986), chlorotic or epinastic (downward curving) leaves (Bowler, 1980; McFarlane and Wheaton, 1990). Evans *et al.* (1986) reported that poorly drained grain crops displayed restricted tillering, fewer and smaller vegetative shoots and restricted ear development. The main factors which cause these characteristics are inadequate oxygen and nutrient supply to roots, increased concentrations of toxic gases and restricted root exploration within the soil profile. Most plants are particularly susceptible to anaerobic conditions during periods of active growth, when soils are warm and when soil flora and fauna are highly active (i.e. using large volumes of oxygen in respiration) (Bowler, 1980) and during germination, before emergence of the seedling from the soil, when oxygen is supplied from a film surrounding the seed (Setter and Belford, 1990).

Anaerobic soil conditions resulting from waterlogging may reduce plant root respiratory metabolism and decrease the ability of roots to absorb or uptake nutrients (Evans *et al.*, 1986). Uptake of macro-nutrients N, P and K and micro-nutrients B, Cu and Zn is reduced in barley, maize and clover (Cannell, 1977). Eden (1986) reported anaerobic soils may induce nutritional deficiencies in kiwifruit, particularly of K and Mg. Nutritional deficiencies may induce premature leaf senescence, a means by which nutrient deficient plants can supply young, growing tissues with N and K (Evans *et al.*, 1986).

Poor drainage may result in restricted vertical root growth, with rooting confined to soil above the permanent winter water table. Root dieback at depth and compensatory root growth near or at the soil surface may be associated with elevation of water tables during wet periods (Evans *et al.*, 1986; Setter and Belford, 1990).

The incidence of plant disease increases in anaerobic soils (Bowler, 1980; Eden, 1986; Howatson, 1986). Plants growing in anaerobic soils are more susceptible to injury by root rot organisms. Additionally, anaerobic soils favour a number of soil-borne pathogens such as *Fusarium* and *Phytophthora* (Cannell, 1980).

Under anaerobic soil conditions weed ingress into pastures is likely to increase (Bowler, 1980; Climo *et al.*, 1988) as highly productive grass and clover cultivars are usually less competitive in adverse soil conditions. Increased pugging associated with poorly drained soils may also promote weed ingress into pastures through decreasing grass tiller and clover growing point



densities (Richardson and Wilson, 1986) with an increase in plants which tolerate soils with low levels of oxygen, for example docks, rushes (*Juncus spp*) and *Phalaris spp* (Cox and McFarlane, 1990). Poorly drained soils in Australia have been associated with an increase in the proportion of grass species and decrease in the proportion of clover species (McFarlane and Wheaton, 1990).

### 6.3.7 Conclusion

Poor drainage<sup>is</sup> associated with compacted soils, soils with low hydraulic conductivities or high water tables, and is strongly influenced by water table height and topography. Subsurface pipe drainage lowers the water table to the depth of the drain, thus increasing the volume of air-filled pores. Effects of drainage are primarily related to increased soil aeration, which benefits plant growth and speeds soil warming, and decreased soil moisture content which increases soil resistance to compactive forces. These factors combine to increase management flexibility by increasing species choice and timing of activities. Drainage may however decrease the water holding capacity of a soil and increase leaching of plant nutrients. The response of plant growth and yield to drainage depends on seasonal rainfall, plant species and the inadequacy of the undrained soil. Plants growing in drained soils may have higher yields than those growing in poorly drained soils due to increased nutrient uptake by plants through increased root functioning and soil exploration. Drainage lowers the susceptibility of roots to pathogens and reduces the prevalence of root pathogens while aerobic soils are not favourable to growth of anaerobic soil organisms which may generate products toxic to plants. Installation of drainage disrupts soil horizons and will relieve compaction in the area of the drain. Ripping compacted soils will, however, increase the water content of a soil where porosity is increased and the base of a profile is still compacted, preventing escape of water.

## 6.4 Methods

### 6.4.1 Proctor test

The response of a soil to a compactive force is commonly predicted using the Proctor test which has been used widely as a standard by civil engineers. The Proctor test was used to find approximately the highest degree of compaction for a soil and the water content at which this occurred. The method of applying compaction in the Proctor test is very different from that occurring in agricultural soils where the compactive forces are applied to the soil surface and wheel vibration increases particle packing of dry soils. However the Proctor test is able to show the variability of responses to compaction with different soil types and moisture contents (Soane, 1975).

The Proctor compaction test was carried out in accordance with New Zealand Standard 4402:1986. To avoid soil property changes associated with hysteresis, soil samples passing through a 0.019 m sieve were air dried before being wet up to the required moisture content.

Samples were compacted in the prescribed manner over a range of water contents, including the moisture content at which maximum compaction was achieved.

Other methods used to characterise the effects of compaction are detailed in Section 5.5.

## 6.5 Ohakea trial compaction treatments

The effects of compaction on physical and production properties of Ohakea soils were analyzed using six of the eight treatments, comprising 24 plots asterixed in Table 6.1. Only soil replacement treatments that had both low and high compaction treatments could be included in the analysis (Table 6.1). A model programme for this analysis is part of Appendix 6.1.1.

Table 6.1 Treatments (\*) used for the statistical analysis of the effect of compaction on Ohakea soil replacement treatments (Section 4.3.1 explains the soil replacement treatments). "na" treatments were not constructed.

	Soil Replacement Treatment				
	A only	AB	A on B	Control	Other
High compaction	*	*	*	na	na
Low compaction	*	*	*	.	.

### 6.5.1 Pasture dry matter production and herbage composition

Pasture production from high and low compaction treatments was similar for most of the 14 harvests (10 of 14) (Table 6.2). In the first harvest, pasture production was significantly depressed in the high compaction treatment. Conversely, pasture production in harvests 5, 6 and 11 was greater in the high compaction treatment. Over the 23 month life of the trial total dry matter production of high and low compaction treatments was similar, being 16,186 kg ha<sup>-1</sup> and 16,005 kg ha<sup>-1</sup> respectively. Non-significant trends indicated that while the pasture was establishing (harvests 1 to 3) the low compaction treatment had a more favourable soil environment for pasture than the high compaction treatment (Graph 6.2). After harvest 3 the high compaction treatment either had no significant effect on pasture production or provided more favourable soil conditions for pasture growth (Figure 6.2); in 3 harvests the high compaction treatment produced 10% more than low compaction treatment and 2 harvests produced 5% more than the low compaction treatment.

Table 6.2: Ohakea trial. The effect of high and low compaction treatments on dry matter production ( $\text{kg ha}^{-1}$ ). Harvest dates for the Ohakea trial are given in Table 5.3. "Compaction effect" is the percentage difference in dry matter production between high and low compaction treatments. Significance is the probability that  $P=H_0$  i.e. that the two treatments are not significantly different. Brackets in the row "Compaction effect", and throughout this chapter, indicate a negative value.

Treat.	Production ( $\text{kg ha}^{-1}$ ) at specified harvest						
	1	2	3	4	5	6	7
Low	950±690	790±200	1080±220	590±260	1070±240	870±70	1010±300
High	540±280	710±220	1010±240	600±220	1210±220	970±100	1010±320
Effect	76%	11%	7%	{2%}	{13%}	{11%}	0%
Sign.	05	49	.52	.80	07	01	99

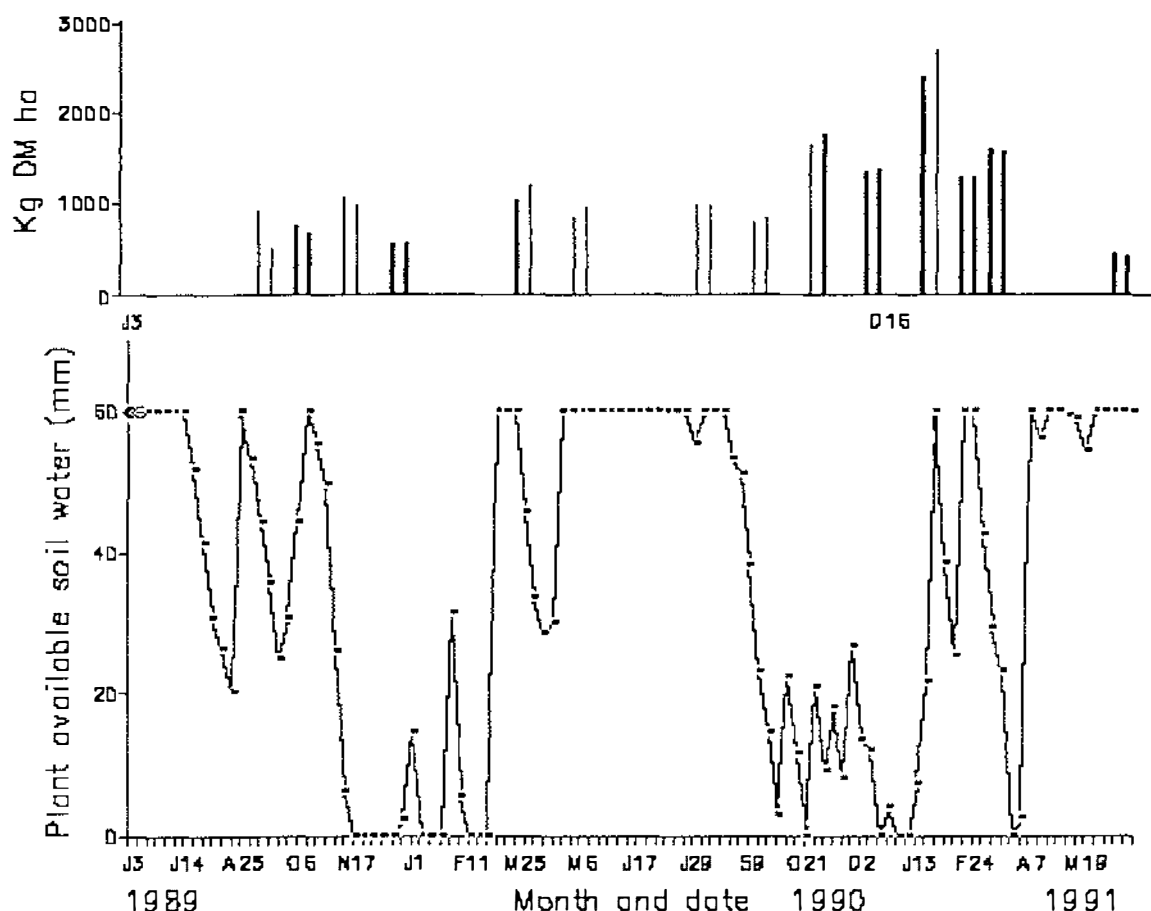
  

Treat.	8	9	10	11	12	13	14
	Low	800±380	1660±310	1370±350	2410±480	1320±205	1610±100
High	880±260	1790±260	1390±220	2710±340	1300±150	1590±110	470±150
Effect	{10%}	{8%}	{1%}	{12%}	2%	1%	2%
Sign.	54	22	64	.04	82	80	33

Herbage production bore little relation to soil moisture levels prior to harvest (Graph 6.2) or total days of water surplus or deficit prior to each harvest (Table 5.3). Note, however, that these were gross measurements and harvests were timed according to pasture mass and height, not changes in soil moisture levels.

A analysis of possible correlation between pasture production and soil bulk density at 0, 0.1, 0.2 and 0.3 m depths was carried out to identify if dry matter production could be related to a specific depth of compaction. The analysis assumed that bulk density and pasture production were linearly related, if at all. In most harvests dry matter production was negatively correlated with bulk density throughout the soil profile to 0.20 m depth, although in most instances the correlation was not significant. Additionally, significant correlation coefficients were low, between 0.31 and 0.41. Two harvests displayed correlations with compaction at 0.30 depth and these were both positive. In harvest six compaction at 0.30 to 0.35 m may have been a factor contributing to the significant positive relationship of high compaction with dry matter production (Table 6.3), despite significant negative correlations of pasture production and bulk density in the soil surface to 0.15 m depth (Appendix 6.1.2).

Dry matter production was significantly negatively correlated with bulk density at one or more soil depths in harvests 1 to 8 (excluding harvest 5) and harvest 14. Soil bulk density at the



Graph 6.2: Dry matter production of high and low compaction treatments ( $\text{kg ha}^{-1}$ ) (top graph) with calculated weekly plant available water (mm) for an Ohakea soil with 60 mm of plant available water in the surface 0.3 m (bottom graph). The low compaction treatment is the LHS bar of each pair of bars.

compacted layer (at 0.20 m) was negatively correlated with plant growth in only harvests 1, 3 and 4. These negative correlations, however, were only reflected in significant differences between high and low compaction treatments for Harvest One. Significant negative correlations between production of dry matter and bulk density in the surface 0 to 0.15 m of the soil profile indicates that low levels of compaction in surface layers may adversely affect production of pastures in Ohakea soils, i.e. the position of compaction in the soil profile as well as the degree of compaction is important.

An analysis of possible correlation between soil macroporosity at 0, 0.1, 0.2 and 0.3 m and dry matter production showed significant positive correlations existed in harvests 1 and 14 at single soil depths (Appendix 6.1.3).

Dry matter production from individual harvests was significantly negatively correlated with macroporosity at a single, variable soil depth in 5 of the 14 harvests. Where bulk density was negatively correlated with dry matter production, macroporosity was generally positively

Table 6.3 Summary of significant bulk density and macroporosity correlations with dry matter production. The entire table of data is presented in Appendices 6.1.2 and 6.1.3. Within each box the Pearson Correlation Coefficient is given on the LHS and the RHS number is the Probability that the correlation is due to chance. Brackets indicate a negative correlation.

Harvest Number	Soil depth (m)	Correlation coefficient and probability			
		Bulk density		Macroporosity	
1	0.20-0.25	(.39)	.06	.34	.06
6	0.30-0.35	.67	.001	(.61)	.001
7	0-0.05	(.42)	.02	(.45)	.01
9	0.20-0.25	.31	.09	(.31)	.10

correlated with dry matter production and vice versa (Table 6.3). Horizons with high bulk densities usually have low volumes of macropores. The significant negative correlation of both macroporosity and bulk density with dry matter production found in harvest 7 at 0 to 0.05 soil depth may result from a lower soil water holding capacity in soils with high levels of macroporosity, as macropores are not generally filled with water (i.e. the soil dries out faster). Pasture of AonB, ABmix and Aonly soil replacement treatments responded differently to the compaction treatment. The AonB treatment consistently displayed a trend of greater or similar dry matter production from the low compaction treatment plots (Appendix 6.1.4). In harvest 1 and harvest 14 this interaction was significant. Conversely, the ABmix treatment had higher or similar dry matter production in all high compaction treatments for all harvests, however, a significant result occurred only in Harvest 6. The Aonly treatment displayed a weak trend of low compaction benefitting pasture production in Harvests 1 to 3 and reducing or not affecting pasture production in harvests 4 to 14. These trends were reflected in cumulative dry matter production for each soil replacement treatment. High compaction gave a 7.8% and 6.1% advantage in the ABmix and Aonly soil replacement treatments respectively, and a 9.4% disadvantage in the AonB soil replacement treatment.

Herbage dissections were performed on 2 of the 14 harvests. The percentage of grass in high compaction treatment swards in harvest one was significantly ( $P=0.08$ ) lower than in swards of low compaction plots (Appendix 6.1.5). The percentages of clover and weeds were not affected by the compaction treatment in either harvest. The percentage of grass within each treatment was not as variable as the percentage of weeds and clover, therefore the mean grass components had smaller standard deviations and were significantly different from each other. In harvest two the proportion of grass in both compaction treatments were similar. Clover was slow to establish and increased in total dry mass at the expense of ryegrass.

## 6.5.2 Bulk density

Bulk densities of compacted and uncompact treatments at the conclusion of the trial were similar at soil depths of 0, 0.10, 0.20 and 0.30 m (Appendix 6.1.6). At 0.20 m depth compacted treatments had significantly higher bulk densities only at  $P=0.15$ . This surprisingly low probability, given that compaction treatment was applied at 0.20 m depth, may result from measurement of bulk density using 0.05 m deep cores. These cores may have effectively "diluted" bulk density in the narrow, c.0.02 m thick compacted zone with uncompact material with a lower bulk density.

Bulk density samples were taken from the surface of the compacted layer of selected high compaction plots at the time of trial construction and from low compaction treatments at 0.20 to 0.25 m depth 8 weeks after trial construction. The delay allowed sufficient soil settlement to enable extraction of entire cores. High compaction treatments had bulk densities which were on average  $0.31 \text{ Mg m}^{-3}$  higher than low compaction treatments (Table 6.4).

Table 6.4 Bulk density ( $\text{Mg m}^{-3}$ ) measured at the compacted surface or equivalent depth at plot construction. The mean value is on the LHS and standard deviation on the RHS.

Treatment	Low compaction	High compaction
Bulk density ( $\text{Mg m}^{-3}$ )	$1.31 \pm 0.19$	$1.64 \pm 0.11$
Number of samples	16 (4 plots)	13 (4 plots)

Bulk density results were examined to see if there was any difference in bulk density within and between soil replacement treatments subjected to the same initial compaction treatments. At the time of trial destruction the low and high compaction of only the Aonly treatment were significantly different (Appendix 6.1.7). This may result from differential settling of soil underlying the compacted layer disrupting it. The disturbed soil mass below the Aonly compacted layer was 0.5 m thinner than that below the AonB and ABmix treatments, hence the compacted layer on the Aonly soil replacement treatment may have remained more intact. The decision as to whether soil measurements should be taken at standardised depths or at variable depths depending on the location of the thin compacted layer, to facilitate determination of the effects of compaction on properties of soil and plant roots, is discussed in Section 6.9.1.

At the end of the trial cores were also excavated from one plot where the compacted layer could be located as a zone of elevated resistance to a knife pressed into the sides of pits. Cores removed at 0.19 m from an ABmix treatment had a mean bulk density of  $1.61 \pm 0.22$ , while cores taken at 0.20 m depth had mean bulk density of  $1.38 \pm 0.14$ , indicating that sampling at the 0.20 m depth may not have included the compacted layer.

## 6.5.3 Macroporosity.

Macroporosity measured at 10k Pa suction was similar in compacted and uncompacted treatments at all depths. At 0.20 m depth compacted treatments had higher macroporosity only at a probability of 0.14 (Appendix 6.1.8), therefore compaction was ineffective, not permanent or was located above or below the sampled volume. When macroporosity of low and high compaction treatments was split by soil replacement treatment the high compaction Aonly treatment had a lower mean macroporosity than the low compaction treatment at 0.20 m depth (Table 6.5). Macroporosity of ABmix and AonB soils for both high and low compaction treatments were similar at a soil depth of 0.20 m (Table 6.5).

Table 6.5 Mean (LHS) and standard deviation (RHS) macroporosity (measured at 10 k Pa suction) of high compaction and low compaction treatments for each soil replacement treatment. "High" = high compaction treatment, "Low" = low compaction treatment, "N" = number of samples. Samples were taken at soil depths of 0 to 0.05 m, 0.10 to 0.15 m, 0.20 to 0.25 m and 0.30 to 0.35 m. (units % by wt).

Soil Depth (m)	AB		Aonly		AonB		N
	high	low	high	low	high	low	
0	.25±.04	.19±.07	.18±.03	.18±.01	.19±.01	.14±.05	48
0.10	.29±.06	.19±.13	.21±.03	.21±.02	.22±.03	.20±.03	48
0.20	.21±.08	.19±.05	.18±.03	.22±.01	.20±.01	.22±.04	48
0.30	.30±.01	.20±.04	.20±.07	.17±.04	.21±.06	.19±.04	44

## 6.5.4 Root length

Potential differences in root length between high and low compaction treatments were affected by high sample variation. High compaction treatments produced 65% and 60% of the rooting length of low compaction treatments at the 0.20 and 0.30 m depths respectively. Associated probabilities of significance were comparatively low, however, with  $p = 0.12$  and  $0.13$  respectively (Appendix 6.1.9). Separating results of root length by soil replacement treatment showed that root length in the compacted zone of the AonB soil was significantly shorter than in the corresponding low compaction treatment (Table 6.6). Conversely, root lengths in both compacted and uncompacted treatments were similar at all ABmix soil depths. Longer roots in the surface 0 to 0.15 m depth and shorter roots in the 0.20 to 0.35 m soil depth associated with the high compaction treatment were a trend of Aonly and AonB soil replacement treatments (Table 6.6).

Root length and bulk density at each soil depth were analyzed for possible correlations (Table 6.7). A significant negative correlation existed between root length at 0.20 to 0.35 m and bulk density at these depths. Root length at 0.20 and 0.30 m was positively, though not significantly, correlated with bulk density at 0 and 0.10 m depths (Table 6.7). Additionally, root length at both



Table 6.6 Mean (LHS) and standard deviation (RHS) root length (m per 1.2 l of soil sample) of high compaction and low compaction treatments for each soil replacement treatment. "High" = high compaction treatment, "Low" = low compaction treatment, N=number of samples.

Soil Depth (m)	AB		Aonly		AonB		N
	high	low	high	low	high	low	
0	472±134	455±306	532±257	673±105	459±126	425±213	21
0.10	109±42	119±76	149±98	103±24	206±143	88±22	21
0.20	45±25	39±18	42±30	74±20	25±10	59±21	24
0.30	28±21	42±28	24±14	41±32	20±11	38±11	23
Total	653±140	690±264	709±237	809±183	710±292	612±228	21

0.10 and 0.20 m was positively correlated with bulk density at 0.30 m depth (Table 6.7). High surface bulk densities would seem to favour rooting in deeper soil horizons.

Table 6.7 Correlation analyses of root length with bulk density and root length with macroporosity. The full data tables are presented in Appendix 6.1.11 and Appendix 6.1.12. Within each box the RHS number is the probability that the correlation is due entirely to chance. The Pearson Correlation Coefficient is given on the LHS where  $P \leq 0.10$ . Brackets represent a negative value.

Soil depth (m)	Bulk Density		Macroporosity	
0.0	0.73		0.56	
0.10	0.14		0.81	
0.20	(0.39)	0.03	0.36	0.06
0.30	(0.33)	0.10	0.28	

A significant positive correlation was found between macroporosity and root length at 0.20 m depth. Significant negative correlations were found between macroporosity at 0.30 m and root length at 0.10 m depth, and macroporosity at 0.10 and root length at 0 m depth at the time of root sampling. Favourable levels of macroporosity at one soil depth may increase rooting at that depth and, assuming limited plant resources, decrease rooting at other depths. - it appears that deeper rooting is more "favoured" by the plant if soil conditions are beneficial at the greater depth.

Table 6.8 Effect of soil compaction treatments on oven-dry root mass (g per 1.2 l soil). Samples were taken at soil depths of 0 to 0.05 m, 0.10 to 0.15 m, 0.20 to 0.25 m and 0.30 to 0.35 m. Brackets represent a negative effect of compaction.

Treatment	Soil Depth (m)				
	0	0.1	0.2	0.3	Total
Low compaction	1.8 ± 0.8	.37 ± .16	.19 ± .04	.16 ± .12	2.68 ± 0.7
High compaction	2.8 ± 1.8	.41 ± .21	.15 ± .07	.08 ± .05	3.44 ± 1.8
Significance	.27	.54	.23	.03	.56
No. of samples	24	24	24	24	24
Compaction effect	(1.0)	(.04)	.04	.08	(.76)

Low compaction treatments produced significantly heavier root mass than high compaction treatments at the 0.30 to 0.35 m soil depth (Table 6.8). At all other soil depths both high and low compaction treatments had statistically similar root masses. There was no significant interaction between soil replacement and soil compaction treatments related to root mass at any soil depth, partly due to the large variation of root mass within treatments (Appendix 6.1.10).

Trends show root mass in the surface 0.05 m of the ABmix treatment was most affected by compaction with 50% less root mass in low compaction <sup>than in high compaction treatments</sup> compared to a decrease of 20% for Aonly and AonB soil replacement treatments. Root mass at 0.3 m depth was most affected in the Aonly treatment with a 60% decrease in root mass of the high compaction treatment, compared to decreases of 35% and 45% in the ABmix and AonB treatments respectively (Table 6.8). Root mass and bulk density were significantly negatively correlated at 0.20 m (Table 6.9). Bulk density had a negative but insignificant correlation with root mass at all other soil depths. A positive, but non-significant correlation was found between bulk density at 0 to 0.15 m with root mass at 0.30 to 0.35 m. Root mass and macroporosity at 0.20 to 0.25 m depth were significantly positively correlated.

#### 6.5.5 Soil volumetric water content and depth to water table

The compaction treatment had <sup>significant</sup> no influence on soil volumetric water content at either 0 to 0.15, 0.15 to 0.30, 0.30 to 0.40 or 0.40 to 0.60 m depths on 5 of the 7 dates from November 1989 to June 1991 (Appendix 6.1.13). On 30-10-90 compacted plots had lower volumetric water contents at 0.15 to 0.30 m depth by an average 2.7%. On 12-5-91 water content was also significantly lower in compacted plots by an average 1.5% at 0 to 0.15 m depth.

Table 6.9 Correlation of root mass with bulk density and root mass with macroporosity. Within each box the RHS number is the Probability  $> |R|$  under  $H_0: \rho=0$ . The Pearson Correlation Coefficient is given on the LHS where  $P \leq 0.10$ . Brackets signify a negative correlation. Samples were taken at soil depths of 0 to 0.05 m, 0.10 to 0.15 m, 0.20 to 0.25 m and 0.30 to 0.35 m.

Soil depth (m)	Bulk Density		Macroporosity	
0	0.98		0.43	
0.10	0.49		0.89	
0.20	(0.39)	0.03	0.35	0.06
0.30	0.17		0.72	

Table 6.10 The effect of high and low compaction treatments on soil volumetric water content ( $\theta$ , measured by TDR) and water table height (WT). TDRx = measurement number. Brackets signify a negative effect of compaction. The measurement dates are 22-1-93, 7-2-93 and 20-2-93. Results of soil volumetric water contents on other dates are in Appendix 6.1.11.

Treatment	Measurement				
	TDR 5	TDR 6	TDR 7	WT 1	WT 2
Low compaction	30.8±3.1	29.2±2.3	34.9±7.6	24.8±12.9	30.4±14.1
High compaction	30.6±2.4	29.4±2.7	34.4±5.0	25.1±11.5	31.7±11.5
Significance	0.70	0.85	0.56	0.92	0.70
No. of samples	24	24	24	24	24
Effect	(0.2)	0.2	(0.5)	0.3	1.3

Application of the high compaction treatment influenced soil moisture most greatly in the surface 0 to 0.20 m, which was anticipated given that the compacted layer was placed at 0.20 m depth. Volumetric water contents below the compacted zone, i.e. from 0.30 to 0.60 m, were unaffected by compaction treatment on all four measurement dates.

## 6.6 Ashhurst trial compaction treatments

Cores excavated from the surface of the compacted layer of three plots, immediately following compaction, had significantly higher mean bulk density than cores at an equivalent depth in six uncompacted Aonly and AonB treatments (Table 6.11). No samples were taken from ABmix treatments, as a high stone content prevented the use of cores.

Table 6.11: Ashhurst trial. Soil bulk density ( $\text{Mg m}^{-3}$ ) of high and low compaction treatments immediately following compaction. Significance = 0.004.

Treatment	High compaction	Low compaction
Bulk density ( $\text{Mg m}^{-3}$ )	$1.40 \pm 0.08$	$1.27 \pm 0.12$
Number of samples	30 (6*5 reps)	18 (3*6 reps)

A Proctor compaction test of the A horizon of the Ashhurst silt loam showed that maximum bulk density of the soil was  $1.46 \text{ Mg m}^{-3}$  under this standard method. Vibration-rolling the compacted treatment soil achieved 95% of this compaction level.

High and low compaction treatments produced similar quantities of pasture dry matter in all 9 harvests. Over all harvests total dry matter production was 18% higher in the high compaction treatment plots, being  $17,010 \text{ kg ha}^{-1}$  from high compaction plots and  $13900 \text{ kg ha}^{-1}$  from low compaction plots (Appendix 6.2.1). Due to high variability within individual treatments this was not a significant difference. Volumetric water content measured on one occasion was similar in both compacted and uncompacted treatments (Appendix 6.2.2) although variability of the measurements was high.

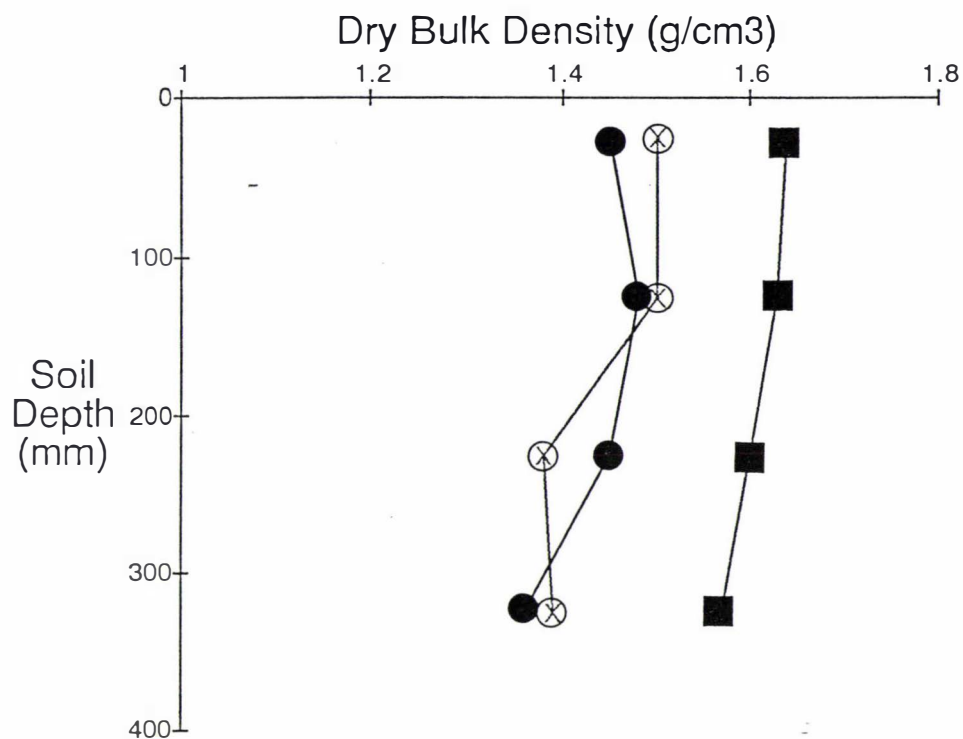
## 6.7 Rangitikei compaction treatments

Two pairs of high and low compaction treatments were compared. The first pair of treatments comprised Rangitikei sandy medium which was spread using either heavy or light bulldozers. The second pair of treatments comprised fill which was either in its natural compacted state or had been disturbed to c.0.20 m.

### 6.7.1 Commercially reclaimed area

In 1989 an area adjacent to the Rangitikei Trial site was commercially reclaimed using "high compaction" and "low compaction" methods of spreading soils. The commercially reclaimed area was covered with Rangitikei fine sand stripped from an adjacent site using a back-actor and dump trucks. The sand, which comprised topsoil and underlying 1.5 to 2.5 m of sand was spread over an adjacent mined and back-filled area to a depth 0.4 to 1.1 m. The sand was the same material used in construction of the Rangitikei trial plots. Sand in the "high compaction" area, c. one third of the reclaimed site, was spread with a wheeled 16 tonne tractor which exerted approximately  $1.1 \text{ kg cm}^{-2}$  ground pressure. Fine sand in the "low compaction" area was spread by a wheeled 2 tonne Bobcat which exerted approximately  $0.4 \text{ kg cm}^{-2}$  ground pressure. The number of passes of each vehicle was unknown. Both low and high compaction reclaimed

areas were raked, cultivated, fertilised and sown with a mixture of legume and perennial grass species.



Graph 6.3 Rangitikei trial. Bulk density ( $\text{Mg m}^{-3}$ ) of high (■) and low (⊗) compaction, commercially-reclaimed areas and control treatment (●) at depths of 0 to 0.05, 0.10 to 0.15, 0.20 to 0.25 and 0.30 to 0.35 m.



Photograph 6.1

Rangitikei trial. The commercially reclaimed area following rainfall, May 1989. The highly compacted area is on the LHS and the low compaction area on the RHS. Note surface ponding on the high compaction area.



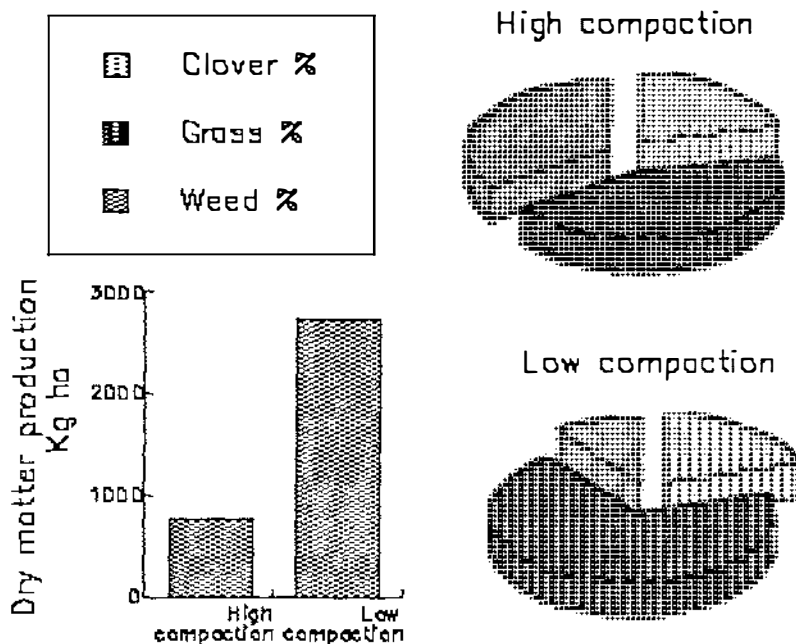
Soil physical characteristics and pasture growth were monitored in the "high compaction" and "low compaction" commercially reclaimed areas. Duplicate bulk density cores taken from three sites in each of "high" and "low" compaction areas six months after pasture sowing, showed that the "high compaction" area soil had significantly greater bulk densities than the "low" compaction and control areas at 0.10, 0.20 and 0.30 m sample depths. Similar bulk densities were recorded near the soil surface of both "low" and "high" compaction treatments where cultivation had relieved compaction. An unmined area used for grazing bulls and arable cropping, was chosen adjacent to the reclaimed area for a control site (see Figure 4.9). "Low" compaction and control areas had similar bulk densities at 0.10 and 0.30 m sample depths.



Photograph 6.2 Rangitikei trial. December 1989. Pasture in the high compaction area (RHS) is less productive than the low compaction area (LHS). Clover in the high compaction area is flowering (under stress).

A proctor compaction test using Rangitikei fine sandy loam C (unweathered) horizon showed that the maximum bulk density found in the high compaction area was 1.25 times the maximum compaction observed during the proctor test (Graph 6.1). Results of macroporosity measurements mirrored those of bulk density measurements, with similar levels of macroporosity in the cultivated zone at the soil surface. Additionally, the "high compaction" area had lower macroporosities at 0.2 and 0.3 m soil depths than the low compaction and control treatments (Appendix 6.3.4). The two compaction levels resulted in visibly different infiltration and pasture characteristics. Photographs taken in the week following pasture drilling showed surface water ponded on the highly compacted area after rainfall with no visible ponding on the low compaction area (Photograph 6.1).

The "high" compaction area produced less than a third of the total dry matter production of the "low" compaction area in the first harvest (Graph 6.4). The high compaction area contained three



Graph 6.4: Rangitikei trial. Dry matter production ( $\text{kg ha}^{-1}$ ) (bar graph, LHS) and herbage composition (% dry matter) (pie graph, RHS) of harvest one, 28-11-1989 from commercially-reclaimed, "high" and "low" compaction areas.

times as many weeds and significantly less grass than the low compaction treatment. The percentage of clover, by oven-dry mass was the same in both treatments, however, clover in the high compaction treatment was mainly reproductive (flowering) and that of the low compaction treatment was entirely vegetative (Appendix 6.3.6 and Photograph 6.2). In the second harvest three months later dry matter production in the high compaction area had increased from 30% to 38% of the low compaction area and herbage composition in both areas was not significantly different (Appendices 6.3.7a and 6.3.7b). Pasture production and composition in the compacted area was more variable than that in the low compaction area (Appendix 6.3.7a). A control area, sown at the same time as the commercially reclaimed area and with the same species was not constructed.

#### 6.7.2 Ripped fill and undisturbed fill treatments

Pasture production from in situ, undisturbed fill (high compaction) plots was significantly lower than production from simulated ripped fill (low compaction) treatment plots in five of seven harvests (Photograph 6.3 and Table 6.12). Vegetation on the high compaction plots was not totally killed by pre-sowing herbicide sprays. Additionally, the sowed ryegrass/clover sward established very poorly in the high compaction plots and the original vegetation was probably better adapted to the highly compacted and inhospitable media than the introduced ryegrass/clover sward. Pasture production was similar in both high and low compaction treatments in harvests six and nine. Distinctive flushes in vegetation on the undisturbed fill occurred prior to these harvests and may be due to the restricted rooting conditions of the high

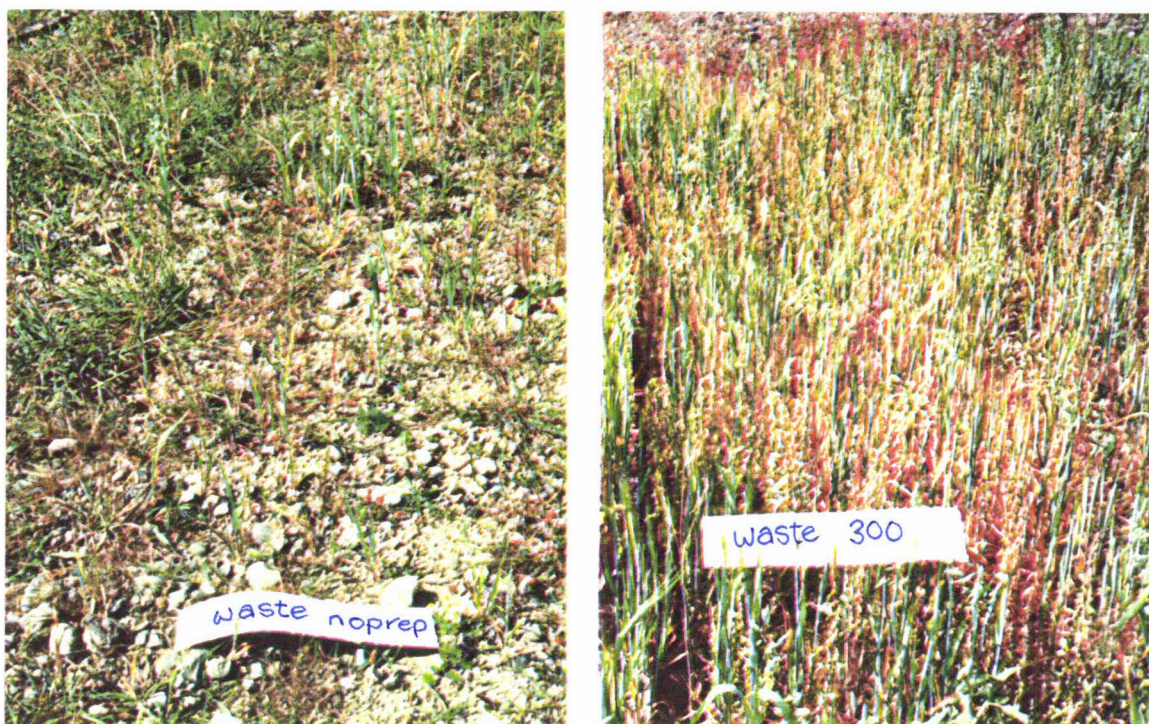


Table 6.12: Rangitikei trial: pasture dry matter production ( $\text{kg ha}^{-1}$ ) mean (LHS) and standard deviation (RHS) of low compaction and high compaction fill treatments. Comparisons of pasture production begin in Harvest Four as there was nothing to harvest in the high compaction treatment until that harvest.

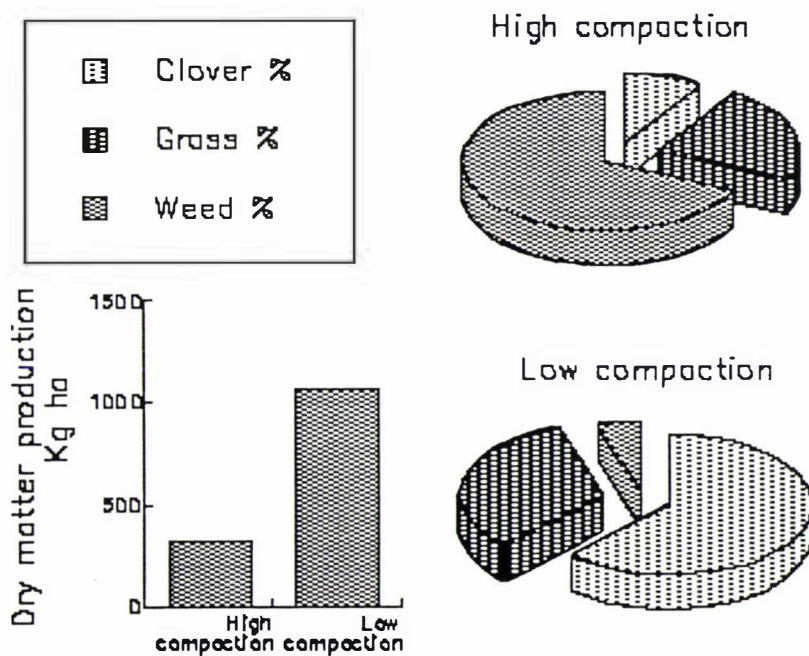
Harvest	Level of compaction		Significance
	High	Low	
4	340 $\pm$ 30	1080 $\pm$ 290	0.01
5	400 $\pm$ 110	1470 $\pm$ 440	0.001
6	270 $\pm$	2240 $\pm$ 630	0.89
7	880 $\pm$ 110	1470 $\pm$ 310	0.03
8	830 $\pm$ 180	1430 $\pm$ 850	0.001
9	380 $\pm$ 80	300 $\pm$ 50	0.13

compaction treatment allowing only a short "window" of favourable growth conditions. Additionally, the high compaction fill plots contained a thatch layer which contributed to the dry matter harvested when it grew tall enough. Production from the high compaction treatment was extremely variable and was reflected in large standard deviations (Table 6.12).

Composition of pasture of the high compaction treatment was significantly different from that of the low compaction treatment in harvest four and eight (Appendix 6.3.8). The high compaction treatment contained a higher percentage of weeds, i.e. non-clover or grass species. Regular mowing dramatically decreased the percentage of weeds in both treatments. The decrease in weed species favoured an increase in the percentage of clover species present in the high compaction treatment with the result that clover percentages were similar in both compaction treatments in harvest eight. In both dissected harvests the proportion of grass species was similar in both compaction treatments.



Photograph 6.3: Rangitikei trial. The barley and oats crop on high compaction (undisturbed, in situ) fill treatment (LHS) and low compaction (ripped) treatment (RHS). Note the failure of barley and oats to establish on the high compaction plot.



Graph 6.5: Rangitikei trial. Dry matter production ( $\text{kg ha}^{-1}$ ) (bar graph, LHS) and herbage composition (% dry matter) (pie graph, RHS) of harvest five compacted and ripped fill treatments.

## 6.8 Ohakea trial drainage treatments

The effect of soil drainage treatments on pasture and soil physical characteristics was analyzed using data from all eight treatments, comprising 32 plots of the Ohakea trial (Table 6.13), as all plots were either drained or undrained (Chapter 4.3.1 and Figure 4.8).

Table 6.13 Ohakea trial: Treatments used in analyses of drainage effects. "\*" = treatment included in the statistical analysis. "na" treatments were not constructed.

Treatment	Soil Replacement Treatment				
	A only	AB	A on B	Control	Other
High compaction	*	*	*	na	na
Low compaction	*	*	*	*	*

### 6.8.1 Soil volumetric water content and depth to water table

The drainage treatment (Figure 4.8 ) was consistently associated with lowered soil volumetric water contents at all measured increments to 0.60 m. The water content at 0 to 0.15 m and 0 to 0.20 m was lowered by c.3%, with statistical significance ranging from 0.03 to 0.16 over 7 measurements. Soil volumetric water content in the drained treatment was significantly lower at depths greater than 0.20 m at only the first recording (Appendix 6.4.1). The variability in water content increased with soil depth (Table 6.14 and Appendix 6.4.1). This was probably influenced by increased stone contents which reduced the number of samples able to be taken.

Table 6.14: Ohakea trial. Mean volumetric water contents (%) of drained and undrained treatments measured by TDR on October 30 1990. The "effect of drainage" is the reduction in volumetric water content (%) resulting from drainage.

Treatment	Volumetric water content (%) at soil depth (m)			
	0-0.15	0.15-0.3	0.3-0.4	0.4-0.6
Drained treatment	24.7±2.8	26.8±5.8	42.4±8.0	31.4±3.8
Undrained treatment	29.6±3.8	33.3±2.8	50.0±4.5	36.0±2.9
Significance	.03	.03	.07	.14
Number of samples	32	32	30	28
Effect of drainage (%)	4.9	6.5	7.6	4.6

Two measurements of the depth to free water on 12 August and 29 August 1991 showed the drained treatment had a significantly lower water table than the undrained treatment with the water table of the drained treatment depressed by 0.15 and 0.13 m respectively in each measurement (Appendix 6.4.2).

#### 6.8.2 Soil bulk density and macroporosity

The bulk density at 0.30 to 0.35 m soil depth was higher in drained plots. Additionally, bulk density was consistently marginally higher on drained plots by 0.02 (0.10 to 0.15 m depth) to 0.09 Mg m<sup>-3</sup> (0.20 to 0.25 m depth) (Appendix 6.4.3). Changes in bulk density at soil depths greater than 0.10 m may have been caused by differential moisture contents at the time of trial construction, with drained soils <sup>being</sup> nearer the critical moisture content, identified in the proctor compaction test of the Ohakea soil (Section 5.5), and thus more susceptible to compaction. Macroporosity, measured at 0.1 k Pa suction was not significantly affected by the drainage treatment (Appendix 6.4.4).

#### 6.8.3 Pasture dry matter production and herbage composition

Draining the Ohakea soil resulted in a significant increase in pasture dry matter production in harvests 8, 13 and 14, and a significant decrease in production in harvests 6 and 11 (Table 6.15 and Appendix 6.4.5). In the first 5 of 14 harvests and periods where soil moisture levels were estimated to be non-limiting on a weekly basis (Chapter 5.6) there was no significant dry matter production effect associated with the drainage treatment (Table 6.15).

Table 6.15 Ohakea trial. Influence of drainage on pasture dry matter production. "none" = differences not significant at  $p=0.10$  i.e. no effect of drainage, "+" = significant positive effect at  $p=0.10$ , "++" = significant positive effect at  $p=0.05$ . "--" significant negative effect at  $p=0.10$ .

<b>Harvest</b>	1	2	3	4	5	6	7
<b>Influence of Drainage</b>	none	none	none	none	none	--	none
<b>Harvest</b>	8	9	10	11	12	13	14
<b>Influence of Drainage</b>	++	none	none	--	none	++	+

*Correlation analyses of volumetric water content and dry matter production*

Soil volumetric water content was measured using a TDR from October 10 1990 to February 20 1991, corresponding with Ohakea dry matter harvests 9 (October 28 1990), 10 (December 6), 11 (January 18 1991), 12 (February 10) and 13 (March 3). Soil moisture content was positively correlated with dry matter production in periods of probable water deficit (Table 6.16). For example, positive correlations with moisture content occurred with harvests cut in January and February. Negative correlations occurred in periods of probable water surplus, for example in harvests cut in September and July. A soil moisture balance calculated from daily evapotranspiration and rainfall record is shown in Graph 5.5.

Table 6.16 Ohakea trial. Summary of correlation of volumetric water content with dry matter production for Harvests 8 to 14. "none" = no significant correlation at  $p=0.10$ , "+" significant positive correlation at  $p=0.10$ , "-" = significant negative correlation at  $p=0.10$ , "++" = significant positive correlation at  $p=0.05$ . "-/+" correlation differs with the depth over which volumetric water content is determined.

<b>Harvest</b>	8	9	10	11	12	13	14
<b>Correlation</b>	-	-/+	none	+	+	none	-

Pasture production was more frequently correlated with soil moisture contents in the surface 0 to 0.20 m than soil water contents in the 0.20 to 0.60 m soil depths. This probably because the bulk of pasture roots are concentrated in the surface 0.20 m of the soil profile.

#### 6.8.4 Root mass and root length

Root mass and root length measurements taken from drained and undrained plots at the end of the trial in August 1991 were similar (Appendix 6.4.6). Table 6.17 shows a trend of increasing significance of drainage on root length as soil depth increases to 0.35 m.



Table 6.17 Ohakea trial. Pasture root length (m per 1.2 l of sample) of drained and undrained treatments at 0 to 0.05, 0.10 to 0.15, 0.20 to 0.25 and 0.30 to 0.35 m depths at the Ohakea trial. Brackets indicate a negative number, i.e. disadvantage of drainage.

Treatment	Soil Depth (m)				
	0	0.1	0.2	0.3	Total
Drained	510±210	110±90	44±9	35±19	690±220
Undrained	530±150	140±60	54±42	25±18	740±180
Significance	.81	.25	.48	.20	.56
Number of samples	28	27	30	30	30
Advantage of Drainage	(20)	(30)	(10)	10	(50)

## 6.9 Discussion

### 6.9.1 Compaction treatments

In this section results from each of the four trials are discussed and reasons for differences in measured characteristics offered. Areas in which the compaction trial may have been improved to further define effects and directions of future research are identified in Chapter Seven.

In three of the four trials high compaction treatments were defined by a zone of significantly greater bulk density in the soil profile than occurred in their equivalent low compaction treatments. Bulk density was not measured in the Rangitikei fill high compaction treatment as the contrast with the low compaction (ripped) treatment was extreme. Additionally, any excavation method was subject to large errors due to a wide variety of constituent materials; from steel, bitumen and concrete blocks to porcelain; and uneven dimensions of holes.

Pasture growth of the Ashhurst trial was not significantly affected by the level of compaction imposed in any of the nine harvests, although the high compaction treatment consistently outproduced the low compaction treatment and total dry matter production was 18% higher in the high compaction treatment plots. Potential differences in production may have been masked by variation of soil across the trial, evidenced by the large standard deviations associated with results (high within-treatment variation) and differential soil moisture contents within the trial (Figure 5.2). Moderate compaction of a shallow, gravelly soil with high hydraulic conductivity and low water holding capacity, such as the Ashhurst soil, may aid growth of pasture by reducing loss of water by percolation through the base of the profile. The mean bulk density

achieved in the Ashhurst trial by compaction,  $1.40 \text{ Mg m}^{-3}$ , is not normally regarded as limiting to plant roots in a silty textured soil. Even if roots were restricted, the location of the compacted layer at 0.20 m depth provided a reasonable volume of uncompacted soil for unimpeded root exploitation.

At the Ohakea trial bulk density in the surface 0.25 m of the soil profile was usually negatively correlated with dry matter production, although only 25% of correlations were significant. In the Ohakea trial and the commercially reclaimed Rangitikei trial, compaction was most limiting to pasture growth during the plant establishment phase, with the largest differences between high and low compaction treatments occurring in the first harvest. The shallow and extensive (widespread) compaction characteristic of the Rangitikei commercially-reclaimed area resulted in dramatic reductions in dry matter production. Additionally, herbage of the high compaction treatment contained a high percentage of weeds. Clover-ryegrass swards are generally selected for maximum production in soils of high physical and chemical fertility and are generally less competitive in adverse soil environments than weed species. Unfavourable soil conditions in the high compaction area were also flagged by early flowering of white clover; This may have been an indicator of water stress induced by restricted root penetration into the compacted soil horizons. Major differences in pasture composition were evident only in the first harvest of both Ohakea and Rangitikei trials. Comparison of herbage composition of the Rangitikei fill compaction plots was influenced by not permanently killing the original vegetation and poor establishment of sown pasture in the hostile environment of the high compaction treatment.

The compaction treatment at the Ohakea trial was less severe than that of either Rangitikei trial, as the compacted zone was deeper and of lower intensity. Implementation of a high compaction treatment at 0.20 m, equivalent to the base of the A horizon in Aonly and AonB treatments, resulted in an average increase in bulk density of  $0.31 \text{ Mg m}^{-3}$  at the beginning of the trial. Soil cores excavated from compacted and uncompacted treatments immediately following compaction and more than two years later indicated that the band of high compaction in the Ohakea trial had either altered in depth or had been disrupted. The compact zone was probably maintained in at least the Aonly and ABmix treatments and was probably located at a shallower depth in the AonB treatment, leading to sampling at a standardised depth of 0.20 to 0.25 m missing the compacted zone (cores used for taking soil samples for bulk density were 50 mm tall). Prodding the soil profile with a knife located the compacted layer in some plots at 0.18 and 0.19 m depth.

The level of compaction attained, and possibly the continuity of the compacted layer was not generally sufficient to have a significant effect on overall pasture production despite dry matter production was negatively correlated with bulk density at soil depths of 0 to 0.20 m in 57% (8 of 14) of harvests with seven of the first eight harvests being negatively correlation with bulk density at one or more soil depth. However, the high compaction treatment only limited pasture productivity significantly in the first harvest. This result was unexpected given the location of the compacted layer at 0.20 m. These results indicate pasture was particularly sensitive to elevated



levels of compaction in the pasture establishment phase. Roots of plants establishing in the compacted plots were more likely to have been limited by low soil temperatures or high moisture contents than have been impeded physically, however, root penetration in low compaction treatments was probably faster. In the long term a small number of roots were still able to penetrate the compacted soil through cracks (low resistance pathways) and gain access to moisture and nutrients below. In 71% of harvests there was no significant difference in dry matter production between high and low compaction treatments. In 21% of harvests (3 of 14) high compaction treatments significantly outproduced low compaction treatments. In the remaining 13 harvests high compaction treatments either promoted or had no impact on pasture production. Ryegrass was the only sward component significantly affected by the compaction treatment with a significantly ( $P=0.08$ ) lower percentage of ryegrass dry matter in high compaction treatment swards in harvest 1.

The impact of the high compaction treatment on pasture production and rooting characteristics in the Ohakea trial varied between the three soil horizon replacement treatments. Where soil horizons were replaced in order (the AonB treatment) pasture production was consistently higher on low compaction plots, although the margin was rarely statistically significant (2 of 14 harvests). Compacted plots of the ABmix treatment consistently outproduced their low compaction counterparts. The ABmix media may have had a paucity of micropores (drained between 10 and 1500 k Pa) in which soil moisture is contained. Compaction may have increased plant available water by slowing water movement through the soil profile and increasing the number of small, water-containing pores in the compaction zone by disrupting voids created by lumps of non-friable, sticky Bw<sub>2</sub> horizon. The Aonly soil replacement treatment benefitted from low compaction during pasture establishment but subsequently produced more pasture on compacted plots. I had expected pasture production from the Aonly treatment to vary seasonally with compacted treatments producing more pasture during summer months and less pasture during extended wet periods when compaction impeded drainage of water from the profile and exacerbated anaerobic soil conditions. The absence of depressed winter production in compacted plots could have been due to the high tolerance of pasture, particularly ryegrass, to restricted rooting conditions and long periods of low soil oxygen conditions. The result may have been accentuated if the Ohakea soil was not as poorly draining as indicated by the gleyed subsoils. Consequently results indicate a summer moisture deficit was probably the greatest factor limiting pasture growth at the Ohakea trial.

Both high and low compaction treatments of the Ohakea trial had similar macroporosity values at all measured soil depths with the exception of the Aonly treatment in which the high compaction treatment had a lower macroporosity at 0.20 to 0.25 m depth, the compacted zone, than the low compaction treatment. There were few significant correlations between macroporosity and pasture production and such correlations were not expected as levels of soil macroporosity measured at 0.1 k Pa suction were generally above 16% of the soil volume; a level usually non-limiting to root growth. Two of 14 harvests showed positive correlations between macroporosity and pasture dry matter production. Additionally, significant negative correlations

between macroporosity and pasture dry matter production were found for 36% (5 of 14) of harvests. Two of these three soil depth and harvest combinations also showed significant positive correlations with bulk density, which is expected as generally increased bulk density is associated with destruction of macropores. This adverse effect of high macroporosity may result during dry conditions where a lower soil water holding capacity is created as macropores are not generally filled with water. One harvest and soil depth showed a negative correlation with both bulk density and macroporosity, which is not expected and could be due to the beneficial effect of increased plant available water in micropores created with compaction (high bulk density) being outweighed by restricted plant root exploration. Large standard deviations associated with macroporosity determinations at all soil depths for the ABmix soil replacement treatment was probably due to the formation of irregular pockets of loamy A horizon material within a more poorly structured matrix from mixing of soil A and B horizons during trial construction.

In 5 of 7 in situ volumetric water content measurements the compaction treatment had no significant effect on soil volumetric water contents to 0.60 m depth. Additionally, volumetric water content from 0.30 to 0.60 m was not significantly affected by compaction treatment on any measurement date. On two occasions soil volumetric water content from 0 to 0.30 m was significantly drier in high compaction treatments, possibly due to greater root length and hence water extraction in the surface 0 to 0.20 m.

The high compaction plots had total root lengths which were 65% and 60% of equivalent low compaction treatments at 0.20 and 0.30 m soil depths respectively, although these differences were not significant due to high sample variability. High compaction Aonly and AonB soil replacement treatments tended to have longer roots in the surface 0 to 0.15 m depth and shorter roots in the 0.20 to 0.35 m soil depth. This suggests that compensatory rooting occurred in the surface (less compacted) zone of high compaction treatments, i.e. high surface bulk densities favoured rooting in deeper, presumably more favourable, soil horizons. Conversely high bulk densities which restricted root exploration at 0.30 m depth promoted root exploration above this depth. Results from correlations of root length with bulk density indicated that high surface bulk densities favoured greater rooting development in deeper soil horizons that were probably more amenable to root growth, although the majority of roots were still in the surface 0.15 m of soil. Conversely high bulk densities at 0.30 m, which limited root exploration, promoted root growth measured as root length at shallower depths. A significant positive correlation was found between macroporosity and root length at 0.20 m soil depth. Correlations between macroporosity and root length indicated that deeper rooting is "favoured" by pasture if soil conditions are beneficial at the greater depth.

Low compaction treatments produced significantly greater root mass than high compaction treatments only at the 0.30 to 0.35 m soil depth with no significant interaction between soil replacement and soil compaction treatments related to root mass at any soil depth, probably partly due to a high root mass variability. Root mass at 0.20 m and bulk density at 0.20 m were significantly negatively correlated; conversely root mass and macroporosity at 0.20 to 0.25 m

depth were significantly positively correlated. Significant negative correlations were found between macroporosity at 0.30 m and root length at 0.10 m depth, indicating that favourable levels of macroporosity at one soil depth may promote root development at that depth and, assuming limited plant resources, decrease rooting at other depths.

Surprisingly, total root mass was significantly positively correlated with bulk density at 0.20 m. This may be a function of compensatory rooting, and indicates how a high density horizon at depth may result in higher or similar pasture production compared with low compaction soils in periods with a water surplus or no water deficit (i.e. in periods of high water table plants with roots concentrated in surface horizons may have a larger proportion of active roots). However, pasture with a shallow root distribution is susceptible to periods of drought. This is exacerbated when roots within compacted zones are shorter, fatter and less efficient at water and nutrient removal thus much less efficient than normal roots on a per mass basis (Section 6.2.3).

Root length and root mass measurements are intrinsically highly variable. Root length was less variable than root mass and although there was no positive correlation between root length and pasture production from any harvest, experiments by other researchers have shown that root length may provide a clearer indication of above ground yield than root mass. The paucity of replicate samples from each Ohakea plot exacerbated this variability. Root cores were not taken from the Ashhurst trial or commercially- reclaimed Rangitikei trial. Sampling for roots from the Rangitikei trial high compaction fill treatment area was attempted... and abandoned due to lengthy excavation times and the probability of large errors associated with pulverising of roots by crowbars when excavating "cores" and difficulty in digging a hole of consistent volume and dimensions.

Pasture in the Ohakea, Ashhurst and Rangitikei trials were ideally managed. Plots were harvested only when soil conditions were least conducive to compaction. "Pasture utilisation" was restricted to two days every 4 to 8 weeks. Under less than ideal stock management small initial differences in sward density or soil hydraulic conductivity could be amplified and exacerbated in a self-perpetuating cycle of pugging --> compaction --> decreased infiltration of water --> wetter soil --> increased pugging. The commercially reclaimed area at the Rangitikei trial showed, in small areas, the potential effect of poor grazing management.

The trials focused primarily on the effect of different levels of compaction on pasture productivity. Other adverse factors that have been related to excessive compaction and were observed at the Rangitikei commercially reclaimed trial site included:

- \* poorer quality pasture and lower utilisation of pasture if grazed during wet periods due to trampling/contamination by mud. Additionally, shorter pasture requires more effort by stock to graze and in severe situations may decrease intake by stock.
- \* costs of weed control (spraying).
- \* decreased flexibility of land use due to a lower number of days that animals can be grazed without pugging damage.

- \* erosion through water run off during the establishment phase. Rill-erosion channels 50-100 mm deep were observed at the site.
- \* increased machine costs as more power is needed to cultivate the compacted area.

### 6.9.2 Drainage Treatments

Measurements of volumetric water content and depth to water table indicated that the drainage treatment was acting as designed and decreasing the amount of moisture in the soil profile at all measured increments to 0.60 m with an average 3% decrease of soil volumetric water in the 0 to 0.15 m depth and an average 0.12 m reduction in depth to free water in drained plots. Measured soil physical properties were similar in both drained and undrained treatments although bulk densities of drained plots were elevated significantly at 0.30 to 0.35 m depth. This differential bulk density was not reflected in soil macroporosity measurements at this depth. Bulk density differences may have resulted from the moisture content of drained treatment soil at that depth at the time of trial construction closer to the critical moisture content at which the soil was most susceptible to compaction.

The drainage treatment had no significant effect on pasture root mass or root length at any soil depth measured at the end of the trial. In 64% (9 of 14) of pasture harvests drainage had no significant effect on pasture production. Dry matter production was significantly higher in drained plots in 3 of 14 harvests and significantly lower in 2 harvests. The impact of drainage over time followed a cyclic trend probably related to the availability of water and oxygen, with drainage advantageous to pasture dry matter production in periods of moisture surplus and detrimental to growth during periods of moisture deficit. Undrained treatments would have increased growth in summer months and this may compensate for depressed growth in winter, however pasture is generally more valuable in late winter and early spring when feed deficits are usually most critical. Pasture dry matter production was more frequently correlated with water contents in the surface 0.20 m soil, which contained the greatest root mass and length, than in water contents of deeper horizons. Volumetric water content was generally positively correlated with dry matter production during periods of water deficit, and negatively correlated with dry matter production in periods of water surplus. Depressed pasture yields associated with the undrained treatment during periods of moisture surplus are probably linked with inadequate oxygen supply to roots. Additionally, in Yellow Brown Earth and Brown Granular Loam soils anaerobic conditions may mobilise levels of Mn toxic to plants, although this effect is more likely to occur in horizons containing large amounts of Mn concretions (Singleton *et al.*, 1987). Where the horizon containing concretions was dispersed throughout the soil profile (the ABmix treatment) this effect may also have affected pasture productivity.

Benefits of drainage may increase over time. In the initial years disruption of the gleyed soil profile would have resulted in an increase in hydraulic conductivity; over time soils will consolidate and this may be reflected in greater differences in soil water contents thus enlarging the difference in soil moisture and aeration status between drained and undrained treatments.

This effect would probably have been exacerbated if the plots had been grazed by animals or traffic occurred under sub optimal soil conditions.

## 6.10 Conclusion

### 6.10.1 Compaction

#### *Ohakea trial*

- \* The compacted treatment ( $\rho_d 1.64 \pm 0.11$ ) had significantly higher bulk density than uncompacted treatment ( $\rho_d 1.31 \pm 0.19$ ) at 0.20 m depth immediately following construction of the trial.
- \* Two years later, bulk density and porosity at 10 k Pa suction of low and high compaction treatments were not significantly different.
- \* Pasture dry matter production either benefitted or was not significantly affected by moderate compaction of the soil profile at 0.20 m depth, except in the first harvest when the low compaction treatment produced significantly more than the high compaction treatment.
- \* Trends showed that the ABmix soil replacement treatment was favoured by the applied "high" compaction treatment, while the AonB treatment was negatively affected by high compaction.
- \* Pasture production was negatively correlated with bulk density at depths to 0.20 m
- \* The effect of compaction varied with depth of profile, with lower levels of compaction than that applied at 0.20 m adversely affecting production of above-ground dry matter and roots.
- \* Greater root mass was produced at 0.30-0.35 m depth in low compaction treatments
- \* Root length and root mass were highly variable and were statistically similar in both high and low compaction treatments, although high compaction treatments produced 65% and 60% shorter roots at 0.20-0.25 and 0.30-0.35 m depths.
- \* Root length in AonB treatment was shorter in high compaction treatments.
- \* Root length and bulk density were negatively correlated at 0.20-0.25 and 0.30-0.35 m depths.
- \* Root length and macroporosity were positively correlated at 0.20-0.25 m depth.
- \* Root length at 0.10-0.15 and 0-0.05 m and macroporosity at 0.30-0.35 and 0.10-0.15 m depth were respectively negatively correlated.

#### *Ashhurst trial*

- \* The high compaction treatment ( $\rho_d 1.40 \pm 0.08$ ) had significantly higher bulk density than uncompacted treatment ( $\rho_d 1.27 \pm 0.12$ ) at 0.20 m depth immediately following construction of the trial.



- \* Low and high compaction treatments produced statistically similar dry masses of pasture, although total production over 9 harvests was 18% higher in the high compaction treatment.

#### *Rangitikei trial*

- \* The commercially reclaimed, high compaction area had significantly greater bulk densities and lower macroporosity (10 k Pa suction) at 0.10-0.15, 0.20-0.25 and 0.30-0.35 m depths.
- \* The high compaction treatment of both commercially reclaimed and fill areas produced significantly less pasture dry matter in most harvests. The high compaction commercially reclaimed area produced less than 40% of the low compaction treatment.
- \* Both high compaction treatments contained a greater % of weeds. In the commercially reclaimed area both high and low compaction treatments contained similar percentages of clover, although clover in the high compaction treatment was dominantly reproductive, and that of the low compaction treatment predominantly vegetative.

#### 6.10.2 Drainage (Ohakea trial)

- \* Drainage lowered the volumetric water content of the soil at all measured increments to 0.60 m by a mean 3% in seven measurements (at four depths).
- \* Pasture production was similar in both drained and undrained treatments in the majority of harvests.
- \* Pasture production was greater from drained plots in 3/14 harvests and undrained plots in 2/14 harvests.
- \* Drainage had no significant effect on bulk density or macroporosity at depths to 0.25 m. Root mass and root length were similarly unaffected by the imposed drainage treatment at all soil depths to 0.35 m.

The effects of compaction may be significant only when very high compaction levels are present, during pasture establishment, when soils are imperfectly drained or when weather conditions exacerbate deficiencies in plant available soil water or soil oxygen. Adverse effects related to compaction are accentuated by shallower or restricted rooting systems which deprive plants access to nutrients and water. Both drained and low compaction treatments are beneficial under sustained periods of high soil moisture during which gaseous diffusion is reduced i.e. anaerobic conditions, ion reduction and ethylene/carbon dioxide concentrations increase. Conversely moderately compacted and undrained conditions were beneficial to plant production during periods of moderate moisture deficit as moisture levels were elevated in those treatments. Extreme moisture deficits were not experienced during the trial. In such circumstances pasture production may be elevated in undrained and low compaction plots where a greater length and mass of roots at depth can more fully exploit moisture at depth.

## Chapter Seven Principles and recommendations for reclamation of soils in the greater Manawatu region.

### 7.1 Determining the success of reclamation

The objectives of reclamation vary depending on the post-mining land use and desires of people and groups with interests in the project. Successful reclamation is when the short, medium and long term objectives of the reclamation project have been achieved. Agricultural reclamation is primarily concerned with achieving the same yields as were produced prior to mining, with the same range of crops and similar management inputs, for example similar timing of crop operations, classes of stock, rate and frequency of fertiliser applications and pest control. In other words, the reclaimed land is at least as agriculturally productive as comparable unmined land. However, even in agricultural reclamation objectives may not simply be production orientated. Objectives may include:

- i) Land stability. Soil losses by erosion and nutrient leaching are reflected in quality of water discharged from the area (suspended solids and nutrient contents).
- ii) Site aesthetics. The visual appearance of a mined site may be determined by the level of the land surface, the angle and contour of batters and scarps and percentage of ground covered with vegetation.
- iii) Flood mitigation. Flood mitigation on the reclaimed area or adjacent areas is important when mining Recent soils without flood-bank protection.
- iv) Provision of wildlife habitat. Wildlife habitats can be created using lakes in pits formed where mining extends below the water table. Such reclaimed habitats are popular for trout fishing and shooting of waterfowl in Canada. In England, establishment of copses and hedgerows on reclaimed land is promoted to enrich wildlife.

#### 7.1.1 Methods and measurements of the success of reclamation.

This section presents methods and measurements that can be used to determine the actual productivity of a site reclaimed to agricultural use. Evaluating the success of reclamation is more accurate when the site is thoroughly characterised before operations begin (particularly the soils) and control (comparison) areas are retained.

Methods of site and soil characterisation are included in section 7.4 (Recommendations).

A "control" site may take several forms. All controls must be on soils as similar to those mined as possible and are ideally initiated at the same time reclamation begins. The four main options for controls for agricultural reclamation in order of preference are:

- i) Sited on soils at the mine-site, similar to the soils to be disturbed, which are cultivated at the same time as reclaimed soils, sown with the same species and subjected to similar management techniques as reclaimed areas.



- ii) Not sited on the mine-site but subjected to the same management techniques as reclaimed areas. This type of control is used when no suitable areas of the original soil remain on site. It is necessary to be as close to the mine as possible because rainfall patterns and other climatic factors may vary spatially, especially where orographic effects occur.
- iii) Sited on undisturbed land with different management from reclaimed areas located on or off the mined site. Undisturbed areas with original pasture species and maintaining separate management systems from reclaimed soils may<sup>be</sup> used in addition to, "control" areas but should not usually be used instead of type (i) and (ii) controls (Chapter 4.3). This type of control is invaluable, however, where indigenous or complex ecosystems are disrupted by mining.
- iv) Historical information about the characteristics of the soils, production and management that were present at the mine-site before land disturbance.

Controls located on soils at the mine-site under equivalent management systems as reclaimed areas are the best indicators of the success of reclamation, i.e. whether productivity of reclaimed soils is equivalent to that of original soils. Historical information on its own is of limited value as management techniques may change with the changes of ownership sometimes associated with mining. The special requirements of management of reclaimed land and alterations in the areas of land available for agricultural use within a mined farm also affect the value of historical information. Additionally, crops grown in past seasons are subject to different climatic conditions. Historical data on crop management can also be time-consuming to collect and may be prone to inaccuracies as farmers tend to report the best yields or years.

The ability of a company to achieve the productivity targets required and the probability of achieving the pre-mining productivity of a reclaimed soil can be assessed before reclamation begins with an evaluation of the mining company's reclamation plans for a site. The detail and plausibility of reclamation aims, scheduling, guidelines and staff education will all point to the likely success of the proposed reclamation, as will the evaluation of any reclamation trials and how trial results are incorporated into the methods used in large-scale reclamation. Generally trials utilising the same earth-moving equipment and post-mining management used in large scale reclamation are more valuable than trials which use different methods to those practised in commercial-scale reclamation.

The most important soil parameters which control the success of reclamation are:

### *Soil physical properties*

The success of reclamation will be indicated by physical properties of the reconstructed soil profile immediately following soil placement and seed-bed preparation, except where nutrient limitations or toxicities occur. An examination of the profile of a reclaimed soil before sowing can allow rectification of conditions and avoid the expense of a failed crop, although preventing the creation of adverse soil conditions in the first place is usually more cost effective than ameliorating adverse properties of replaced soils. Physical properties, along with organic matter, control the balance of moisture and aeration, soil temperature and soil resistance<sup>which</sup> are major controls of plant establishment and growth and soil microbiological activity (Chapter 6.2 and 6.3). The most important and practical measurements of soil physical properties are:

- i) Bulk density. Elevated bulk densities at the soil surface will affect seedling germination and establishment while elevated bulk densities in the surface to 0.15 to 0.25 m may adversely affect pasture production and tolerance of adverse climatic conditions. Bulk density below the surface 0.20 m will change very little over time, unless deep ripping is implemented. Elevated bulk density at depths greater than 0.20 m may not detrimentally affect pasture growth, as most pasture roots occupy the surface 0.15 m of the soil profile, but will probably limit the versatility of the soil as measured by the productivity of crops with deeper optimum rooting depths than pasture. Any decrease in productivity of these crops may be due to a limiting of the rooting zone and will be exacerbated in climates where summer moisture deficits or winter moisture surpluses occur (resulting from moisture and oxygen deficits respectively). Penetration resistance may also be used to estimate the level of soil compaction.
- ii) Pore size, continuity and volume. These characteristics govern the rate at which water moves into the soil (infiltration rate or saturated hydraulic conductivity,  $K_{sat}$ ) and how quickly water moves through the soil (drainage rates or unsaturated hydraulic conductivity). The volume, number and continuity of macropores (measured indirectly by  $K_{sat}$  or volume of air in a soil core at -10 k Pa) also determines the volume and movement of air in soil and thus influences plant root and microbiological activity. The number of medium sized pores determines how much water is available for plant growth (Chapter 6.2.1). All these characteristics may be affected by compaction. Additionally, compaction of subsurface layers can lead to perched water tables and saturation of the soil profile above the compacted zone.
- iii) Tensiometer measurements. Measurements of water tension indicate whether plants are likely to be under moisture stress. Experiments in Wellington, Palmerston North and

Taranaki have shown that the rate of ryegrass leaf extension declines when soil moisture deficit reaches 50 to 60 mm (Scotter et al., 1979b; Parfitt et al., 1985a; 1985b). In a soil with a layer which impedes root extension within the surface 0.5 m, for example a compacted layer, this decrease in pasture leaf extension (growth) may be dramatic (Parfitt et al., 1985a).

When determining soil physical data evaluate both the variability (standard deviations) and mean values of bulk density and pore size characteristics. If soil physical characteristics are poor, successful reclamation will probably be substantially more expensive because, unlike soil chemical properties, physical properties are difficult and/or take a long time to improve, especially at depths greater than 0.20 m. Management parameters such as the timing of operations, days of possible grazing and extent of pugging usually reflect soil physical characteristics while soil chemical properties may indicate potential stock health risks from deficiencies or toxicities.

#### *Pedological features*

- i) Soil structure and texture. Pits dug immediately following soil replacement allow detection of features likely to inhibit reclamation success, such as laminar zones of high compaction or sharp textural changes, which may form barriers to water and root movement. They may also reflect the extent of topsoil dilution. The size of structural units may indicate the pattern and extent of rooting before crops are established. Examination of soil structure over time will indicate changes in stability and resilience of the reclaimed soil.
- ii) Aeration. Over time, the level of oxygenation throughout the profile of most reclaimed soils in New Zealand is exhibited by soil colour. Grey, blue or green (gleyed) colours indicate zones of poor aeration; where the water table is extremely high, or perched, during wet months pale mottling may extend into topsoil areas. Black iron-manganese concretions develop in iron-rich soils where the water table remains high and fluctuates over periods of moisture surplus. Rust-coloured layers in sandy-textured material indicate the position of pans which will restrict water and root movement.

#### *Biological and chemical properties*

- i) Carbon content. Total carbon content of a soil is useful to measure at the time of soil replacement and over time to indicate the build-up of soil organic matter. Total carbon can also be used to indicate the extent of dilution of topsoil by other materials.

- ii) Soil respiration. This is an indicator of the activity of soil micro-organisms and thus the development of nitrogen cycling. When land is disturbed there is an initial increase in respiration rate as micro-organisms mineralise organic matter in soil including newly accessible (aerated) substrates. This flush, which occurs with any soil cultivation, is usually followed by a drop in microbiological activity as an equilibrium is established. Consistently increasing soil respiration over time can indicate development of soil biological and chemical fertility, allowing a reduction in inputs of chemical fertilisers. The number, volume and siting of samples is critical to achieve a representative assessment of soil respiration.
- iii) Presence and numbers of macro-organism species, for example earthworms, arthropods and ants. In Australia the species of ants present in reclaimed areas is used to indicate the degree to which natural ecosystems, similar to original undisturbed ecosystems, have been reached (Majer, 1983).
- iv) Amount of total and readily-available nutrients. These are a measure of the potential and readily available pools of plant nutrients and therefore indicate which fertilisers will be required. Toxic levels of elements are not usually encountered in aggregate mines, particularly where aggregate is sourced from river terraces.

#### *Plant productivity*

- i) Gross measurement of above-ground plant production is the standard measure of soil productivity. It is relatively quick to measure and, particularly for arable crops, the saleable portion of the total above-ground yield of the crop influences profitability. Gross productivity measurements, however, can mask important differences in crop production, especially in perennial pastures.
- ii) Ideally, detailed measurements of crop characteristics should be used in addition to measurements of gross productivity. In pastures, leaf extension rates and maturity status of tillers indicate the rate of tissue turnover in a sward and hence the amount of organic material being added to the soil.
- iii) Spatial characterisation of root length and root diameter are effective, but time consuming measurements which reflect the effect of soil physical and chemical conditions, and indicate the optimum depths and types of remedial management required. For example, concentrations of roots above or below a compacted layer will identify the depth at which remedial ripping will be most effective.

- iv) The location and maximum depth of roots in a soil profile indicate the resilience of a crop to periods of low soil moisture. Roots are best characterised at times of the year when they are actively growing (spring and autumn) and/or when limitations to growth are expected to occur. For example, anoxic conditions resulting from a high water table are most easily identified during periods of high soil moisture.

## **7.2 Identification of resilient soil types and classification of soils in the greater Manawatu region by ease of reclamation**

The best sites to mine for aggregate are those containing soils which are easy to reclaim to the chosen post-mining land use, all other things being equal (Chapter 8.7). In the context of this research these become the easiest soils to return to their previous physical and chemical productivity and versatility (note this includes biological fertility which is intricately linked to both chemical and physical fertility). The ease of achievement of reclamation objectives with a given soil varies with the post-mining land use and the position of that soil in the landscape. For example, creation of wetlands is easier with a soil which restricts percolation of water through the base of the profile or when mining will lower the surface of the land below the water table. However, establishment of marginal plantings around wetlands is easier with a free-draining soil.

The soils most easily restored to their pre-mining productivity and versatility have the following characteristics:

- i) Moderate to high saturated and unsaturated hydraulic conductivity (infiltration and drainage rates respectively).
- ii) High physical fertility: aggregated topsoils and subsoils with strong, stable structures.
- iii) Moderate to high levels of organic matter in topsoils. This usually means the soils have moderate to high levels of plant available water and are resilient to gross disturbance. The amount of plant-available water is particularly crucial during seedling germination.
- iv) High levels of bio-chemical fertility, measured by biological activity (level of respiration and earthworm numbers) and organic matter content will normally have a greater resilience to disturbance with nutrient cycling and soil structure re-establishing faster following disturbance. The chemical fertility of a soil is of lower importance, given the ability to supplement soils with inorganic fertilisers.
- v) Moderate to high cation exchange capacity. This enhances the ability of the soil to store and supply nutrients to plants.

Conversely, some soils with very little structure or organic matter are relatively easy to reclaim. An increase in production of these soils is not difficult to achieve with intensive biological and chemical additions, for example Waipipi iron sands and West Coast alluvial sands. The reclamation of these sands is detailed in Chapter 3.3.

In summary, the easiest soils to reclaim are:

- i) the most productive and versatile soils.
- ii) Recent or stony free-draining soils limited by moisture deficits and/or flooding. Such soils, located in areas with a low risk of flooding, may, however, be regionally highly sought-after for specialist crops such as grapes or stone fruit.

Knowing the characteristics of easily reclaimed soils, there are four choices available to planners:

- i) Promote mining on high-quality land where there is a higher chance of maintaining soil productivity and versatility. Successful reclamation means that the cost of mining will be only the cost of not farming these soils while aggregate is extracted. In England this period has been as short as one year. Stringent controls should be applied and monitored to reduce the risk that these very valuable soils may be permanently degraded through compaction, erosion and loss or dilution of topsoil.
- ii) Promote mining on land more difficult to reclaim (usually low productivity soils) and accept that there will be a higher risk of degradation of soil agricultural productivity and versatility.
- iii) Promote mining on land that is more difficult to reclaim where alternative post mining land uses are viable' that is uses not related to agricultural productivity, for example, housing subdivisions, wetlands or water recreation (Chapter 8.6).
- iv) Promote mining on soil types that may be improved by mining, for example soils with iron pans, soils which comprise two contrasting layers (e.g. peat over sands) and highly variable soils. The uniform nature of reclaimed soils in mined areas means crops germinate, grow and ripen evenly. Hence productivity, especially of arable or horticultural crops, may be markedly improved, and management decisions are simplified. This aim has met with mixed success in New Zealand to date with abject failure occurring in Nelson aggregate mines (Chapter 3.3.7) and success on West Coast gold tailings (Chapter 3.3.8).

Factors influencing the adopted choice depends on the availability of economic areas of various soil types, possible post-mining use options and the experience and ability of the mining company. A wise procedure may be to allow small-scale trials using the equipment and techniques proposed for reclamation, as has occurred in the Nelson area. Influences on the choice of post-mining land use are described in Chapter Eight.

The most difficult soils to reclaim contain some or all of the following properties:

- i) Poor infiltration and low hydraulic conductivity.
- ii) Horizons with chemical properties which limit pasture growth (e.g. high acidity)
- iii) Susceptibility to compaction or loss of soil structure. These include soils with high clay contents, some volcanic soils which exhibit thixotropic properties, soils in areas with high rainfall.

- iv) Subsoil or C horizons with particular physical or chemical characteristics which limit plant roots and need to be separately stripped and/or replaced, for example pyritic wastes. Although rocks which are chemically active are usually unsuitable as aggregate (Chapter 2.3).

Additionally, characteristics of proposed sites for aggregate extraction, which make any soil difficult to restore include:

- v) Where no control can be exerted over the depth of the water table. This may elevate the soil moisture content so that replacing soils without causing great compaction, especially of the lower horizons, is difficult. Additionally, where excavation of gravel lowers the soil surface so that the water table affects soil moisture and aeration of the upper 0.5-1.0 m of the soil profile, the versatility of the soil may be lowered by preventing the growing of crops with low tolerance to anaerobic soil conditions such as stone fruit, grapes and asparagus.
- vi) Where soils are very shallow. Most material in aggregate excavations is saleable and hence removed from the mine site. Where excavation stops at a medium inhospitable to exploitation by plant roots, for example a very dense or anaerobic material, and only a thin layer of soil is available for reclamation, plant roots are physically restricted. Shallow soils and adverse base conditions most frequently occur at quarries in steep terrain and, in Manawatu, on terraces where gravels overlie massive Quaternary or Tertiary mudstone or siltstone.
- vii) Where reclamation aims to recreate very specific and/or variable moisture relations within soil profiles, costs of reclamation may be higher and techniques more difficult, for example, where reclaiming to indigenous ecosystems.

Conversely, the location of some mine sites may create site-specific opportunities to utilise waste materials to aid reclamation success. Fine-textured (clay and silt "slimes") material derived from washing aggregates may increase the cation exchange capacity and increase development of structure and moisture retention. Organic wastes, for example rotted sawdust, sewage sludge, cow-shed sludge or effluent can also be utilised to increase levels of soil organic matter and thus increase soil cation exchange capacity, moisture content, development of soil biota and nutrient cycling.

The success of reclamation at a specific site is not solely influenced by the soils at the site. Many of the factors which influence the quality of reclamation also influence the choice of post mining land use and are presented in Chapter Eight. Other factors which influence the success of reclamation include:

- i) The chosen post mining land use. In agriculture, the soil and environmental requirements of specific crops vary, for example kiwifruit are less tolerant of compaction and anaerobic soil conditions in spring than pasture.



- ii) The appropriateness of reclamation practices/techniques that are adopted. Operators and consent authorities should resist the temptation to transfer specific practices from one site or soil to another without fully considering the characteristics of each site or soil.
- iii) Constraints imposed by availability and type of machinery. Earth-moving equipment may only be available for reclamation purposes during winter months when demand for aggregate is low. Some types of machinery do not have the capability to separately strip soil horizons less than 0.10 m thick.
- iv) Location of the mine. Topographical features of adjacent sites may influence reclamation outcomes. For example mines located on the edges of river terraces are generally easier to integrate into the landscape at the cessation of mining because the surface can be lowered to that of the adjacent, lower terrace.

### **7.3 Recommendations for reclamation of aggregate mines in the greater Manawatu region.**

The following recommendations are based on the philosophy that the aim of reclamation to agricultural land is to create an optimal soil physical and chemical environment for growth of plant species, which will stabilise the soil and return large quantities of organic matter to the soil. Recommendations are presented chronologically, i.e. in the order in which a reclamation programme is implemented. Hence planning is followed by soil stripping and replacement, then establishment of pasture and control plots, and finally management of the reclaimed land after revegetation. Establishment of controls is discussed in Section 7.4. Most of the recommendations are based on general reclamation principles and are equally applicable to all aggregate mines in the greater Manawatu region, i.e. in areas which have a climate with an evenly distributed rainfall and moisture deficits for 3 to 4 months over summer (Chapter 4.1.2).

Recommendations for stripping and replacement of soil horizons (7.3.3) and on establishment of plants (7.3.4) are given for each of the three soils used in this research. The recommendations are based on results from the Ohakea, Rangitikei and Ashhurst trials. Finally, soil series in the greater Manawatu region, which are most likely to be associated with extraction of aggregate, are grouped according to their ease of reclamation.

#### **7.3.1 Planning for reclamation**

A plan of reclamation activities is ideally formulated before mining begins and is a valuable addition to applications for resource consents related to aggregate extraction. Plans should contain a detailed characterisation of the site before excavations begin and descriptions of the site at different stages during the life of the mine and after reclamation. Site characterisation should include information on soils and their variability, information on past land management and production, together with a description of aquifer and surface water characteristics. The

potential impacts of the proposed mine on air, water and soil resources of the site should be identified to allow the planning of reclamation to minimise any adverse effects on these resources and the community. The section on mine activities should detail how site preparation for mining and reclamation of mined areas will be integrated in terms of scheduling. Rolling reclamation is preferred, where feasible, as it minimises the area of soil exposed at any one time, reduces the length of time soils are stockpiled and spreads the cost of reclamation activities. Plans should include measurable objectives of reclamation activities: these will usually comprise objectives related to soil characteristics and plant productivity, but may also include goals associated with employee education and "client" satisfaction.

When the aggregate resource is not fully characterised, reclamation plans may not be able to be specific as key factors such as the depth of extraction and amount of material available for reclamation may vary. Additionally, where a mine has a long operating life community needs and reclamation opportunities may change so the post-mining land use cannot be definite. In this case several reclamation options can be investigated and/or a generic post-mining land use chosen (Chapter 8.6.3)

### 7.3.2 Stripping and handling of soil

Reclamation of soils must, above all else, aim to maintain or create soil physical conditions favourable for plant growth. It is most cost effective to ensure soils have favourable soil physical properties at the time of soil replacement as amelioration of poor physical properties is costly and difficult once topsoil has been replaced and vegetation has been established. The probability of creating suitable soil physical conditions is dramatically increased when excessive compaction is avoided.

At nearly all mine sites compaction of the surface 0.5 to 1.0 m of the plant growth medium should be MINIMISED by the adopting the following procedures:

- i) Use machinery that has low ground pressures such as tracked vehicles or light vehicles with wide or dual tyres at low inflation pressures. Minimising the load on vehicle axles is important as research by Smith and Dickson (1990) showed that an increase in wheel load at a constant ground pressure resulted in an increase in the depth of compaction, which is more difficult to ameliorate than compaction near the soil surface.
- ii) Avoid use of motor scrapers, if possible, as these must pass over the soil surface during stripping and replacement of soil.
- iii) Avoid movement of soils or traffic over soils with moisture contents above their plastic limit, especially during rainfall and when the soil surface is likely to be at or above field capacity.
- iv) Avoid multiple passes of vehicles during soil stripping and replacement: excavate and place soil without running over the soil surface. Where multiple passes must be made

(e.g. scrapers) vehicles should run in the tracks of the previous vehicle so that the minimum volume of soil is compacted. Load and unload stockpiles without travelling over the heaps.

- v) Avoid double-handling soil.
- vi) Protect soil in stockpiles from vehicular traffic and manage to prevent soil degradation: make piles low (<2 m) with a large surface area to maximise aeration, minimise the time soil is stored and vegetate if storage is greater than six months.
- vii) Minimise land smoothing, tilling and cultivation - a rough surface encourages seedling germination and can be smoothed at a subsequent pasture renovation.

### 7.3.3 Replacement of soil horizons

#### *Ohakea soils*

Compaction should be minimised in the top 0.15 m of the soil in Ohakea soils as even bulk densities as low as  $1.3 \text{ Mg m}^{-3}$  at the soil surface can be adverse to seedling growth and root proliferation (Chapter 6.5). Where A and B horizons are stripped together moderate compaction below 0.15 m ( $\rho_b = 1.4$  to  $1.6 \text{ Mg m}^{-3}$ ) is beneficial to plant growth, by reducing the number of voids in soil profiles and increasing the plant available moisture<sup>held</sup> in the soil. Compaction levels less than  $1.5 \text{ Mg m}^{-3}$  will not be detrimental to pasture production if restricted to depths greater than 0.15 m.

Where topsoil is deep (0.10 to 0.20 m), the more freely draining nature of Ohakea topsoils will assist establishment of pasture and its resistance to damage from grazing. Where heavy machinery is used and/or vehicles track over the subsoil horizons when replacing the A horizon the A and B horizons should be stripped together to the 0.30 m depth or the maximum depth possible to spread on the reclaimed surface at one time (which ever is the shallowest). This will ensure 0.30 m of reasonably uncompacted media with the benefits of topsoil characteristics. The remaining subsoil horizons should be stripped and replaced together to reduce the compaction that takes place when horizons are replaced on top of each other (given that in an aggregate mine disposal of the B horizons of the Ohakea soil, which have low  $K_{\text{sat}}$ , is probably impractical).

If stock can be excluded or carefully controlled during reclamation management or pasture is harvested for silage, mulched or grazed only under conditions of low soil moisture another option is to strip all horizons in one operation, thus mixing A and B horizons. A reclaimed area comprising mixed soil horizons will be slower to revegetate and be more susceptible to damage by vehicles and stock for longer periods each year, but if managed correctly will ultimately produce as much pasture dry matter as undisturbed soils.

### *Ashhurst soils*

In Ashhurst soils, moderate compaction ( $1.4$  to  $1.6 \text{ Mg m}^{-3}$ ) below  $0.15 \text{ m}$  depth is beneficial to plant growth by increasing the volume of soil pores capable of storing plant available moisture. As Ashhurst soils are sensitive to compaction at relatively low moisture contents, soil movement should be undertaken only during extended dry periods. The trial on Ashhurst soils showed A and B horizons may be stripped and replaced together with no decrease in yield of pasture (Chapter 5.6.2). However, where horizons are mixed, stones will be brought to the surface and these are damaging to equipment used for cultivation and tillage, thus reducing the potential of the reclaimed soil for arable or annual horticultural crops. Additionally, dilution of organic matter by horizon mixing will probably slow the establishment of nutrient cycling and biological recovery and increase the requirement for continued applications of organic or inorganic fertilisers.

### *Rangitikei soils*

Rangitikei soils may benefit from the formation of a moderately compacted layer at c.  $0.20$ - $0.30 \text{ m}$  depth where pasture is the planned post-mining land use to increase the amount of plant available moisture. This may have the same effect as layers of coarse sand or fine silts in the original profile which increase the volume of plant-available water potentially stored in the soil by forming barriers to drainage. Thus compaction at depth will probably aid reclamation of all layered, free-draining soils of alluvial origin which are low in organic matter. High levels of compaction ( $> 1.6 \text{ Mg m}^{-3}$ ) are, however, detrimental to pasture production during periods of moisture deficit, particularly where they occur at less than  $0.15 \text{ m}$  depth.

It is unnecessary to separately strip and replace topsoil of recent soils, for example a Rangitikei soil (Chapter 4.2.3), which have a shallow A horizon and negligible B horizon. Although spreading of an undiluted topsoil layer aids pasture establishment and re-establishment of microbial communities (hence nutrient cycling and soil structure), the addition of suitably humified organic material may achieve the same result at reduced cost.

### *Fill material*

The properties of a fill govern its suitability as a plant growth medium. The highly variable and undifferentiated fill at the Rangitikei trial site (Chapter 4.2.4) limited its suitability for direct establishment of pasture. Although trials showed that the ripped fill produced similar amounts of pasture as areas covered with  $1.0 \text{ m}$  of sand in 6 of 9 harvests (Chapter 5.6.1), ripping would probably be uneconomic as steel cables and concrete blocks were located within  $0.10 \text{ m}$  of the surface. Ripping would increase the amount of water stored in the soil profile as compaction of the fill extended to at least  $0.7 \text{ m}$ , so water would not drain through the profile, unless there was lateral movement of water. The increased amount of water would benefit plant growth but

decrease trafficability of the area and thus reduce flexibility of management. The fill area at the Rangitikei trial site would be best reclaimed by smoothing and shaping the surface of the fill area, to promote shedding of water, and then spreading Rangitikei sands to a constant depth. Where the fill surface is not shaped, or smoothed out, the depth of sand should be increased to promote evenness in pasture growth and thus flexibility in management. Deep-rooting crops growing in low rainfall periods are advantaged by deep soils (at least 1.0 m deep), while pasture species will grow equally well in soil depths of 0.1 to 0.40 to 1.0 m.

Where fill is used on a site, its value as a plant growth medium is generally increased by separating organic materials and soils from inorganic fill, and placing the latter at the base of the filled area. This allows ripping and cultivation of the fill surface and reduces differential settling. Further separation of soils into freely-draining (sandy and loamy) and poorly-draining (clay) soils enables discrete placement of different materials, ensuring the most favourable plant growth medium at the surface.

#### 7.3.4 Establishment of pasture

##### *Ohakea soils*

All actions associated with pasture establishment on Ohakea soils should be carried out with the over-riding objective being to minimise compaction. Thus a minimum amount of cultivation and surface levelling should be carried out and these operations should occur during relatively dry soil conditions. A nurse crop would probably not benefit pasture establishment in Ohakea soils as the additional trafficking associated with establishment of the nurse crop may increase soil compaction. Additionally, Ohakea soils have moderate moisture holding properties and are not highly susceptible to wind erosion. Applications of fertilisers to Ohakea soils can be heavier and less frequent than on Rangitikei soils.

##### *Ashhurst soils*

Pasture can be successfully established on all but very shallow Ashhurst soils without the use of nurse crops. Establishment will be most successful when seeding occurs in autumn and early spring when warm, moist soil condition favour development of seedling root systems. If reclamation occurs during summer (extended periods of soil moisture deficit), barley+oats or lupin nurse crops may aid pasture establishment because dilution of topsoil, commonly associated with soil movement, reduces the characteristically low volume of plant available moisture in Ashhurst soils. Application of fertiliser to reclaimed Ashhurst soils should follow the "little and often" practice, however six-monthly additions of fertiliser are adequate where topsoils are replaced.



### *Rangitikei soils*

Pasture establishment on Rangitikei soils is limited by its susceptibility to wind and water erosion and low volume of plant available moisture. Where pasture is seeded directly to Rangitikei soils a roughened surface will decrease erosion. Drilling is likely to be a more successful method of establishment than broadcast seeding by reducing desiccation of seedlings. Additionally, pasture should be established during autumn and winter when levels of soil moisture are generally high. Pasture establishment in Rangitikei soils is aided by planting a nurse crop of barley and oats. These plants rapidly stabilise the soil surface and, when mown to 0.10 to 0.20 m, create a sheltered environment for establishment of pasture (Chapter 3.3.2). A nurse crop of barley and oats is especially beneficial when pasture is established prior to or during periods of low soil moisture. Where the land surface is sloped, contour drilling strips of barley + oats will slow run-off of water. Additions of fertiliser to reclaimed areas should be "little and often", as Rangitikei soils are characterised by a low capacity to store and supply plant nutrients.

### *General principles*

Recovery of the productivity of reclaimed soils is fastest when the soil physical and chemical conditions are favourable to plant growth. Maximisation of soil organic matter and soil macro- and micro-fauna assist the development and long term maintenance of both soil chemical and physical conditions. Maximisation of a large, active soil macro- and micro-biological community assists soil productivity and resilience of the soil-plant system to adverse environmental or management conditions, because they affect so intricately soil structure, moisture relations and nutrient availability to plants. The following recommendations boost build-up of organic matter in soils:

- i) Plant highly productive grasses and clovers. Grasses have a high turnover of organic matter and symbiotic bacteria in clover nodules continuously supply nitrogen to the soil (Palmer and Moorehead, 1990), thus nitrogen losses by leaching are much lower than if inorganic nitrogenous fertilisers are applied. Clovers are particularly beneficial in soils with poor nutrient retention (low cation exchange capacity). Black locust (*Robinia pseudoacacia*) is supported by Ashby *et al.* (1984) and Vail and Wittwer (1982) as being more effective in promoting development of soil than pasture due to an extensive root system, nitrogen fixation and the ready incorporation of litter into soils.
- ii) Inoculate reclaimed land with soil microbial communities by spreading topsoil and establishing plants with mycorrhizal associations. Earthworms can be introduced by seeding with sods from areas with high worm populations.
- iii) Provide food sources for soil microbial and macro-faunal communities by spreading or incorporating organic matter to soils. Partially broken-down or humified organic matter such as cow-shed effluent, manure or sewage sludges with low C:N ratios are the most effective food sources. Applications of inorganic fertilisers initially, especially nitrogen,

may also be required to ensure lack of nutrients does not limit growth of microbial populations. In the medium term organic substrates will be supplied through pasture turnover. In Australia, populations of arthropod decomposers have been encouraged by replacement of partially rotted tree stumps and logs.

- iv) Plant nitrogen-fixing, deciduous trees such as alders (*Alnus and Casuarina spp*) and black locust in shelter belts at exposed sites to benefit pasture growth while limiting nutrients taken from the soil by trees. Pine trees have lower fertility requirements than many other trees, however deciduous trees generally return more nitrogen, magnesium and calcium to the soil so build up soil structure faster (Berry, 1983). Seeding rates of grasses and legumes should be reduced to 2-5 kg ha<sup>-1</sup> and fertiliser applied at planting time as slow release granules near the roots of seedlings in areas where tree seedlings or shrubs are planted. This minimises competition between ground-cover species and trees for light, water and nutrients (Cunningham and Witwer, 1984; Schoenholtz and Burger, 1984).

Maximising inputs of organic matter is not as important where soils are subject to intensive cropping systems before and after mining. Near Palmerston North, for example, Manawatu and Rangitikei soils are intensively cultivated by market gardeners. The soil in these enterprises can be basically inert with very low levels of organic matter as all plant moisture and nutrient requirements are supplied artificially, by irrigation and frequent applications of inorganic fertilisers respectively.

### 7.3.5 Land management after reclamation

The aim of land management after reclamation should be to get reclaimed land back to its previous level of production and resilience to adverse management before handing it over to full control of the prior owner (where land is leased) or a new owner. The productivity of reclaimed land should be proven before original management techniques are resumed. The productivity and resilience of a reclaimed soil is encouraged by maximising levels of soil organic matter in the surface 0.2 to 0.3 m. Pasture should <sup>therefore</sup> be managed to maximise plant growth rather than to maximise utilisation for animal production. Reclaimed land often has a lack of resilience to stress conditions and should be managed conservatively (Roe, 1987). Ideally, only light classes of stock (sheep and calves) should be used to graze pasture. Grazing should be restricted to short periods when soil moisture contents are below the plastic limit to minimise pugging, minimise selective grazing and maintain an aerated soil. Grazing regimes which encourage grass tillering help cushion the soil surface against compactive forces.

Including deep rooted plant species in seeding mixes and introducing species of earthworms that burrow deeply aids aeration and build up of organic matter deeper in the profile. Deep rooting of pasture is promoted by not removing an excessive proportion of the sward at any single



grazing and not grazing hard during periods of moisture deficit (summer months). Cultivation every 3-5 years aids build-up of organic matter by incorporating any thatch layer, aerating and loosening the soil while minimising adverse effects on micro and macro organisms. At all reclamation sites erosion should be minimised, especially insidious sheet and rill erosion which strips the most productive topsoil layer.

The flexibility of management demanded by the practices specified in this section is best achieved by farming reclaimed areas in conjunction with another property. At large extraction sites rolling reclamation provides this flexibility as unmined areas and areas at different stages of reclamation are present at any one time.

### 7.3.6 Classification of soils in the greater Manawatu region by ease of reclamation to agricultural use.

Soils in the greater Manawatu region have been divided into four classes according to the ease of reclaiming the soils to their former actual and potential agricultural productivity (Table 7.1). Class One soils are most easily reclaimed and characterised by moderate to high levels of organic matter and structure in topsoils with moderate to high plant-available water holding capacity, saturated and unsaturated hydraulic conductivities in both topsoil and subsoil horizons. Class two soils are moderately easy to reclaim and have similar drainage characteristics as Class One soils, however, shallow topsoils and poorer structures mean establishment and maintenance of plant growth may be more difficult given adverse environmental conditions.

Table 7.1: Classes of soil series according to ease of reclamation in the greater Manawatu region. Physiographic information on the soils series is given in Chapter 2.5.2.

Class	Ease of reclamation	Soil series
1	Easy	Karapoti, Tarata, Ashhurst (except shallow phase), Kawhatau (except shallow phase), Hautere, Koputaroa, Table Flat, Levin
2	Moderately easy	Rangitikei, Te Arakura, Manawatu, Kairanga, Ashhurst and Kawhatau shallow phases, Kopua, Parewanui (except heavy silt loam)
3	Difficult	Kiwitea, Crofton, Raumati, Parewanui heavy silt loam
4	Very difficult	Ohakea, Paraha, Milson, Marton, Tokomaru

Class Three soils are difficult to reclaim, requiring a higher level of skill to avoid levels of compaction that will adversely affect establishment and growth of plants and restrict management options. Class Four soils are very difficult to reclaim, with high susceptibility to compaction and poorly-drained with subsoils which are prone to dispersion in wet conditions. Soils on the Ohakea terrace are also subject to inundation by water and sediment sourced from adjacent higher terraces. The recommendations assume that the permanent water table depth of the reclaimed soils is greater than 0.5 m from base of profile and that in excess of 0.5 m of rooting depth is present before a medium that prevents root proliferation.

#### 7.4 Future trials

##### 7.4.1 Design of trials

Future trials could include a wider range of "control" treatments than those used in the Ashhurst and Ohakea trials. For example, at the Ohakea trial the addition of a control in which the soil was ripped to 0.50 m and cultivated would help determine what proportion of the yield increase resulting from replacing soil horizons in order was due to decreased compaction and increased  $K_{sat}$  or  $K_{unsat}$  between 0.20 and 0.70 m which was not identified by measurements of soil porosity at 5 and 10 k Pa suction. At the initiation of the trials an additional treatment, the addition of organic sludge from the anaerobic pond of a dairy farm, was investigated. The treatment was discarded due to the cost of transport and difficulty of containing liquid sludge within the confines of small plots. This treatment would have been of particular interest in the trial investigating reclamation of Rangitikei fine sandy loam as the sludge would have dramatically boosted the level of organic matter in the soil.

Table 7.2: The soil replacement treatments in the Ohakea Trial. The \* identifies the additional treatment which would allow 8 treatments to be used in a statistical analysis of the effect of compaction.

Soil replacement treatment	Aonly	ABmix	AonB	Control
High compaction	1	2	3	*
Low compaction	4	5	6	7

NOTE: A key to the treatments is given in Chapter 4.3.1, Figure 4.6.

The inclusion of control treatments in the Ohakea and Ashhurst trials which were subjected to compaction at 0.20 m depth would have aided statistical analysis of the effects of compaction by providing a "partner" compacted treatment for the uncompacted control which was planted at the same time as the reclaimed treatments. This would increase the number of plots able to be included in a statistical analysis of the effect of compaction, as shown in Table 7.2 for the Ohakea trial.

Experimental error is sourced from variation in the experimental techniques applied and the natural variability of the soils used. Variation in experimental techniques was minimised by refining most techniques before they were used on samples from which data would be used in statistical analyses. Where more than one person was involved, for example in some harvests of pasture, each person completed one operation on all the plots, where possible. The natural variability of the soil at each trial site differed. Soils in the Rangitikei trial were relatively homogenous *in situ* and additionally were mixed during soil stripping and construction of the trial, however, soils at the Ohakea and Ashhurst trial were variable (Figures 4.4 and 5.8). The variability of soils was controlled in the Ohakea trial by characterising soils in the greater area of the trial and restricting the area of the trial to a narrow strip parallel to the high terrace. Plots were relatively narrow and long so that gradients occurred within each plots rather than between plots as much as possible. The only way replication could have been increased, given the restricted area of Ohakea soils in the area of the trial site, would be to eliminate one of soil replacement treatments or the compaction treatment.

Table 7.3: The probability that any differences between harvests of pasture and measurement of volumetric water content (TDR) at the Ashhurst trial can be ascribed to variation between the two blocks of treatments. The nearer the values are to 1.00 the less the probability that variation can be ascribed to differences between blocks.

Source of variation	Harvest				
	1	2	3	4	5
Blocks	0.90	0.25	0.38	0.03	0.60
	6	7	8	9	TDR
Blocks	0.01	0.67	0.09	0.30	0.02

At the Ashhurst trial variation of soils existed <sup>with</sup> deeper soils at one end of the trial and shallower soils at the other end of the trial. Constructing each block of randomised treatments as a single row of long and narrow plots would have ensured that the variability within each block was greater than variability between the blocks. Statistical analyses to determine the probability that differences in soil and pasture measurements could be ascribed to variation between the two blocks of treatments showed that variation between blocks was a significant factor in one third of the harvests of pasture and when volumetric water content was measured (Table 7.3). Thus the results from the trial may have been more definitive if the alternative trial design had been used.

#### 7.4.2 Construction and management of field trials

Each of the three trials was constructed with different machinery. Each type of machinery had limitations and advantages. The first trial, the Ashhurst trial, utilised a tractor-trailer unit with the tractor having an excavating arm (back-actor) attachment. As this equipment meant plots on one side of the excavated plot had to be travelled over, it was not possible to place "undisturbed" treatments within the trial matrix. Additionally, the short arm of the tractor back-actor meant that only half a plot could be excavated at a time, thus soils within a plots could not be exactly homogeneous. In contrast, the long armed "Gradall" machine which was operated by a skilled contractor in construction of the Ohakea trial (Photograph 4.6) was able to excavate plots without touching adjacent areas and could have integrated undisturbed treatments within the trial matrix, resulting in a more rigorous statistical analysis. The small front-end loader and truck used to construct the Rangitikei trial was probably as accurate as the Gradall excavator but more cost-effective because topsoil had to be transported from an area c.200 m from the trial site.

Results from compaction treatments at the Ohakea trial encourage further studies investigating the effect of different depths and forms of compaction on plant and soil characteristics, especially root length at different times of the year. For example, compaction created by replacement of soils with motor-scrapers could be simulated by compacted layers every 0.1 to 0.2 m down the soil profile. I would be interested in investigating the cumulative effect of pugging by grazing animals and cycle of increased susceptibility to compaction and decreased plant productivity which was postulated as an effect of poor management of the Ohakea ABmix treatment (A and B horizons mixed together and replaced). Since plots at all three trials varied in elevation by up to 1.0 m a high density of animals would have been needed to prevent transfer of fertility to higher and more freely-draining plots where animals prefer to camp.

Following the experience of having the compacted layer disrupted by settlement of soil in some treatments (Chapter 6.9.1), future compaction should aim to create compacted layers at least 50 mm thick, which would be more resistant to disruption by soil settlement. Such compacted layers could be created by spreading 50 mm of soil on top of the first compacted layer and

compacting the soil. Additionally, if the equipment used to create the trial and the shape of the site permitted, it may be possible to wet the compacted layer to the moisture content under which maximum compaction has been predicted to occur from laboratory Proctor tests by stockpiling soils while they "cure" to an even moisture content. This procedure would maximise the bulk density of the compacted layer. Following the experience of the compacted layer being substantially higher in the profile at the end of the trial, due to consolidation of the surface 0.20 m of soil, the placing of one or more narrow strips of plastic at the surface of the compacted zone would enable accurate location of the compacted layer at later dates.

Where plots are small, as at all three trial sites, drains are probably best placed between plots rather than through the middle of each plot. The former placement reduces disturbance of the control and undisturbed soil profiles and, as long as drains are intensively spaced and the soil has reasonable lateral drainage, the drainage treatment would still be effective. The placement of drains in the Ohakea trial through the centre of each plot (Figure 4.8) was chosen because, given the low hydraulic conductivity of the B horizons, the Aonly treatment may not have been adequately drained when drains were placed between plots since the surface of the Aonly treatments was 0.5 m lower than the surrounding soil surface. Installing drainage between plots after construction of the soil replacement treatments at the Ohakea trial would have enabled excavation of the plots to a greater depth while maintaining the depth of the drains.

In future trials I would exclude treatments with surfaces which were more than 0.20 m higher or lower than undisturbed ground surface (Photograph 4.7). This would allow the use of commercial cultivation and sowing equipment, which would create levels of surface compaction equivalent to that occurring in commercially reclaimed areas. Alternatively a wedge-shaped trial design could have been used in the Rangitikei and Ashhurst trials. A wedge design allows treatments with greatly varying depths and reduces the effects associated with differing plot heights without preventing the use of commercial cultivation equipment. At the Rangitikei trial the thick end of the wedge would have been 1.5 m high, grading down to the surface of the fill. The major disadvantages of such a wedge design is the increased likelihood of wind and water erosion of the poorly structured sand and the consequent difficulty of containing topsoil within the appropriate treatments. Additionally, the effects on pasture production of any differential ponding of water or variation in soil conditions at the base of the wedge is not easy to eliminate through statistical analysis because treatments with different depths cannot be randomly positioned on the wedge. A wedge design could also have been used at the Rangitikei trial site where the B horizon which was removed was only 0.20 to 0.30 m deep. The position of all the "Aonly" (only topsoil replaced) soil plots at one end of the trial would also have reduced the environmental variables probably associated with the shallow hollows which were constructed in the trial design which was implemented.

Ryegrass and clover were chosen to vegetate the trials to ensure results could be applicable to as many aggregate mines as possible as most reclaimed areas in New Zealand are sown with pasture species. Differences in the productivity of different replacement treatments may have been more marked with alternative species, however to achieve the objectives of the trial, alternative species could only have been used as an initial planting, as in the Rangitikei trial. The barley+oats crop at the Rangitikei trial, for example, showed a strong response to increased depths of soil. Species could be chosen that were deeper rooting, or sensitive to moisture deficits or anaerobic soil conditions to give an indication of soil versatility after replacement.

Pasture establishment at the Rangitikei trial site, using seeding rates recommended for pasture renovation ( $23 \text{ kg ha}^{-1}$ ), was initially unsuccessful and resowing was necessary. Pasture seeding rates for trials where soil or climatic conditions are unfavourable would probably be more successful with markedly higher of  $c.45 \text{ kg ha}^{-1}$ , in line with guidelines of McRae (1983). Once pasture was established sampling herbage in  $0.5 \text{ m}^2$  quadrats with electric hand shears followed by defoliation with motor mowers was successful. It would be interesting to investigate the palatability and differences in the composition of pasture in future experiments as mowing generally creates a sward which is more clover dominant, with a higher proportion of rosette weeds than grazed pasture.

In commercial aggregate operations where there is no market for fill, aggregate is stockpiled with soil overburden until clean, unweathered gravels are reached (Winiata pers. comm., 1988). The results gained from the Ohakea and Ashhurst trials simulate reclamation practices at these sites where soils are replaced on a stripped overburden of mixed silt, sand and weathered gravels. At sites which have a final base of unweathered gravels and have not retained overburden containing weathered gravels, stockpiled soils are spread directly onto a free draining surface. Further trials with the same soil replacement and compaction treatments as the Ohakea trial would be an interesting extension of this research, as results from the Ohakea trials in particular are not directly applicable to the above reclamation situation as a coarse layer can alter the amount of moisture stored in the soil profile (Clothier *et al.*, 1977). Such further trials should be established on active or abandoned mine sites where weathered gravels have been stripped, as the scale of excavations required on most Ohakea and Ashhurst soils to get down to unweathered gravels (1 to 5 m) would be too large for small-scale field trials.

#### 7.4.3 Measurements of pasture and soil physical properties.

##### *Measurements of above-ground pasture*

The differences in productivity of pasture resulting from different soil replacement treatments would have been more accurately characterised if more sensitive measures of herbage production were used at critical times of the year. Experiments by Parfitt *et al.* (1985a;1985b)



showed that the extension of ryegrass tillers decreased as soil moisture deficits increased past 50 to 60 mm, with the rate of decrease varying depending on the soil type. Measurements by Dr A. Younger at the Rangitikei trial site, which included daily extension rates of individual ryegrass tillers and clover stolons (Section 5.5.6), showed that tissue turnover was more rapid in topsoiled plots compared to nil-topsoil plots. Over a similar period, measurements of total production from mown quadrats showed both topsoiled and nil-soil treatments were producing similar masses of dry matter.

Ideally both cumulative pasture production using gross harvesting methods and pasture production over short periods, using fine measurements such as leaf extension and rates of senescence, are measured. Fine measurements over periods of 6 to 12 days should be carried out when plants are under stress due to moisture or oxygen deficits. The extent of moisture stress can be determined by tensiometer readings, soil moisture content (measured by TDR) or mm of moisture deficit calculated from daily evapotranspiration records. Periods of oxygen deficit are when soils are at or above field capacity for extended periods during spring or autumn, i.e. when soil temperatures were warm and soil biota are actively respiring. Harvests should be timed to catch production over periods of similar soil moisture/climatic conditions, i.e. at the conclusion of extended wet or dry periods. Harvests of dry matter should be done within days of any rainfall which occurs after a long dry period because daily leaf extension rates can bounce back from 1 to 7 mm only 4 days after 10 mm of rain (Parfitt *et al.*, 1985b). Such compensatory growth may obscure differences in production over dry periods when soil temperatures are conducive to plant growth.

#### *Measurements of below-ground pasture*

All the measurements associated with pasture roots displayed high sample variation which masked any differences between trial treatments. Measurements of root length were less variable than root mass. The variability of surface samples would probably have been reduced if samples were taken from 10 to 60 mm depth rather than from 5 to 50 mm. Elimination of the surface 10 mm would avoid the problems caused by surface roots and stolons of grasses and clovers and reduce contamination of root samples with humus, dead plant material and seeds. Excavation of samples from the Ohakea trial using six to eight small diameter cores rather than excavating one or two relatively large pits (Chapter 5.5.6) would have been considerably faster, given a more representative sample and may have been more accurate. This is the solution adopted by Matthew (1992), who, faced by variable root measurements, decided to reduce variation by taking smaller diameter samples and bulking 10 samples per plot. Large cores taken with a hydraulically driven corer were unable to be used any of the trials due to the presence of stones. Stones cause problems because as well as deforming the sharpened edge of the corer, they cause compression of the soil or realign the sampler so that a fixed volume is not sampled. However, the smaller cores used to excavate samples from the

Rangitikei trial could have been utilised at the Ohakea trial: where few stones were present the corer was hammered into the soil and where stones were present the corer was gently pressed into the ground and stones picked out from the area below it.

Increasing the number of samples processed at each depth for each plot (replicates) would probably also have decreased the variability associated with root measurements, however as washing the roots was very time consuming, this could only have been an option if the number of treatments to be compared was reduced or only two depths, for example 50 to 100 and 200 to 250 mm, were sampled. This is the approach advocated by Troughton (1957) to minimise variation. Alternatively, in horizons that were not stony, for example the surface 0 to 200 mm of all the Ohakea treatments in the Ohakea trial, trends in rooting patterns could have been established from selected treatments by removing six to eight, 50 mm diameter soil cores at periods of maximum root growth during the period of the trial and filling the hole up with similar material. Any comparisons involving high compaction treatments would have been restricted to above 0.20 m to avoid disrupting the compacted zone.

Matthew (1992) reviewed the limitations of different techniques of root measurement. These included root length and root mass, extraction of soil moisture, root staining, counting roots by the core break method and imaging technology. Matthew chose to measure root growth by measuring increases in root length over time in refilled cores. This involved inserting 70 mm diameter cores of 6 mm mesh net stocking filled with loose soil material into the soil profile. I believe this method is best suited to sandy soils and media such as tailings which are structureless and homogenous and therefore would not have been suitable for the Ashhurst and Ohakea trials, but would have been useful for comparing some of the homogenous treatments used at the Rangitikei trial.

#### *Physical properties of soil*

Minimising the variation of soils within a trial is essential to reduce the extraneous influences not associated with the applied treatments. I found that a relatively fast method of determining the homogeneity of soils was to use a TDR (Time Domain Reflectometer) to measure the volumetric soil moisture content. The moisture content of a soil reflects soil texture and density and will pick up perched water tables or the effect of underlying horizons which may not be easily identified using soil cores. Using two lengths of TDR probes, for example 0.20 and 0.40 m, would increase the accuracy of the method.

The value of TDR measurements at both Ohakea and Rangitikei trials would have been increased if they had been calibrated with tensiometer measurements, which indicate how available soil moisture is to plants, i.e. the degree of moisture stress plants experience. The use of TDR probes was limited in the Ohakea trial by the gravel content of the lower horizons, which made

inserting probes longer than 300 mm into the Aonly treatment difficult. Additionally, using permanent (*in situ*) probes over the summer months was impractical as the soil shrunk away from the probes, especially in the ABmix treatment, so that full contact with the soil did not occur.

It would be interesting, in future trials, to track the fluctuation in soil oxygen status and plant-available soil moisture (PAM) on a treatment by treatment basis and plot these against plant productivity. Determining the fluctuation in oxygen status could be calculated indirectly from data on water table depths gained from access tubes inserted to 180 and 700 mm depths (for the Ohakea trial). The shorter tube would identify perched water tables caused by the compaction treatment which could form a barrier to percolation of water through the soil profile. I found that observing the height of the water table in 500 mm deep pits gave an insight into the differences between drained and undrained treatments at the Ohakea trial. Knowing the height of the water table enables calculation of the volume of water filled pores by setting the head, or suction in the soil generated by gravity. This approach would be useful at other trial sites where perched water tables are present.

Determining the distribution of pores from retentivity curves assumes circular pore geometry and hydrophilic surfaces. Additionally, hydraulic characteristics are affected by the discontinuity of macropores across horizon boundaries. I tried to compensate for this by taking cores at increments of 100 mm down the soil profile. However, measurements taken at 0.20 to 22 m depth may have missed the compacted layer where macropores, and therefore transmission of air and water, would have been reduced. The identification of the compacted layer, as described in Section 7.6.2, and sampling both from this layer and from consistent depths would aid characterisation of the effects of compaction on PAM.

Estimating PAM on a treatment by treatment basis for the free-draining Ashhurst soil and undisturbed Rangitikei soil would be best achieved using field-based estimates of Field Capacity and Stress Point. The field method comprises covering the unvegetated soil surface (before sowing of pasture) with an impermeable sheet and measuring the reduction of soil moisture content from saturation point to a point when the drop in moisture content evens off. This technique is not suitable for soils which are poorly drained or soils which contain an impermeable base, as some Rangitikei trial treatments, or a perched water table, as occurred in the Ohakea soil. The moisture content of such soils reduces only gradually, so that a specific point is hard to define as Field Capacity. For these soils I think a more practical upper limit of soil moisture is the content at which soil oxygen becomes limiting in the surface 100 mm (for pasture). This value could be varied according to soil temperature to take into account the faster depletion of oxygen when soil temperatures are warm i.e. the utilisation of soil oxygen is greater when soil microorganisms and roots are most active. The soil moisture content at Stress Point could be estimated by measuring leaf extension rates as soil moisture levels drop, or more simply (and less accurately) by measuring the soil moisture content at which pasture wilts. The

practical outcome of such modelling would be to specify easily measured physical parameters that reclaimed soils must reach to ensure pasture productivity is maintained.

Reclamation trials which investigate the effects of compaction or include a best-case reclamation option, i.e. minimum compaction and damage to soil structure, should utilise the Proctor compaction test. This test can be used to identify the maximum and minimum moisture contents at which soil is susceptible to compaction. If a source of water is available and contractors are flexible, manipulation of the moisture content of the soil has the potential to increase the effectiveness of applied treatment. I would like to trial the commercial application of the proctor test to identify critical moisture contents of different potential rooting media to allow limits to be set on timing of soil stripping and replacement operations.

## **Chapter Eight: Controls on reclamation and post-mining land use options.**

### **8.1 Introduction**

Chapter Eight describes the legislation which has controlled aggregate extraction. In January 1988 central government established a comprehensive Resource Management Law Reform to produce new, integrated resource management legislation. Subsequently the Resource Management and Crown Minerals Acts became operative on 1 October 1991. In this chapter pre 1991 controls on aggregate extraction are described because the new acts have been developed from the old legislation (Resource Management Bill, 1990; Ministry for the Environment *et al.*, 1990) with new policies and plans developed around their old equivalents and because changes are occurring slowly as district and regional plans are revised and government policy statements are formulated.

The drastic land disturbance associated with mineral extraction represents a unique opportunity to reshape the landscape and fashion a different land use. This chapter outlines, with New Zealand and overseas examples, the wide variety of reclamation options and the factors which influence the choice of post-mining land use for an individual site. Environmental controls on aggregate extraction and post-mining land options in the greater Manawatu region are described using results of a survey of selected aggregate extraction sites. The conclusions of the survey are examined in the light of overseas post-mining land uses.

### **8.2 Legislative requirements of aggregate extraction before the Resource Management Act 1991**

Prior to October 1991, legislation controlling aggregate extraction was complex; regulated by provisions in a variety of Acts (Joll, 1980; CALNIG, 1986; Resource Management Bill, 1990). Ministries, government departments, regional authorities and local authorities were conferred a variety of rights through legislation. Sometimes more than one organisation or government department was the authorising body for a single aggregate resource (Joll, 1980; Taranaki Catchment Commission, 1981). Aggregate mining was controlled by permits in mining statutes, through aggregate extraction licenses in non-mining statutes and through water quality and erosion control legislation. The location, ownership and method of extraction of an aggregate resource determined which regulations were applicable (Ward and Grant, 1978).

#### **8.2.1 Licenses for extraction**

Until October 1991, extraction of aggregate from Crown-owned river bed or land required a licence issued by the organisation which was responsible under the applicable legislation

(Taranaki Catchment Commission, 1981). Under the Harbours Act 1950, for example, the Secretary for Transport issued licences for aggregate removal from the foreshore, seabed, harbour bed or bed of a navigable river (Ward and Grant, 1978; Taranaki Catchment Commission, 1981). However, the advent of shallow draught jetboats extended the limits of navigable rivers, leading to some overlap of responsibility with Catchment Boards (Joll, 1980), although by administrative agreement the Ministry of Transport restricted its licensing role to the foreshore (Taranaki Catchment Commission, 1981). The Harbours Act also allowed port authorities and harbour boards to remove aggregate for their own uses (CALNIG, 1986; Ministry of Energy, 1986).

The Land Act 1948 delegated control over extraction of aggregate from Crown-owned river beds to Catchment Authorities which are now incorporated within Regional Councils. The Land Act provided for bylaws to control removal of aggregate from any watercourse or unalienated Crown land through requiring a permit or licence (Ministry of Energy, 1986). Under the Land Act, licences could also be issued by the Land Settlement Board which was served by the Department of Lands and Survey (Ward and Grant, 1978; Ministry of Energy, 1986). The Public Works Act 1981 allowed any government department to acquire land for aggregate extraction (Taranaki Catchment Commission, 1981; CALNIG, 1986) with the Minister of Works issuing licences (Ward and Grant, 1978). Finally, under the Forest Act 1949 aggregate within state forests was regarded as forest produce (CALNIG, 1986; Ministry of Energy, 1986) and the Minister of Forests was empowered to issue licences for extraction of aggregate (Ward and Grant, 1978).

Under these non-mining statutes, applications for licences and permits to remove aggregate were not subject to public debate and there was no procedure for considering public objections (Ministry of Energy, 1986). Land owners had the right to mine privately-owned minerals on their property without any mining permit or licence (Palmer, 1982; Ministry of Energy, 1986) for any agricultural, pastoral, household or building purpose on their own land (Taranaki Catchment Commission, 1981). However, the Governor General could declare it in the national interest that no mining at all be carried out in a particular area (Palmer, 1982). A water right under the Water and Soil Conservation Act 1967 and a planning consent under the Town and Country Planning Act 1977 may also have been needed.

### 8.2.2 The Town and Country Planning Act 1977

Where aggregate was extracted from privately owned land, the Town and Country Planning Act 1977 (TCPA) conferred substantial powers upon regional and local governments to control aggregate extraction through designation, zoning and ordinances. Where privately owned minerals were extracted without affecting natural water, these were the only controls on extraction (Taranaki Catchment Commission, 1981). Designation allowed government departments or local authorities to reserve a defined area of land to enable public works on that land. Designation



could also be used to preserve aggregate deposits from sterilisation (Taranaki Catchment Commission, 1981). Sterilisation of aggregate deposits happens when development which prevents aggregate extraction in the future occurs, for example residential or commercial building.

Zoning was the most common method of controlling aggregate extraction under the TCPA (Taranaki Catchment Commission, 1981). District schemes defined zones for different land uses. Land uses in each zone could include controls on extraction through ordinances, site specific conditions of operation or bylaws. Ordinances detailed zoning requirements such as specific restoration procedures or standards applied to development proposals and were legally binding on both operator and council (Horowhenua County, 1980; Taranaki Catchment Commission, 1981). In each zone, mineral extraction could be either a predominant, conditional, non conforming, existing or designated use or require a specified departure from the plan.

Where aggregate extraction was a *predominant use*, mining was permitted as of right if it complied with zone ordinances and district bylaws. In Paparua and Whangarei District Schemes, for example, 'quarry zones' were defined where quarrying was a predominant use subject to performance standards. In Christchurch quarry zones were used to allow extraction of aggregate from specific locations over the medium term, to avoid extraction in areas where ground water contamination would occur, to control filling and to emphasise that mining is an interim land use (Christchurch City Council Paparua District Scheme Change, 1988). Where aggregate extraction was a *conditional use* or *specified departure* the proposed operation required the consent of the district council and had to be publicly notified. Notification provided a discussion forum for people affected by the proposed activity. Consent was subject to conditions of extraction which were determined by site specific factors, district and regional scheme provisions and matters of national importance specified in section three of the TCPA. These included:

*"the conservation, protection and enhancement of the physical, cultural and social environment ; the wise use and management of New Zealand's resources ; and the avoidance of encroachment of urban development on, and the protection of, land having a high actual or potential value for the production of food"*.

Applicants or affected people could appeal to the Planning Tribunal against district council decisions.

In the late 1970's and early 1980's, Waimea County applied some of the more stringent extraction conditions to firms extracting aggregate from productive terrace-land of the Waimea plains zoned "Rural". The conditions aimed to ensure maintenance of land productivity after mining and included making future workings conditional on satisfactory reclamation, defining the methods of operation and soil restoration and allowing access for monitoring and experimentation. A bond and sureties were also required.

### 8.2.3 The Mining Act 1971

Prior to the 1991 legislative reform, mining and exploration in New Zealand was regulated under mining legislation which was specific to the mineral being mined. A single licence, under either the Iron and Steel Industry Act 1959, Continental Shelf Act 1964, Mining Act 1971 or Coal Mines Act 1979, together with appropriate water rights, allowed the license holder to undertake all work permitted by the licence (Joll, 1980; Ross and Tweedie, 1991). The Iron and Steel Industry Act and Continental Shelf Act made no provision for public participation while the Coal Mines Act allowed minimal public participation (Ministry of Energy, 1986).

The Mining Act was the principle Act for licensing Crown-owned minerals (Ministry of Energy, 1986). Under the Act the Crown could grant a licence for any mineral, defined as including stone, sand and gravel, to be extracted from any land open for mining (Ministry of Energy, 1986). Where aggregate reserves occurred on Crown land a licence was required from the Crown, specifically the Energy and Resources Division of the Ministry of Commerce, through the Mining Act to extract aggregate (Lawrence and Smith, 1983).

The Mining Act contained provisions for protection of the environment (Palmer, 1982) in addition to environmental issues raised in submissions from the public. Environmental assessment was required in the form of environmental assessment questionnaires and environmental impact assessments or reports for large projects. These were subject to review by the Commission for the Environment which was established in 1972. The Commission was replaced by the Ministry for the Environment which was created by the Environment Act 1986. The goals of the Environment Act and the Ministry for the Environment include to ensure that, in the management of natural and physical resources, full and balanced account is taken of intrinsic values, sustainability of resources, future generations and values placed on environmental quality. Under the 1981 amendment to the Mining Act the Minister was required to refer mining applications to the relevant territorial authority, publicise draft conditions and allow people affected by the proposal to lodge objections. Before granting a mining licence the Minister of Commerce had to have regard for environmental and social factors involved, provisions for the protection of land and the wise use and management of New Zealand's mineral resources. Catchment Boards, territorial authorities and Department of Conservation (if the affected land was under their jurisdiction) had important roles in informing the Minister of any environmental and social impacts. Territorial authorities focused on the relationship of the proposed mining operation to district planning objectives (Ministry of Energy, 1986) and Catchment Boards (now part of Regional Councils) concentrated on water quality and soil erosion aspects of the mining proposal. The Department of Conservation has an advocacy role as the Department is required to actively pursue conservation values in major environmental conflicts such as those associated with mining. Any objection under the Mining Act or appeal against the granting of a water right triggered an enquiry by the Planning Tribunal (Palmer, 1982).

Before the Mining Act 1971 mining companies were allowed to pay a small fee to central government in lieu of reclamation. Most companies took this option (Cumberland, 1981; Keating, 1990). Under the Mining Act the Ministry of Commerce (originally the Ministry of Energy) was required to attach conditions relating to land protection and reclamation (Parker, 1991). Thus a general requirement of all mining privileges granted by the Ministry of Commerce was that where the land surface was disturbed it should be restored as far as practicable to a condition at least equivalent to its original state (Mackenzie and Cave, 1991; Macleod and Rouse, 1991). Appendix 8.4 'Alluvial Mining Standard Conditions and Restoration Schedule' is an example of standards which are similar to those associated with quarrying privileges obtained through the Mining Act (Macleod and Rouse, 1991). Standards stated the maximum area allowed to be disturbed at one time, the maximum time for completion of restoration after mining operations cease and restrictions on mining operations to reduce "unnecessary destruction of vegetation, wildlife and property". Model standard conditions for reclamation to pasture included stripping, stockpiling and replacement of soil (if required by the landowner) and replacement of a plant growth medium to support productive vegetative cover meeting the intended post mining land capability and use. Reclamation of land to pasture was specified unless an alternative was agreed with the landowner. Mining inspectors also had discretion over conditions relating to maintenance and vegetation standards. Inspectors determined the degree to which landowner requests regarding revegetation, soil replacement, soil stockpiling and land contouring were implemented. Standard conditions for reclamation of land to forestry specified the grade of certified seedling, planting stocking rate and minimum acceptable survival rate after one year. The establishment of a cover crop to minimise erosion and burial of logs and stumps was also required. The 1981 amendment to the Mining Act made provision for bonds and 3 yearly bond reviews to ensure reclamation of mined sites was completed and adequate (Palmer, 1982).

#### 8.2.4 Water quality and erosion controls

Prior to the Water and Soil Conservation Act 1967, Catchment Boards, now incorporated within Regional Councils, were required to issue water rights and water conservation orders and protect water quality. Water rights were required for damming, diversion, abstraction or discharge of water (Taranaki Catchment Commission, 1981; Lawrence and Smith, 1983). Most aggregate mines required water rights because most aggregate processing operations require water for washing aggregate and most aggregate extraction sites discharge storm-water run off. Additionally, water courses may be diverted or dammed to supply water or allow access to an aggregate resource (Joll, 1980). The 1967 Act contained provisions for public participation in water right applications in specific procedures for lodging objections and obtaining a hearing before the Catchment Board.

The 1959 amendment to Soil Conservation and Rivers Control Act 1941 included safeguards against land use practices that would cause accelerated erosion and flooding (Lawrence and

Smith, 1983). Section 34 of this amendment provided for regulation of land practices that would cause erosion or deposits in water courses via what became called Section 34 notices (Joll, 1980; Hawkes Bay Regional Council, 1993). Catchment Boards were charged with the responsibility to use Section 34 notices and Section 149/150 bylaws (Lawrence and Smith, 1983). Under a Section 34 notice certain activities involving land disturbance could not be carried out within a specified area without the prior approval of the Catchment Board (Hawkes Bay Regional Council, 1993). Bylaws enabled Catchment Boards to control aggregate extraction from any water course through granting or withholding extraction permits (Taranaki Catchment Commission, 1981; Lawrence and Smith, 1983). Extraction that might compromise aquifer quality or was on floodable land, especially within stop bank berms, was also subject to Catchment Board regulation (Taranaki Catchment Commission, 1981).

The TCPA required that District Councils have regard for the principles and objectives of both the 1959 and 1967 Acts when making planning decisions (Nelson Bays United Council Technical Liaison Committee, 1979). Control on extraction was also exerted through the Fisheries Act 1983 under which it was unlawful to deposit material into water where it would affect fish or the food of fish.

#### 8.2.5 Operational Controls

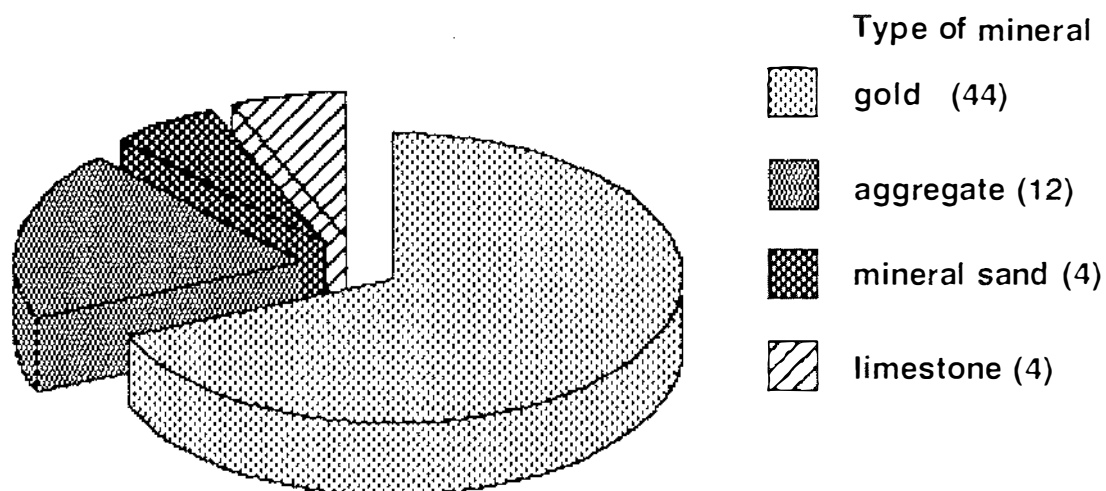
Aggregate extraction is bound by a variety of laws, by-laws and regulations relating to operational procedures. These range from weight restrictions on truck loads to hours of work and permissible noise levels. The Quarries Act 1944 legislated safety and management on quarry sites with a working face higher than 4.5 m (Taranaki Catchment Commission, 1981). Other extraction operations are controlled by the Clean air Act 1972 which specified maximum permissible levels of air pollutants such as dust from roads and processing sites. Producers must also reach specifications determined by various aggregate producers (see Section 2.3). The Local <sup>Government</sup> Amendment Act 1979 gave local, and sometimes regional, authorities the power to invoke bylaws to prohibit or regulate certain activities. Although aggregate extraction is not specifically mentioned most of the effects of extraction could be controlled by bylaws under this legislation (Taranaki Catchment Commission, 1981). The Occupational Health and Safety Act, 1993 also influences aggregate extraction operations and procedures.

#### 8.2.6 Effectiveness of pre 1991 legislation

Under pre 1991 legislation environmental controls on aggregate operations were inadequate in many areas. Environmental planning was restricted because resources were generally managed independently of one another through fragmented, single purpose legislation applied by many agencies. These agencies had overlapping responsibilities and inconsistent resource management systems as the result of legislation developing in an ad hoc manner over time

(Ministry for the Environment, 1988b; Resource Management Bill, 1990). The TCPA controlled and planned land use rather than the environment or natural resources and this led to little integration across land, air and water boundaries (Ministry for the Environment, 1988a; Resource Management Bill, 1990). Extraction of aggregate cuts across these boundaries as extraction can potentially effect water quality and quantity, beds of rivers and lakes, air quality, natural hazards (flood patterns) and sustainable land management (Taranaki Regional Council, 1992).

The processes associated with gaining a consent to extract aggregate were often complicated and adversarial and could involve multiple hearings and appeals which were expensive and time consuming (Resource Management Bill, 1990). Environmentalists were concerned that pollution laws did not emphasise prevention of pollution (Bewick, 1988) and monitoring and enforcement of licence conditions were inadequate (Mackenzie and Cave, 1991). The Taranaki Regional Council, for example, reported in 1992 that it had been unable to be proactive in managing the aggregate industry in the past. Enforcement procedures were lengthy and cumbersome with inadequate penalties (Bewick, 1988) and Maori rights under the Treaty of Waitangi were not recognised.



Graph 8.1: The number and category of applications for mining licences to the Ministry of Commerce in 1990 (data from Mackenzie and Cave, 1991).

The pre-1991 legislation resulted in environmental controls that focused on off-site effects, reflecting the major concerns of objectors and the legislative groups involved in the consents process. These factors were apparent in the survey of aggregate sites in the greater Manawatu region (Section 8.6).



The Ministry of Commerce processes a relatively small number of applications for aggregate extraction, for example, 12 applications were granted in 1990 for the whole of New Zealand (Graph 8.1). Standard conditions for site reclamation issued by the Ministry of Commerce for these applications (Section 8.2.3) may be inadequate in some cases, for example, the standard requirement to establishment a cover crop where land is reclaimed to forestry may result in smothering of tree seedlings and the requirement to bury or burn logs prevents their utilisation to create sheltered microclimates for shrub and tree seedlings.

### **8.3 Legislative requirements under Resource Management Act 1991 and Crown Minerals Act 1991.**

The Resource Management Act (RMAct) was enacted on 1 October, 1991. The RMAct provided uniform principles and methodology for determining resource use by replacing all or part of over 75 environmental and planning statutes and regulations including the Town and Country Planning Act 1977, mining legislation and water and soil legislation. The main purpose of the RMAct is to ensure the sustainable management of all natural and physical resources with the exception of minerals. This means the use, development and protection of resources should be constrained by ecological considerations. The focus of the RMAct is on stewardship of natural and physical resources, not the pursuit of social and economic objectives although social, economic and cultural wellbeing has to be considered by decision-makers (Armstrong, 1992). The definition of sustainable management (see Appendix 8.1) includes:

*"safeguarding the life supporting capacity of air, water, soil and ecosystems" (Section 5(2)b)*

Sustainable management can be interpreted as promoting reclamation of mined land, particularly to biologically productive options such as agriculture, forestry or wetlands. Sustainable management requires establishing the level of degradation that can be tolerated without affecting the environment's life supporting capacity for future generations or 'biophysical bottom line'. Principles of the RMAct include the maintenance and enhancement of amenity values which can also be achieved through reclamation. Additionally unreclaimed extraction sites near water bodies conflict with one of the matters of national importance specified in the RMAct, i.e. "preservation of the natural character of the margins of rivers and lakes".

The RMAct divided responsibility for resource management between three interconnected tiers of government (although every person has a general duty to avoid or mitigate adverse environmental effects). Central government has an advisory and policy setting role with the Department of Conservation having particular responsibilities in monitoring coastal plans and the Ministry for the Environment required to monitor the performance of local and regional government. Central government, mainly through the Ministry for the Environment, can issue National and Coastal Policy Statements and National Environmental Standards which become

binding on Regional and District Councils in the formation of their plans and rules. A policy statement on mining reclamation techniques or minimum standards, for example, could require detailed soil and overburden characterisation or specify maximum topsoil stockpile heights and storage times. Central government also has call-in powers on proposals of national importance, for example where mining might affect a national treasure or possibly where an aggregate 'super quarry'(supplying more than one region) was proposed.

Under the RMAct Regional Councils are responsible for control of land use for the purpose of soil conservation (Section 30(1)(c)(i) RMAct), water quality, water quantity and hazardous substances and identification of natural hazards. Under Section 13 of the RMAct the bed of a lake or river cannot be disturbed unless a land use consent is granted by the appropriate Regional Council. Thus Regional Councils have responsibility for any aggregate mining within the bed of a river or lake. A river can be loosely interpreted as including all land within the 100 year flood plain. In the Manawatu this would include the accumulating Holocene river terraces on which the Manawatu, Kairanga, Rangitikei, Parewanui and Otaki soil series are sited.

The Local Government Law Reform Bill (No 2) introduced in December 1991 clarified the functions of Regional Councils as bodies regulating resource management (Fyson, 1992). A Regional Council can only control land uses outside the beds of lakes and rivers if the activity may impact soil conservation, water quality or quantity or natural hazards (Section 30(c) RMAct). A Regional Council may also be involved if the effects of a proposed activity are of regional significance. Regional Councils must prepare objectives and policies in relation to any actual or potential effects of the use, development or protection of land which are of regional significance. In general, an activity may be regionally significant if it impacts (in addition to the former items) wetlands, historical sites or waahi tapu, valuable landscape features or significant areas of indigenous vegetation. A mandatory regional policy statement and regional coastal statement prepared by each Regional Council specifies the environmental issues, aims and policy of the region, together with provisions for monitoring of the environment.

District Councils are primarily responsible for land use and noise control (Section 31 of the RMAct), exerting control through mandatory District Plans which replace the TCPA District Schemes. District Councils are primarily responsible for aggregate extraction outside river-beds (Taranaki Regional Council, 1992) and land reclamation. District Councils must develop rules to control land activities and the effects of these activities because under the RMAct all land uses are permitted unless rules will be contravened by an activity. Rules developed by District Councils that impact aggregate extraction sites cover: noise, hours of work, blasting and vibration, roading and traffic, lighting, building construction, effects on amenity values and location of operations if this can be justified. District Councils are also primarily responsible for avoidance of natural hazards.



The RMAct states a number of duties and restrictions to achieve the objective of sustainable management. Under the RMAct all land uses are permitted unless controlled and the use of other resources, such as water and air, is generally prohibited unless expressly allowed by a rule in the regional or district plan. There are five types of consents: **land use**, for any use of land; **subdivision** consent; **coastal**, for use of a coastal marine area; **water**, for the use or taking of water; and **discharge** for discharge of any contaminant into water, air or land. Nearly all mining operations will require water consents, just as water rights were required under the Soil and Water Conservation Act 1967. Under the RMAct Regional Councils have responsibility for environmental assessment, establishment of conditions and enforcement of mining licence conditions (Mackenzie and Cave, 1991; Mew and Ross, 1992). Most mining operations will also require discharge and land use permits which were gained in the past through the Mining Act 1971. This will affect few aggregate operators as a minority of sites, mainly hard rock quarries, were granted consents under the Mining Act 1971 (Palmer, 1982). The Energy and Resources Division of the Ministry of Commerce has requested local authorities to coordinate independent reviews of proposed mining operations for relatively large mining projects (Mackenzie and Cave, 1991). Extraction of aggregate from coastal areas could be restricted as the coast is seen as a particularly vulnerable area and a consent from the Minister of Conservation is required for "restricted coastal activities", i.e. those which cause significant changes.

Regional and district plans spell out when activities may require a resource consent. In the Manawatu-Wanganui area the Regional Council specifies that a land use consent is required for "removal of sand or shingle". Within this rule extraction sites producing less than approximately 150 m<sup>3</sup> gravel each year are regarded as having negligible environmental and social impacts, however site inspections determine the impact of extraction and thus whether a resource consent is required.

There are five kinds of activities which should eventually be described by their effects on the environment, rather than by use or product as under the TCPA 1977. **Permitted activities** are allowed as of right by a plan so require no consent although standards may be included and activities must conform to 'rules', equivalent to bylaws under the TCPA. An environmental assessment is required for a **controlled activity** if stated in the plan and conditions are attached to the consent. A **discretionary activity** is permitted at the discretion of the council if it does not contravene the plan and usually involves a public hearing. A **non-complying activity** contravenes or is not provided for in the plan but is not prohibited. No consents can be granted for **prohibited activities**, where the effects of an activity are greater than specified maximum levels or standards. Aggregate extraction is usually a controlled or discretionary activity, requiring an environmental assessment and resource consent/s. The Fourth Schedule to the RMAct (Appendix 8.2) acts as a checklist on the scope and content of an environmental assessment, however, the schedule is subject to regional plans and national and regional policy statements.

Prior to the RMAct some pits and quarries had not been subject to specific statutory requirements to produce plans for management or reclamation. Under the RMAct after a transition period all operations will be subject to management plans and controls (Happy, 1992). For example, water permits and discharge permits will be reviewed in 35 years (if the water right was for greater than 35 years) or 10 years if the original water right was for 10 to 35 years.

### 8.3.1 Regional and district rules

Rules may control land use practices. For example the Manawatu-Wanganui Regional Council passed "Bylaw 1991", an interim 'rule' under the RMAct, which required that written consent from the Council was needed before disturbance of:

*"land surfaces that will result in exposure of land or soil to erosive processes, facilitate flooding or cause deposits in water courses"(4.1(ii)).*

The objective of the rule is to minimise erosion of soil into natural water. The rule is based on the former Section 34 notice identified in Section 368 of the RMAct which allowed various notices operative before the RMAct to be deemed provision of a transitional regional plan (Chapter 8.2.4). Section 5 of Bylaw 1991 requires that:

*"no person shall without written consent remove or excavate any gravel in or from the vicinity of a watercourse where that removal or excavation may affect the movement of water in or about any water course or may affect the stability of the alignment of the watercourse".*

Gravel is defined in the bylaw as "sand, shingle, metal, silt, topsoil, aggregates" (a technically inaccurate definition when compared to the definition of aggregate in chapter 2.1). The bylaw affects all aggregate extraction sites which excavate below the water table, where mining may cause aquifer contamination, and within stop bank berms, where extraction may endanger flood protection works by diverting flood waters. Extraction sites on high and intermediate terraces may be exempt from the bylaw as extraction on these terraces usually occurs above the water table and water run off tends to collect within the pit. Because "land" includes land covered by water, District Councils may also make rules relating to river beds, however District Plans must concur with regional plans and policy statements.

### 8.3.2 The process of gaining a resource consent

The RMAct introduces a single, standardised consent process (Milne, 1992) in which impact assessment is an essential part. An application for a resource consent from a Regional or District Council entails completion of a form based on the Fourth Schedule of the RMAct in which the proposed activity is described (see Appendix 8.2). An application for a land use consent for aggregate extraction, for example, would specify the area of land and volume of material extracted, methods of extraction and processing and the term of extraction. Since most quarries leave pits and have the potential to have significant adverse effects on the environment, a

description of alternative locations and/or methods of site extraction, processing and reclamation is also required. The resource consent application must also contain an assessment of the actual or potential effects of the activity on the environment, including visual impacts of the proposal, and the mitigation of the adverse effects together with a description of monitoring proposed by the applicant. Owners and occupiers of properties with a common boundary or water body and other people interested or affected by the proposal must be identified. The extent and results of consultation with affected people and the applicants response must be summarised in the resource consent application. Additionally, if the applicant is not the land owner written consent allowing access to the specified property is required from the land owner.

Public notification of the resource application in newspapers is required if affected parties do not consent to the proposed activity. The advantages of non-notified resource consents in terms of time and expense encourages consultation and promotes mediation to reach compromises (Dart, 1992). Combined hearings allow multiple consents, which are often associated with an extraction site, to be heard together. Joint hearings can be held where consents on a single project are required from both Regional and District Councils (Milne, 1992).

The RMAct provides for increased community participation in environmental decision making. Anybody or any group can submit objections or supporting statements to proposed activities and iwi are required to be consulted by all levels of decision makers. For example, the Ministry of Commerce has held hui to obtain input from iwi into development of minerals programmes. Iwi are groups of Maori, based on historical tribal locations, for example the Tainui and Te Arawa peoples (Tauroa, 1989). Consultation was defined legally in a 1992 High Court decision as 'sufficient time and information supplied to the consultee and genuine consideration of advice by the party obliged to consult'(Anon, 1992e). Some councils have put aside budgets to contract iwi input (Shields and Webber, 1992). Issues of special importance to Maori would involve traditional taonga (possessions and values held in great respect), spiritual values and land. In the past proposed developments involving sacred sites, for example burial grounds and pollution of water have been of particular concern to Maori groups.

In deciding the outcome of a resource consent application a consent authority must consider the purpose and principles of the RMAct, any applicable national and regional policy statements, the regional plan and, if applicable, the district plan. Negative effects are balanced against social and environmental benefits. Post-mining land uses associated with site reclamation can provide major benefits to offset environmental and social costs associated with extraction. For example creative reclamation of a water filled pit can enhance the environment through wetland creation or help achieve community goals by creating a water sports facility or residential subdivision featuring lake-front sections.

### 8.3.3 Enforcement powers of Councils

The environmental responsibilities of an extraction operation may include compliance with conditions of the resource consents and compliance with minimum standards in regional plans and regional rules. Conditions may specify that the holder of a resource consent is liable for any breach of conditions before the consent expires and for any adverse effects on environment during or after the life of the consent (Lynch, 1992). Additionally a bond or bonds may be required and may be forfeited if conditions are breached. Bonds may be automatically adjusted for inflation and may take the form of a guarantee by a bank or insurance agent (Quigg, 1990). The Macraes Joint Venture (Chapter 3.3.5), for example, was required to supply a four million dollar bond available from the start of mining until 51 years after mining has ceased (Peat, 1991).

Where a company or individual does not comply with requirements an authority has two options. The authority can issue an **abatement notice** requiring or prohibiting an activity and/or requiring mitigation or restoration of the environment (Dart, 1992; Lynch, 1992). Abatement notices may be appealed by the company within seven days to the Planning Tribunal but, regardless of the outcome, the company has to pay for the cost of issuing the notice (Dart, 1992; Lynch, 1992). Alternatively a Regional or District Council can request an **enforcement order** from the Planning Tribunal (Lynch, 1992; Milne, 1992). The Planning Tribunal decides the terms and conditions of the order which may require the offender to act positively, for example clean-up, or negatively, for example to stop doing something (Dart, 1992<sup>b</sup>; Caldwell, 1993). All compliance costs of an order are met by the persons to whom it is issued. If the offender still fails to comply with the enforcement order the authority can act to remedy the situation themselves and seek reimbursement by the offender (Lynch, 1992). Additionally, "any person" can apply to the Planning Tribunal for an enforcement order. Case law has shown enforcement orders have been used by a wide range of people including public interest groups and business competitors (Caldwell, 1993). "Any person" can also commence a prosecution under the RMAct.

New provisions significantly increase the exposure of companies, directors and managers to environmental liability as the permitted defences are narrower than under the TCPA (Happy, 1992; Lynch, 1992; Caldwell, 1993). If conditions are breached strict and criminal liability occurs. This means it is not necessary to prove that the defendant intended to commit the offence and **principals** for example company directors and managers, are liable for the actions of their employees. On conviction penalties can comprise up to two years imprisonment and fines of \$200,000 and \$10,000 per day for a continuing offence (Lynch, 1992; Milne, 1992; Solomon, 1992; Caldwell, 1993).

#### 8.3.4 Extraction under the Crown Minerals Act 1991

One of the most important last-minute changes to the RMAct was the complete removal of part 9 of the RMAct to form the Crown Minerals Act 1991 (Fitzsimons, 1992). This separated analysis of the environmental effects of mineral extraction from the analysis of optimum extraction rates, pricing and allocation of mineral resources which is detailed in the Crown Minerals Act (Fitzsimons, 1992). Crown owned minerals include "industrial rocks and building stones" (aggregate) on land owned by or alienated from the Crown after 1 October 1991 and minerals reserved in favour of the Crown before this date.

Mineral programmes will be formed to guide management of each mineral group (Mackenzie and Cave, 1991). The mineral programme for aggregates, for example, will specify: whether or not, and to what extent, prospecting, exploration and mining of aggregate is permitted; policies and procedures to apply in granting mineral permits; royalties for aggregate; and areas of land which are excluded from mining (Taranaki Regional Council, 1992). Mineral programmes will also contain administrative details such as specifying the types of permit, registration of prospecting and mining rights on land titles and procedures for land access (Mackenzie and Cave, 1991).

Under the Crown Minerals Act exploration and extraction of Crown minerals requires a minerals permit from the Crown (Ministry of Commerce). The Ministry of Commerce has produced a permit questionnaire that is similar to the Environmental impact assessment forms that were required under the Mining Act and its amendments (Mew and Ross, 1992). The Ministry of Commerce, however, has no environmental responsibilities. The Crown Minerals Act requires formal consent from a land owner for land access for prospecting or mining (Ross and Tweedie, 1991; Mew and Ross, 1992). Only a small proportion of aggregate mines operated under the Mining Act and this trend will probably continue under the Crown Minerals Act. Neither the Crown Minerals Act nor the RMAct applies to any aggregate extraction site licensed under the Mining Act 1971. At these sites mining licence conditions related to soil conservation, water quality and quantity and hazardous wastes are monitored by Regional Councils. District Councils have responsibility for monitoring land use, noise and vibration, hours of work and land reclamation (Taranaki Regional Council, 1992).

#### 8.3.5 Effectiveness of the Resource Management Act

The full effects and implications of the Resource Management Act are unclear two years after its enactment. Regional plans and policy statements are still being prepared, thus existing controls remain until regional policy statements are created. Controls on extraction will probably vary between regions as each region will have different environmental goals and concerns. Interim or transitional district plans, will be altered as they become due for replacement from 1990 to 1994 (Young, 1992) and are reviewed in terms of principles and requirements of the RMAct. Mr

Palmer, the Minister for the Environment in 1988 who initiated the Resource Management Act, said:

*"The law is only the beginning, the (Resource Management) Bill sets up a sound framework. How effective it is in achieving sustainable management practices will be over to local communities, professionals and politicians" (Ministry for the Environment et al., 1990)*

It may take 10 years of court activity before legal precedents and definitions associated with the RMAct are set through Planning Tribunal and court decisions (Dart, 1992b, Happy, 1992). Case law has exposed a need for amendments to the RMAct as a result of the skill of advocates interpreting the law and through inadequacies in the RMAct (Dart, 1992<sup>a</sup>). The first Resource Management Amendment Bill was introduced into parliament in 1992 to clarify policy intent and make grammatical and technical amendments to the RMAct (Anon, 1992g).

Table 8.0: The number and method of formal enforcement procedures used by Regional Councils from the passing of the Resource Management Act 1991 to August 1993. Data from Tompkins Wake Barristers and Solicitors.

Regional Council	Method of enforcement		
	Prosecutions	Abatement Notices	Enforcement Orders
Northland	0	10	0
Auckland	7	31	8
Waikato	4	20	0
Bay of Plenty	5	3	1
Taranaki	7	675	0
Manawatu-Wanganui	0	4	0
Wellington	5	?	1
West Coast	2	21	0
Canterbury	0	7	2
Otago	0	1	1
Southland	0	1	0



A survey conducted by Tompkins Wake Barristers and Solicitors showed that, up to August 1993, few prosecutions had been issued by Regional Councils. The results, summarised in Table 8.1, show that there is a split between the 5 councils which have issued 4 to 7 prosecutions each and 4 councils which had no experience of prosecutions. The use of abatement notices also varied widely between regions, with 4 of the councils issuing less than 5 abatement notices over the two year period and Taranaki Regional Council issuing 675 in the same period. Abatement notices were generally seen as a useful basis for a negotiated settlement and effective at getting the offender to take required actions. However, the 7 day appeal period was identified by several regional councils as inappropriate for situations where immediate action was required, for example many water pollution incidents. Additionally, two regional councils reported that they found increasing monitoring of non-compliant activities and recovering the full costs of the monitoring was a more effective method of getting compliance than issuing abatement notices.

Planning by the mining industry has been constrained because no national policy statements or crown mineral programmes have been released. These will directly or indirectly impact many aspects of aggregate extraction (Roberts, 1991; Mew and Ross, 1992), for example, policy advocating preservation of agricultural land or wetlands or setting stringent regulations may impact the location of aggregate mines and favoured reclamation options. The RMAct has been seen as favourable for the mining industry because resource consents should be based on the environmental impacts of the proposed activity, rather than specific activities themselves, mining should not be discriminated against (Ross and Tweedie, 1991; Bates, 1992). Additionally environmental standards will be based on the receiving environment rather than imported technical standards (Ross and Tweedie, 1991). The RMAct may, however, increase costs and time delays associated with gaining resource consents (Roberts, 1991; Happy, 1992) due to increased public involvement, provisions which allow authorities to recover the costs of hearing consent applications and additional reports from an applicant (Happy, 1992; Penny, 1992).

The RMAct should result in a reduction of damage to the environment (Mew and Ross, 1992) although it has been criticised for removing the sustainability requirement for mining because depletion rates are not considered under the RMAct (Weeber, 1991). Detailed questionnaires associated with resource consents should increase an applicant's awareness of the environmental and social impacts of their actions (Mew and Ross, 1992). The introduction of abatement notices (Lynch, 1992) and the increased likelihood of offenders being successfully prosecuted and fined under the RMAct has assisted councils in control of pollution (Dart, 1992<sup>a</sup>). The probability of being penalised and substantially fined, for infringements has probably increased now that Planning Tribunal judges are involved in convictions rather than district judges (Milne, 1992). Although penalties may still be inadequate to deter infringements by large companies (Milne, 1992) most small to moderate sized companies (including aggregate companies) would regard a fine of \$200,000 a substantial deterrant (Happy, 1992; Rhodes, 1992;



Solomon, 1992). Happy (1992) stated that the level of fines and increased environmental liability has already resulted in aggregate companies examining their environmental responsibilities and setting up improved management and monitoring regimes. Freedom from liability is only guaranteed through full compliance with the RMAct (Rhodes, 1992).

The probability of infringements being detected will vary between regions. Monitoring by territorial authorities is limited by available funding at which is a function of a regions's rateable area and wealth (Young, 1992; Mew and Ross, 1992). Monitoring by the Ministry for the Environment will also probably be limited by funding (Young, 1992). Additionally, monitoring by the Ministry of Commerce, through the Inspectors of Mines is now limited to health, safety and monitoring production for Crown income assessment purposes (Mew and Ross, 1992; Robertson pers. comm., 1992).

Caldwell (1993) stated that the key to operating a business under the RMAct is to be pro-active in environmental matters. This can include minimising the risks of breaching conditions of resource consents, conducting environmental audits to to identify compliance of current operations and avoidance of "inheriting" environmental problems by assessing the environmental performance of prospective investments.

#### 8.3.6 Environmental controls of aggregate mining outside the RMAct

There are two further controls, in addition to the RMAct, on the impacts of aggregate extraction on the environment. Firstly, extraction of aggregate from within the Department of Conservation estate requires completion of a standardised questionnaire which overlaps information required in resource consent applications (Mew and Ross, 1992). The Department has their own policy on reclamation of mined land, in particular advocating return of indigenous vegetation. All mining will be prohibited in areas specified in the 'Protected Areas Bill' which went before a select committee in March 1992 (Anon, 1992f).

Secondly, in 1987 the Ministry for the Environment was given a reporting function on all proposals with significant environmental implications submitted to cabinet or its committees. This function was equivalent to that of Treasury and the State Services Commission, who also report on proposals, and ensures that environmental implications of policy proposals can be considered by Cabinet (Buhrs, 1992).

### 8.4 The social requirement for reclamation

In 1556 Georgius Agricola discussed in "De Metallica" the costs to the environment of mineral extraction and tried to balance these against the economic benefits of minerals to society.

The degree to which society is prepared to accept these environmental costs (detailed

in Section 2.7) has changed over the years, reflecting changing community expectations. The expectations of a community are influenced by its population density, standard of living and level of degradation. An unpolluted environment is usually more highly valued in wealthy communities and where land suitable for development is scarce (Skelton<sup>et al.</sup>, 1990). Different cultures place different values on the importance of individual environmental issues (Sprague, 1991), for example, Maori may associate spiritual values with rivers and hence have an aversion to discharges of effluent into rivers and mixing water from two different sources (Taranaki Regional Council, 1992). Over the last decade environmental concerns and sensitivity towards the impact of mines on the environment has increased and reclamation has become an increasingly important part of mine proposals in Australia, the United Kingdom, Europe, North America and Japan (McCormack, 1976; Carter, 1990; Bell, 1990; Webb, 1990; Wilson, 1990).

The mining industry has been often singled out for environmental criticism because it is usually highly visible, localised and involves massive land disturbance (Mackenzie and Cave, 1991). Although mining has a severe local impact only small areas of land are involved (Bell, 1990). In New Zealand, for example, the total land area occupied by mining related activities occupies c.0.2% of all land use in New Zealand (Mackenzie and Cave, 1991). In comparison, use of agrochemicals and fertilisers, soil erosion and effluent associated with the large scale pastoral and arable farming sector cumulatively has a large environmental impact but the impacts are individually small. The proximity of aggregate mines to cities and transport routes makes them particularly subject to public criticism. Additionally, separation of a mineral from its end use masks the necessity of mining in a modern society. This irony is demonstrated in "no mining" bumper sticker on a vehicle built from, powered by and travelling over the products of mining (Quinn, 1992). The sensitivity of the public towards mining has been raised by some spectacular environmental disasters in the past, such as the Tui mine in the Coromandel (Chapter 3.3.5) and areas of herringbone-shaped tailings in Central Otago and West Coast regions. Public sensitivity has also been raised by the high profile of some large, controversial mining proposals such as hard rock gold mines in the Coromandel Range.

Changing community expectations are reflected in changes in legislation. In New Zealand legislation has changed from facilitating mining to controlling the environmental effects of mining and increasing the level of public participation. Most past environmental problems related to mining were the result of the mining industry working within the environmental expectations and standards of the community at the time (O'Conner, 1991). Until the 1960s and 1970s a mining company that spent heavily on reclamation would probably have been criticised as wasting money, especially as much of the land mined (Central Otago, Coromandel, West Coast) had an income capacity that was low by any other means (Webb, 1990). In New Zealand reclamation has been required by legislation since the 1981 Mining Act.

The aims of reclamation of mined land have changed over time. Initially reclamation was primarily cosmetic and aimed to "remove eyesores which may cause adjacent land to suffer from the inhibiting effects of a depressing environment" (Downing, 1972). Reducing the visual impact of mine sites is particularly important in NZ as the clean, green image is one of our most appealing features to tourists (Ross and Tweedie, 1991). More recently the quality of reclaimed land as the need to maintain flexibility and choice (given future uncertainties) has become important (Cronin, 1988). This has been emphasised by legislation which promotes sustainable land use practices. Mining should be regarded as an interim land use and reclamation has a key role in ensuring sustainable land use and productivity of mined land. Sustainable land use was described by Proctor (1990) as "*the current generation holding the environment, not on a freehold basis, but on a fully repairing lease for the future*".

Sustainability is often used in a narrow sense in New Zealand reclamation. There is an emphasis on restoring the agricultural value of mined land despite a world surplus of many agricultural products. Keating (1988) proposed that the importance of productive farmland to the economy of New Zealand (land-based activities provide 70% of New Zealand's revenue) influences the expectation New Zealanders have of reclamation standards. Pressures to return aggregate mines on alluvial terraces to agriculture may be greater than for other similarly sized mines due to the high value these sites for agricultural production. Mew and Ross (1992) stated that the common argument for reclamation is that it is in the interests of the nation that the total land resource is not degraded to any large extent.

Internationally, a wider interpretation of sustainability is used. The interpretation promotes efficient land use by utilising beneficial, alternative land uses which are possible at mined sites after extraction of the resource (Downing, 1972). In this scenario, mining is only an interim land use (Miller and Mackintosh, 1987). Mining activities have the potential to move large volumes of earth and/or create water filled areas. Creation of wetlands can compensate for loss of wetlands elsewhere. Similarly, urban and commercial development on mined out sites allows pressure to be decreased on the finite resource of highly productive agricultural soils surrounding cities.

In the 1990's unreclaimed mines are not only aesthetically unacceptable but are also ecologically unacceptable to the New Zealand public (Ministry of Energy, 1985). The increased importance of ecological values has been reflected in the growth of membership in conservation and environmental organisations (Wilson, 1990). The environment is no longer seen as a free resource for industries to use, or, in the words of Aitken (1991) "*the zero-cost environmental garbage dump is disappearing...the costs have to be internalised*". Requiring reclamation ensures some of these costs are internalised; that industry, and ultimately consumers, pay the price of a product which includes the cost of minimising adverse environmental effects.

## 8.5 Economic influences on reclamation

Social responsibility and economics are the dominant factors which influence reclamation choices of most larger mining companies (Michalski *et al.*, 1987). Economic influences on reclamation may be measured through a benefit-cost analysis (BCA). A BCA helps fulfill the requirement of the RMAct to state all environmental and social impacts of a mining proposal as a detailed BCA lists all actual and potential, tangible and intangible benefits and costs. A BCA enables comparison of widely variable factors by giving as many factors as possible a monetary value to determine the overall impact of mining. Non-monetary benefits may include a reduction in the time taken to gain additional consents if reclamation is successful (McRae, 1985).

The economic viability of reclamation options depends on many site specific factors including the value of the resource, cost of extraction and processing, depth and type of overburden, depth to water table and the pre-mining land use. The size of a site, its environment, ecology and possible natural sources of seed will also affect the cost of reclamation. Surrounding land uses and the proximity of the site to urban centres can determine the viability of post-mining land uses such as reclamation to waste disposal facilities, residential or industrial subdivisions and active recreation facilities which all need to be located near population centres. The high price of urban land encourages reclamation options such as housing or commercial development which capitalise on such high value land uses. In contrast, sites on the urban fringe suit low intensity reclamation options, such as camping, walking and pastoral agriculture, that preserve the potential for later and more intensive development (Krohe, 1989). The most economic use of remote sites with low land values may be natural vegetation to wetlands and wildlife habitat. Operators in the countryside have a smaller market for overburden, decreasing income from the site and increasing earth moving costs (Pulman, 1990). In England, where land is expensive, reclamation to "hard" end uses such as industrial and residential subdivisions exceeds reclamation to recreation, public open space, agriculture and forestry (Mabey, 1991).

The costs of reclamation are influenced by the conditions attached to mining and resource consents (Bureau of Land Management, 1989). For example, Ministry for the Environment 1993 specifications for landfill construction, operation and restoration increase the costs of this reclamation option.

The economic viability of an after use is influenced by the policies of national and local governments. Central government can determine, or provide guidelines, on who pays for what, i.e. whether functions are government funded, funded by regions or the extraction company. Authorities can provide economic incentives to encourage particular reclamation options through part financing for public works, subsidies, grants, or joint ventures. Reclamation tax write-offs in Western Australia (Wilson pers. comm., 1991) and derelict land grants in England promote

reclamation (Mabey, 1991). Until 1974 reclamation to agricultural land in the United Kingdom was eligible for subsidies of 30% on many farm inputs, including drainage, buildings, fertiliser and fencing.

Local governments in Canada and the United States have subsidised or maintained parks, aquatic centres and nature reserves for public recreational or amenity use with the aggregate extraction company gifting reclaimed land to the local government.

The stage of the extraction operation at which reclamation is planned for may dramatically affect cost of reclamation. The cost of earthworks is higher, availability of soil lower and post-mining land use options fewer for an abandoned mine compared to a mine in the planning and development stages (Pulman, 1990). Alluvial miners on the West Coast and Central Otago have found rolling reclamation, i.e. restoration directly behind the extraction operation, is the most cost effective method of reclamation (Mackenzie and Cave, 1991). Lack of planning increases the cost of reclamation as earthmoving equipment may not be fully utilised. If costs of reclamation are incorporated throughout the life of the mine money can be set aside for restoration out of operating profits. If no funds are set aside, an interim use such as landfill may provide proceeds for restoration (McRae, 1985).

The viability of reclamation can be markedly affected by the chosen post-mining land use as most of benefits of mining depend on the final land use. In New Zealand land reclaimed to agriculture generally has a low financial return, reflecting the returns typical of capital invested in agriculture compared to other financial investments. Conversely, in the United Kingdom in the early 1970's agriculture was regarded as one of the most economic uses for mined land because agricultural products had high returns (Vyle and Downing, 1972). In the 1980's reclamation to nature conservation was a highly cost effective option compared to the traditional open space parks which had high capital costs and were (and still are) expensive to maintain (Mabey, 1991).

In the 1980's and 1990's some New Zealand mining companies, for example Cyprus Gold (Golden Cross mine) and Waihi Gold (Martha Hill mine) have allocated large resources to reclamation and environmental management. Indirect benefits related to surveys of site ecology have included knowledge from botanical, wildlife, soil and geological surveys which lead to greater knowledge of ecosystems. Terrestrial ecology at Macraes flat and Golden Cross led to the discovery of two species of regionally threatened native frogs, one of which had not been found at that latitude before. In Australia mining companies conduct or fund more environmental research than any other group in Australia (Webb, 1990).

Because money has to be borrowed, or income foregone, when spent on reclamation, a discount rate is used to compare monetary benefits and costs received during reclamation at different times. A high discount rate disadvantages reclamation projects that have high initial costs and long term benefits and promotes projects with short term benefits, *cet. par.* For example, the most economical short term use with the least amount of initial investment is water recreation as



it takes minimal time to establish since slopes can be graded during excavation.

The state of a country's economy will also influence the economic viability of post-mining land uses through the affecting the cost of borrowing money, demand for land, growth of cities, the number of potential developers or investors and the amount of spending by local and regional government. In depressed economic times reclamation options with fast returns and immediate visual responses are favoured (Carter, 1990). Short term returns can be realised from intermediate restoration options such as landfill (Anon, 1985c).

Finally, the degree of risk associated with a post-mining use will affect its economic viability. Risk is associated with planning 10 to 40 years in the future when extraction is completed. Risk is also associated with changing demographics, environmental issues and community / industry needs (Munson, 1985). Generally a riskier venture requires a higher return on investment to be viable. In the United States housing is considered a low risk post-mining land use and consequently one of the most favoured reclamation options. Generic restoration is also low risk, as it allows a variety of potential land uses and thus has a wider potential market (Igoe, 1985).

## **8.6 Survey of aggregate producers in the greater Manawatu region**

### **8.6.1 Objectives**

A 15 question survey of aggregate producers in the greater Manawatu region aimed to find out the physical characteristics of aggregate extraction sites and the types of conditions and reclamation plans commonly associated with extraction of aggregate in the region. The survey and covering letter is reproduced in Appendix 8.3.

### **8.6.2 Results**

The survey was posted to 42 aggregate producers in the Manawatu, Wanganui, Rangitikei and Horowhenua districts that were on a list of Central Inspectorate Quarries compiled in December 1990. Over a period of six weeks 80% of the aggregate site operators responded to the written survey. The response was poorest in the Manawatu area where one aggregate company with five extraction sites did not reply.

#### *Legislative requirements*

The survey confirmed that many extraction sites are operating with minimal formal conditions relating to the potential effects of extraction on the environment. Although 89% of the sites required permission for operation from either private owners or public bodies, 36% of sites either had no environmental conditions associated with their operation or the manager did not know



Table 8.1: The number of respondents to the survey of aggregate producers and their location in the greater Manawatu region.

Region	Number of sites questioned		Percentage replies from each region
	Number	Percentage	
Manawatu	18	43	56
Wanganui	8	19	88
Horowhenua	8	19	100
Rangitikei	8	19	88
<b>Total</b>	<b>42</b>	<b>100</b>	<b>83 (average)</b>

if they had any conditions. Younger extraction sites were more likely to have environmental conditions attached to the extraction of aggregate, with 42% of sites which started prior to 1960 (and were still operating) having no conditions, compared to only 17% of sites starting between 1980 and 1991. Extraction sites owned by individuals or the company extracting aggregate were twice as likely to have no conditions than sites owned by regional or local government. Most aggregate extraction sites were owned either by the aggregate extraction company or a private owner (71% of sites) and licensed by local or regional government (75% of licensed sites).

Table 8.2: The number and percentage of sites in the greater Manawatu region which required permission to extract aggregate and have conditions linked with extraction of aggregate.

Requirement for permission and conditions of extraction					
	Yes		No		Don't know
<b>Permission required</b>	34	89%	4	11%	0
<b>Conditions imposed</b>	24	65%	8	22%	5 14%

NB Not all the site managers answered both questions.

Table 8.3: Conditions associated with extraction of aggregate from sites in the greater Manawatu region.

<b>Conditions associated with extraction of aggregate</b>		
<b>General requirements</b>	<b>Number of sites</b>	<b>% of sites with specific condition</b>
Maximum depth of extraction	19	79
Fencing	3	13
Maximum face heights and slopes	10	42
Sealing access roads	6	25
Infilling mined area	5	21
Silt settling/retention ponds	13	54
<b>Reclamation Requirements</b>		
Stripping of soil	8	33
Planting trees as screens/filters	7	29
Spreading imported soil	2	8
Ripping or subsoiling	1	4
Sowing grass/legume pasture	4	17
Preparation of a reclamation plan	8	33
Total no of sites with conditions	24	100

Conditions relating to the site environment generally concentrated on ensuring on-site safety and controlling the off-site effects of aggregate extraction. The most common conditions imposed on extraction sites were specification of a maximum extraction depth, face heights and gradients (79% of sites) and provision of silt traps (54% of sites) reflecting input from the Mines Division of the Ministry of Commerce (site safety) and Regional Councils (former Catchment Boards) (safety of river users and maintenance of water quality). Conditions to meet the concerns of residents close to extraction sites were also common with conditions resulting in reduction of dust through sealing of access roads (25% of sites) and reduction of visual pollution (29% of sites) through planting of shelter belts.

Conditions requiring specific reclamation practices, other than stripping soil from a site before extraction began, were uncommon. The general condition requiring preparation of a reclamation plan was applicable to 33% of the sites that had conditions. Only 17% land-based sites (4 of 24) had establishment of pasture as a condition of aggregate extraction and only 1 site was required

to rip replaced soil. While more than 80% of land-based extraction sites had conditions in addition to those controlling the depth of extraction and the construction of silt traps, extraction sites in rivers generally had only these two conditions.

*Characteristics of extraction sites in the greater Manawatu region*

Most aggregate extraction sites in the greater Manawatu region mine alluvial aggregate which is sourced from the beds and banks of rivers (38% or 15 of 40 sites) and river terraces (28% or 11 of 40 sites). One third of the aggregate mines are "hard rock" quarries (33% or 13 of 40 sites). Aggregate extractors predicted that in the future aggregate would be increasingly sourced from river terraces instead of the beds and banks of rivers. Companies producing aggregate from quarries predicted no change in their source in the future. This probably reflects the different markets supplied by alluvial and quarried aggregate and the non-substitutability of products from one source by the other (Chapter 2.3).

Table 8.4: The area or length of site and year extraction of aggregate started at surveyed sites in the greater Manawatu region. The number of sites is on the LHS and percentage of sites is on the RHS of each box.

Size of aggregate extraction site				
< 10 ha	> 10 ha	1-4 km river	>5 km river	Total
18    51%	11    31%	5    14%	1    3%	35
Year that extraction of aggregate began				
Pre 1960	1960 to 1969	1970 to 1979	1980 to 1991	Total
12    32%	8    22%	7    19%	10    27%	37

The majority of land-based extraction sites in the greater Manawatu region are less than 10 ha in size (62% or 18 of 29 sites) and 5 of the 6 river extraction sites work less than 5 km of river bed. Most extraction sites have been mined for more than 10 years (73% of sites) with 32% of the extraction sites having been used for more than 30 years. Over the last 30 years 7 to 10 extraction sites have started each decade, however only sites which were operational in 1990 were surveyed, so the figures did not include sites which closed before the survey began.

The number of hard rock quarries starting operations in each decade since the 1960's has decreased, although the sample number is small, from 4 in the period from 1960 to 1969 to 1 in period from 1980 to 1991. Before 1960 the ratio of extraction sites sited in river beds to those on river terraces was 7:2. By 1980 to 1991 this ratio had dropped to 5:4. Between these dates

the number of extraction sites located in rivers and terraces fluctuated. As aggregate in all rivers in the region is a diminishing resource, with the possible exception of the Rangitikei River (Chapter 2.5.1), I expect that in the future any new extraction sites in rivers will be temporary, with mobile crushing plants removing aggregate as directed by the Regional Council for river control purposes.

#### *Reasons for the choice of post mining land use*

Managers of aggregate extraction sites gave a wide variety of answers when asked the probable post-mining land use at their site was going to be and what determined the level of reclamation at their site. The most common guiding factor was a site management plan or manager was reported as the main influence for 38% of sites (6 of 16 replies). Surprisingly, the cost of reclamation and consent requirements were factors affecting the post-mining land use option at only 2 sites. A further 2 sites stated that the extent of flooding limited the post-mining options available to them. Other factors which influenced the choice of post-mining options were the amount of overburden, extent of extraction and environmental impact (6 of 16 replies).

Table 8.5: Land use before extraction of aggregate from surveyed sites in the greater Manawatu region.

<b>Land use before extraction</b>		
<b>Land use</b>	<b>No. of sites</b>	<b>% of sites</b>
Arable crops	3	9
Pasture	18	53
"Waste" land	3	9
River bed and banks	10	29
Total	38	100

NB "Waste" land comprised scrub or river floodplain unprotected by flood-banks.

Interestingly, the land use before extraction of aggregate was not stated as a factor affecting the choice of reclamation by any site manager. This is confirmed by comparing land uses before mining and those proposed for the cessation of mining. Of the 18 sites used for arable cropping or pasture production before mining, only 7 of these sites were probably going to be reclaimed to pasture, although a further 8 sites would probably be grassed (comprising 4 sites with an unspecified use, and 4 sites which were to be cleared of equipment and made safe).

A subsequent question was also designed to indicate factors influencing the choice of post-mining land use. Many mine managers do not formally seek advice from others on reclamation (39% or 12 of 31 sites). A similar proportion of managers consulted, or plan to consult, the local Inspector of Mines who is part of the Ministry of Commerce (36% or 11 of 31 sites). Some operators consulted, or plan to consult, the local or regional authority (19% or 6 of 31 sites) while in one case each the landowner and a private agricultural consultant influenced the choice of land use after extraction had ceased.

A broad range of land uses was predicted for the 25 land-based extraction sites by the site managers. The dominant land use was pasture (7 sites or 29%) or minimal reclamation where the site was "made safe" and greened (6 sites or 25%). More imaginative post-mining uses which were proposed included pine plantations (2), residential housing (2), landfills (2), a recreational lake (1) and a car park for an adjacent scenic attraction (1). Managers of 3 sites said that the cessation of mining was too far in the future to determine the post-mining land uses.

### 8.6.3 Discussion

The results of the survey indicate that, at least historically, ensuring productivity of land after aggregate extraction is of less importance to consent authorities than ensurance of safety at extraction sites and amelioration of potential impacts on adjacent land owners. A condition requiring a reclamation plan, usually "to the satisfaction of the consent authority", which applied to 33% of the land-based sites surveyed, may include measures to ensure post-mining productivity equivalent to that existing prior to mining. However, I suspect this condition has generally focused on ensuring stability of the final landform and additionally has sometimes involved establishment of a specified vegetative cover. The absence of requirements to return land to its former productivity was reflected in the hesitancy of site managers to seek advice on site reclamation and that only one site manager stated that consent conditions influenced the choice of post-mining land use.

Planning the post-mining land use of aggregate extraction sites is complicated by the large fluctuations in demand for aggregate (Chapter 2). This means some sites are used intermittently over a number of years and determining when the resource at an extraction site will be exhausted is subject to large errors. Despite this, a relatively wide variety of post-mining land uses was anticipated by site managers in the greater Manawatu region.

#### 8.6.4 Conclusion

##### *Legislation*

- \* Many extraction sites have few conditions related to impacts on the environment.
- \* Extraction sites less than 11 years old are more likely to have conditions than older sites.
- \* Privately-owned sites are more likely to operate without conditions than those owned by public bodies.
- \* Most conditions are associated with safety at the extraction site, water quality and dust control.
- \* The most common conditions relate to reclamation required preparation of an approved reclamation plan and stripping soil before extraction.

##### *Characteristics of extraction sites in the greater Manawatu region*

- \* Most aggregate extraction sites mine alluvial aggregate.
- \* Most land-based extraction sites cover <sup>less</sup> than 10 ha.
- \* Most river extraction sites work less than 5 km of river bed.
- \* Most extraction sites have been mined for more than 10 years.
- \* Most land based extraction sites used to be in pasture.

##### *Post-mining land use*

- \* The site management plan or manager is the main factor influencing the choice of land use after extraction of aggregate.
- \* A wide variety of factors affect the choice of post-mining land use.
- \* The majority of managers of mines either consult the local inspector of mines (Ministry of Commerce) for advice on reclamation (39%) or do not formally seek advice on reclamation (36%).
- \* Pasture (29%) and minimal reclamation (25%) are the dominant post-mining land uses.
- \* Other post-mining land uses planned are forestry, housing, landfills, a lake and a car park.

#### 8.7 Post-mining land uses

In this section the main reclamation options for exhausted aggregate extraction sites are presented. The first two reclamation options, no reclamation and minimal reclamation, are straightforward and are most suited to abandoned or remote sites where minimal resources are available. As section 8.7 progresses, each reclamation option is more complex and requires a larger capital investment and/or a greater level of technical expertise.



### 8.7.1 No reclamation

Abandonment of a site at the cessation of mining occurs mainly at older sites under extraction permits which did not include conditions requiring restoration. Abandonment may also occur at sites on crown land mined by government departments or local bodies which did not require extraction permits. Mine abandonment is also associated with small operations, especially private mines used for personal aggregate requirements such as those on farms. Krohe (1989) describes abandoned sites:

*"the only design opportunity presented by the thousands of severely disturbed industrial landscapes in the United States was in the choice of shapes of signs that announced "No Trespassing". If spent landfills, sand and gravel pits had an after use it was as local swimming holes or ready made graves in which nearby cities could bury their garbage."*

Over time abandoned mines naturally revegetate as seeds of colonising plants are blown in from adjacent areas. The more favourable the rooting medium, in terms of plant water and nutrient supply and exploitable rooting depth, and the more favourable the climate, the faster growing and more dense the foliage. The species which colonise a site depend on land uses in the surrounding area and the ability of individual species to disperse its seed (Bailey and Gunn, 1991). The botanical composition of a naturally revegetated site changes over time as pioneer species (often legumes) are replaced by successive associations of plants which ameliorate the microclimate, build up organic matter and create a more stable, sheltered and moist surface. Natural revegetation of mine sites is often slow and may therefore be environmentally and socially unacceptable (Michalski *et al.*, 1987). Naturally colonised areas can, however, become valuable refuges for wildlife. Exposed rock formations may be of geological interest (Bellamy, 1990). In the United Kingdom many derelict sites have been designated sites of special scientific interest or nature reserves. In some cases quarries and pits are the last known refugia of rare species and contribute significantly to the contemporary wildlife assets of the United Kingdom, particularly limestone quarries (Bailey and Gunn, 1991). Bellamy (1990) praises the disused English quarry pits he grew up near as:

*"the only bits of informal green space left for nature or local people to enjoy"*

Unreclaimed, degraded sites may also have historical, cultural or educational value (Quinn, 1992)

### 8.7.2 Minimal reclamation

Minimal restoration involves rudimentary, low cost works which improve public safety and visual aesthetics of mined out sites. Minimal restoration is generally associated with older mines which operate without conditions which require reclamation of the mine site. Minimal reclamation is also associated with conditions of extraction that lack a definition or standards of adequate reclamation, as reclamation can vary in meaning from sowing grass seed to creating an environment for a productive second use. Minimal reclamation is also associated with sites

where planning for reclamation occurs at or towards the end of site development. In such cases soil and potential rooting media are generally not retained and this limits the possible cost-effective reclamation options.

Minimal restoration may be limited to ensuring the safety of mined out sites to the public by fencing the site, removing machinery and eliminating areas of instability by reducing the height of batters (Krohe, 1989). Minimal restoration may include reducing the negative visual impact of a mine site by blending it with the surrounding area. This may comprise screening the site from public view, softening the angular landforms of a mine, or accelerating natural revegetation. The angular landforms associated with mine faces may be softened by blasting or placing fill against slopes. Trees can visually screen sites and create a more sheltered site microclimate (Pulman, 1990). Although Snaith and Gagen (1991) criticise the promotion of "*screening and greening*" as an poor planning strategy which attempts to maintain the "*myth of the rural idyll*" by concealing production processes, the establishment of plants helps minimise wind and water erosion and so reduce sedimentation of waterways.

Accelerating natural revegetation is generally most successful when an irregular topography with a range of substrates, compaction and moisture levels is created. Uniformity limits a site's wildlife value (Michalski *et al.*, 1987). Minimal revegetation may include modifying the rooting media by decreasing the angles of slopes, roughening smooth surfaces and scarifying or ripping soil to relieve compaction (Michalski *et al.*, 1987; Dietrich, 1990). Revegetation may be indirectly assisted by fencing to exclude browsing animals, mulching, applying fertiliser and herbicides. Direct assistance can involve hydroseeding, direct drilling or broadcasting plant species, particularly leguminous species which produce nitrogen.

### 8.7.3 Generic reclamation

Generic reclamation is reclamation which allows a site to be adapted to a variety of final end uses (Carter, 1989). Generic reclamation is most common at extraction sites which operate over a long time frame and where the end land use is unspecified. This includes sites practising continuous restoration or development of landfills where the ground surface settles over time. Generic landforms are preferred by some developers as they allow modification to a variety of uses such as industrial or residential subdivisions or recreation (Krohe, 1989).

A site reclaimed to a generic plan is structurally stable with gentle slopes (Krohe, 1989). Smooth landforms without localised hollows or high spots minimise uneven drainage and rill or channel erosion, which is common in a newly completed surface (Macdonald-Steels and Haigh, 1988). Often only a minimum depth of free draining material is spread to aid the establishment and growth of a vegetative cover, often a legume and grass sward, which reduces surface erosion and improves the aesthetic value of the reclaimed site.

## 8.7.4 Forestry

Forestry is an alternative to agriculture on mined sites with poor soils and steep or uneven topography (Coppin and Bradshaw, 1982). Reclamation strategies for forest establishment require less grading and site levelling than reclamation to agricultural use, so operating costs are lower and compaction is minimised (Davidson, 1985). Aggregate mines usually have heavy vehicle access and are close to main roads, allowing cost effective tree extraction. Trees may have amenity, erosion control, shelter and wood value (RMC, 1987) and tree production is compatible with many forms of outdoor recreation (Hilditch *et al.*, 1988). On some sites trees with short production cycles like Christmas or firewood coppices can be a profitable interim use prior to a more permanent use like a residential subdivision (Hilditch *et al.*, 1988). Trees generally require little maintenance after the establishment period of two to seven years.



Photograph 8.1: Pine trees (*Pinus radiata*) for production of timber growing in a reclaimed aggregate pit, Greatford, New Zealand.

Aggregate pits have been forested with pine (*Pinus radiata*) trees in New Zealand (Photograph 8.1). The extensive, deep rooting system of pines aids survival in the low water and nutrient holding media that typically form the base of pits in alluvial terraces (Hilditch *et al.*, 1988). The economics of forestry with *Pinus radiata* in New Zealand may be limited by the scattered nature and small size of the sites (Happy, 1992) unless high quality clear wood is produced. McLellan *et al.*, (1979) and Hilditch *et al.*, (1988) suggest that in Canada areas less than 2 to 4 hectares in size or with soil depths less than 0.5 m are less economically viable for production forestry. The small area of most aggregate mines in New Zealand also reduces their commercial viability

as stand-alone plantations unless they are managed with other farm woodlots. However their easy access and proximity to centres of populations make intensive forestry such as production of Christmas trees or coppicing of eu-calyptus for production of firewood viable.

In Scandinavia and parts of the United States aggregate site forestation has been implemented with species for firewood coppicing, fencing timber, pulp wood and biomass production (Bailey, 1985; Gilroy, 1985). These enterprises are suited to areas where mined land is of marginal quality, return to agriculture is not feasible or unnecessary (Bailey, 1985) and tree growth is lower than that of plantations on undisturbed land (Coppin and Bradshaw, 1982).

#### 8.7.5 Agriculture and horticulture

Where aggregate mines are located on land used for agricultural production in England, a condition of extraction is often that the land must be returned to its previous use (McRae, 1985). Operations with a fairly short life where soil and overburden is stockpiled and returned can nearly always be returned to agriculture (Coppin and Bradshaw, 1982). Sometimes new, productive land can be created where relatively unproductive land had existed (Gilroy, 1985) by removing stones in the rooting zone and adding fines to improve the physical properties of the original soil.

Agricultural reclamation ranges from cropping and pastoral land use to small farm factories and establishment of hydroponic glasshouse crops (Bennett *et al.*, 1982). In New Zealand aggregate mines have been reclaimed to pasture for thoroughbred stud horse breeding on Recent volcanic soils at Puketutu Island in Auckland (Cohen, 1990), deer farming in Taranaki (Cowley, 1990) and bull beef production on Recent alluvial soils in Manawatu (Simcock and Stewart, 1990). The small size of many New Zealand quarries mean grazing is generally not viable on a stand-alone basis (Happy, 1992), however pits can often be graded and incorporated into adjacent farms (McLellan *et al.*, 1979). The benefits associated with control of noxious weeds and storm-water run off mean reclamation to agricultural production is commonly practised in New Zealand (Happy, 1992).

In California reclaimed land has grown grape vines producing yield and quality equivalent to premining plantings (Gilroy, 1985; Carter, 1990). In the United States, Canada and the United Kingdom aggregate mines have been reclaimed to stone fruit orchards (Lowe, 1985; Mackintosh and Hoffman, 1985). The low water holding capacity associated with low organic matter (including non topsoiled) rooting media can be an advantage when growing stone fruit which thrive on freely drained soils. This type of media also enables the use of controlled deficit irrigation, where fruit quality is enhanced by placing trees under water stress to limit foliage growth.

In Canterbury, New Zealand, salmon has been grown for export in aggregate pits fed by a natural, cool, high flow aquifer since 1985 (Isaac pers. comm. 1990; Happy, 1992). This type of aquaculture requires clean, silt free, well aerated water which is both chemically and biologically pure (Coppin and Bradshaw, 1982). Baumer *et al.* (1990) reported that a quarry in Kenya was used for two aquacultural enterprises. The reject fish from one enterprise were used to feed the stock of a crocodile breeding enterprise at the same site.

#### 8.7.6 Active recreation and education

Reclamation of mines to sites for active recreation is more common close to or within centres of high population. Generally the more capital the type of recreation requires, the nearer a population centre it must be. Active recreation may centre on water bodies created by aggregate extraction below the water table. Water-based activities include canoeing, sailing, fishing, water skiing, rowing, power boat racing and amphibious aircraft meets (Jackman, 1976; Gilroy, 1985). The Holme-Piernegont centre is an example of a very large multiple water sports centre in the United Kingdom (Gilroy, 1985) while a major water-based recreation resource for the Sydney region, including an olympic-size yatching course, is planned for 1900 ha at Penrith (Jenkins, 1987). In New Zealand flooded aggregate mines have been used for model boating, water-skiing and fishing in New Plymouth, Masterton and Christchurch.

Dry mines have been reclaimed to a variety of active recreation facilities. Mine sites are particularly suited to activities which require areas of land which are otherwise unavailable in or near an urban centre, such as playing fields for outdoor sports like soccer, hockey and rugby, athletic tracks and sports stadiums (Swanson, 1990), for example Mount Smart athletics stadium in Auckland. The free draining pit base sometimes present in alluvial river terrace pits enables high utilisation of sports fields and racetracks with the banks of pits providing "natural" amphitheatres for spectator seating (Krohe, 1989; Coppin and Bradshaw, 1982). Large aggregate mines have potential as golf courses (Swanson, 1990) or innovative additions to golf courses. Overburden and waste material can be placed during mine development to create visually interesting landscape forms which would be uneconomic to construct in normal situations and may also act to suppress noise from motoring activities like motocross, trail biking or power boating, which create nuisances for adjacent residences. Drain outflows and areas of water can form attractive water hazards. Large multiple use complexes combine a number of recreational uses, for example, in Canada an aggregate mine site was converted to a complex incorporating a multi use agriculture/recreation building, covered grandstand, show arena, riding ring and tractor pull area (Swanson, 1990). In New Zealand interim reclamation of the Kimihia coal mine aimed to provide tracks for trail bike, four wheel drive and pony clubs in addition to a grass air-strip and industrial subdivision (Applied Geology Associates, unspecified date).



Mining operations have been converted into tourist attractions. Thorpe Park is a small "Disney World" in England, developed by a mining company on the site of an active sand and gravel operation (Gilroy, 1985; Dietrich, 1990). Sometimes the mining activity itself may be of sufficient historical or operational interest to attract visitors. The Liechwed slate quarry in the United Kingdom, for example, demonstrates slate splitting for tourists and a proposed National Stone Centre in England is set amid four quarries connected by walking paths and include a working museum promoting the mining industry (Gilroy 1985).

Restoration sites can provide the mining industry with an opportunity to influence the public and decision makers about the necessity and benefits of mining and its transient nature. In England aggregate extractors have taken advantage of public footpaths crossing the site to erect displays explaining the change in land use, visual impact, procedures to minimise environmental impacts and reclamation plans. Aggregate mines have also been used for more formal education purposes. Students have studied vegetation succession and natural ecosystems in mines allowed to naturally revegetate (Coppin and Bradshaw, 1982) and in Canada a reclaimed mine is used to demonstrate the extraction of maple sugar to tourists (Anon, 1990a).

#### 8.7.7 Amenity and non-intensive recreation

Large sites, greater than 10 hectares, with a variety of habitats are suited to non-intensive recreation associated with park development such as walks, bicycle and horse riding trails, camping, picnicking, cross country driving or motor cycling tracks. The rough terrain of some sites is attractive to special interest groups such as mountain and motor bikers (McLellan *et al.*, 1979). Parks are particularly valuable facilities in areas of cities and towns where open space and parkland is not available. Bennett *et al.* (1982) suggested that depleted quarries could form the basis for a pattern of recreational facilities and open spaces adjacent to urban Christchurch. Park development may be particularly suited to sites on urban fringes which may have less funding available for development due to a lower population. Nature trails, walks, bicycle and fitness trails, skateboarding and roller skating areas are suited to smaller sites.

In Ontario, Canada aggregate mines have been used for commercial enterprises where a lake is stocked with game (fish or waterfowl) and recreational hunters pay to fish or shoot at the site. Other sites have been reclaimed to waterfowl protection areas which breed or support wildfowl for viewing, interpretation, education and research (Michalski *et al.*, 1987).

Sites have been restored to botanic gardens (Carter, 1989), community parks and zoological gardens (Photograph 8.2). Gardens have been a post mining land use in New Zealand (Hunter, 1990), Australia, the United States and Canada where the Butchart Gardens in British Columbia and Elizabeth Park in Vancouver are stunning transformations of quarries (Van Kekerix and Mankoski, 1985). Landscaping can be enhanced by the large earthworks associated with



Photograph 8.2: An inner city garden reclaimed after clay extraction, Perth, Australia.

overburden and waste material placement during mining of the aggregate resource. Sheer sides of pits and quarries allow creation of features such as waterfalls, terracing and grottos and in Salzburg, Austria, form a part of zoo enclosures.

In the United States parks created from aggregate mines have included landscape or environmental art earthworks (Gilroy, 1985). Art is particularly useful in difficult situations where more conventional approaches like conversion to development or agriculture is not feasible (Krauss, 1985) and can enhance or disguise a mined landscape (Kluesing, 1985). Sculptural landscapes in the United States have been valuable cultural amenities and open space for the future, a location for summer concert series and arts festivals, or act as storm water retention basins (Beardsley, 1989).

#### 8.7.8 Nature conservation

Areas reclaimed to nature conservation can be used concurrently for many other activities, although conservation areas should be segregated from recreational activities to minimise disturbance of wildlife (Street and Kaye, 1989). Most dry pits do not offer any unique ecological assets (McLellan *et al.*, 1979) however natural looking hill sides can be created from dry pits by blasting of buttresses and head-walls in a process called landform replication (Bailey and Gunn, 1991). Dry pits smaller than 5 hectares have limited options for creating habitats for larger wildlife species, such as deer (Green and Salter, 1987), however they can be valuable additions to existing adjacent habitat. MacCullum and Geist (1992) reported that such a site produced far



more than native range in a big-horn sheep habitat. Additionally, the quarry walls formed an ideal escape area for the sheep.

Where water is present at aggregate pits diverse habitats can be created (McLellan *et al.*, 1979). Lowland riverine gravel pits are particularly suited for creation of wetland habitat. The large scale earthmoving and reshaping of the land surface involved in gravel extraction make it possible to manipulate land and water to create many different habitats within the same waterbed. Non-aquatic habitats like woodland, scrub and wet grassland needed by bird species for nesting and feeding can be established around site margins and on islands (Street and Kaye, 1989; Williams, 1991).

In the United Kingdom reclaiming gravel pits to wetlands, or creative conservation, is becoming increasingly popular (Street and Kaye, 1989) as public concern increases at the degradation and loss of wetlands from drainage, fill and pollution (Rapson, 1990). Wetland reclamation in New Zealand would help redress the loss of 92% of New Zealand's wetlands since European settlement, with the associated loss of endemic species and genetic diversity (Pike, 1991). Educational and recreational facilities may be associated with wetlands. These include observation blinds, visitor centres, nature trails and board walks and may be valuable public relations exercises for a mining company (Carter, 1990b). The Wellard Wetlands near Perth, Australia, were created after clay extraction are an example of this type of reclamation and include wetland information boards, hides and tracks (see Photograph 3.8 in Section 3.5.3). In Christchurch "the Groyne", are lakes created from an aggregate extraction operation, set aside as a wildlife and recreational area (Greenup, 1988).

Reclaimed aggregate mines are being used to preserve wetland species. Peacock Springs, near Christchurch, is an active aggregate extraction site where reclaimed areas are being used to preserve endangered species such as the indigenous mudfish (Isaac pers. comm., 1990). An unusual use for steep quarry walls in the United States is the creation of nesting sites for peregrine falcons.

At Amwell, England one aggregate mine reclaimed to nature conservation is being used to reintroduce otters to Hertfordshire where they were last recorded in 1970. However, McRae (1986) warns that natural habitats or nature conservation areas may seem dull, boring and visually unattractive except to the expert and satisfy only a small proportion of the public.

#### 8.7.9 Landfill and waste disposal

Many of the characteristics that make an aggregate site economically attractive are also prerequisites for a profitable landfill operation (Carter, 1989). Both industries prefer sites close to a main road with easy heavy vehicle access, a maximum height above the water table and a location near markets, which are usually large urban or industrial centres. Landfills can be a

viable use as a planned transition after mining or a method of filling abandoned pits. Aggregate mines and quarries have been used as landfills and uncontrolled dump sites in the United Kingdom, Canada, United States and New Zealand. In the United Kingdom landfills are commonly linked with aggregate pits in the South East England and can make a valuable contribution in restoring mineral workings (Tomes, 1990), being subsequently used as housing, road and industrial developments (Thompson, 1990). In the United States and United Kingdom methane gas from landfills is used to generate electricity (Bennett *et al.*, 1982). The potential of an aggregate mine for landfill development depends on the geology and hydrology of the area. These influence the risk of aquifer pollution by landfill leachates.

Until recently aggregate mines in New Zealand have generally been filled without lining systems or control of leachates and methane gas (Happy, 1992). Aggregate pits around Christchurch have been used for disposal of domestic, commercial and industrial waste (Bennett *et al.*, 1982) although the Christchurch Metropolitan Refuse Committee rejected the use of pits for sanitary or general refuse, due to the possibility of leachates contributing to aquifer pollution (Bennett *et al.*, 1982). A large proportion of Auckland city's refuse has been disposed of in the Greenmount Quarry and Winstone's Lunn Avenue Quarry been proposed as a future Auckland landfill site (Happy, 1992) which will include a methane collection system for electricity generation and restoration to parkland with amenity plantings (Boffa Jackman Assoc pers. comm., 1990). In some cases quarries used for landfills have been reclaimed to agricultural use (Bennett *et al.*, 1982; Miskell, 1984).

#### 8.7.10 Commercial and industrial property

Aggregate mines near urban centres are frequently located in industrial zones. This zoning may restrict after uses to industrial developments. Buildings require free draining, stable and flat terrain (McLellan *et al.*, 1979; Werth, 1980). The pit created by mining of aggregate can be suited to hiding industry which is visually offensive such as factories, container storage areas and demolition or car wrecking sites (Werth, 1980). However the mining industry is generally trying to avoid the negative image associated with these unsightly uses (Block, 1985). Generally pits under 2 hectares are ruled unacceptable for commercial or industrial use as a cluster of operations is more viable than an individual business (McLellan *et al.*, 1979).

Aggregate mines and quarries have been developed as shopping centres, hotels, industrial parks, high technology centres, commercial developments and combination facilities in the United States (Gilroy, 1985). In California a coastal aggregate mine was converted to high density residential housing and the associated barge loading area became a commuter ferry terminal (Gilroy, 1985; Carter, 1990). Another United States coastal quarry was flooded to form a 600 berth boat and yacht harbour, with the quarry's deep water barge-loading channel forming

the entrance channel (Carter, 1990). In Whangarei 'The Quarry' is a naturally revegetated quarry site occupied by artists and crafts people who sell their products and tutor craft courses (McNeill, 1992).

#### 8.7.11 Residential Subdivision

Housing is the most common reclamation option for aggregate mines in the United States. Housing offers the most certain return for developers in that country (Krohe, 1989) and is potentially the most profitable post-mining land use (Perry and Thatcher, 1987) even though development of housing requires large capital expenditure (Carter, 1990). In New Zealand housing is an uncommon use of mined land. A housing subdivision on an infilled clay mine in Wellington <sup>is</sup> one of the few housing developments in New Zealand (Robertson pers. comm., 1990). In 1976 the creation of an artificial lake surrounded by a major housing subdivision was proposed after excavation of sand for land fill in Christchurch (Jackman, 1976). Residential developments based on aggregate pits may be a method of relieving pressure on rural areas for lifestyle blocks, especially for abandoned pits lacking topsoil (McLellan *et al.*, 1979).

Water is a highly marketable feature which is often used in the United States to promote exclusive subdivisions featuring sections on a lake edge (Michalski *et al.*, 1987) and commonly owned facilities such as sandy beaches and boat ramps (Krohe, 1989; Anon, 1990<sup>a</sup>). In Ontario, Canada, half of the after uses on private aggregate extraction sites are associated with residential development (Michalski *et al.*, 1987). Where water is absent, extraction of aggregate from hill sides has been used to create terraced residential developments with views of surrounding landscapes (Gilroy, 1985). Gardens and parks have also been used as a selling attraction for expensive subdivisions in reclaimed aggregate mines. This concept originated in Germany where garden festivals associated with the development of a high quality landscape are used as a temporary after use to increase the value of reclaimed land. Garden festivals have also been held in Liverpool in 1984, Glasgow in 1988 and Stoke on Trent in 1986, to attract high quality housing and commercial complexes (Holden, 1989).

#### 8.7.12 Water storage and supply

Aggregate mines have been used as water storage, water supply, flood control and water recharge basins (Carter, 1989). In California and Sydney (Australia) sand and gravel pits are used as retarding basins for flood control and aquifer recharge (Werth, 1980; Bennett *et al.*, 1982; Jenkins, 1987; Wassenaar, 1989). During rainy periods water is diverted through the basins. This reduces pressure on downstream stopbanks and allows water to percolate through highly conductive gravels and sands to recharge aquifers. In New Zealand gravel mines in Hawkes Bay and Canterbury may be suited to this post-mining use. Flood control systems can promote

reclamation to agriculture where topsoil is unavailable. This utilises the gradual build-up of sand and silt deposited as flood waters flow through the retarding basin as a plant rooting medium.

## 8.8 Factors determining post-mining land uses

### 8.8.1 Site limitations

An assessment of the ecology, soils and landscape of an aggregate mine should be the precursor of all reclamation work. An assessment provides a framework from which an appropriate reclamation strategy and post mining land use can be developed (Boffa, 1991) by indentifying the limitations and advantages of the site. For example characteristics of the soil and overburden will influence the speed, effectiveness and quality of revegetation (see Section 8.6.1).

**Table 8.6:** Possible after uses associated with mineral workings based on their physical characteristics (from Coppin and Bradshaw, 1982) ++ = major possibilities, + = minor possibilities.

Possible reclamation uses	Excavation type			
	Deep		Shallow	
	Wet	Dry	Wet	Dry
Original use				+
Agriculture				+
Forestry				++
Aquaculture	+		++	
Intensive recreation	+	+	++	++
Water storage and supply	++		+	
Extensive recreation and parks	+	++	++	++
Nature conservation	+	+	+	+
Landfill and waste disposal		+		+

The viability of potential reclamation options is greatly influenced by the method of aggregate extraction, depth of overburden and site topography which together determine the volume of rooting medium available for restoration. The depth of overburden and excavation have been identified as major factors in determining reclamation options and have been used by Coppin and Bradshaw (1982) to categorise aggregate mines into three groups. Group One excavations, characterised by shallow pits with little overburden, have a limited amount of

material available on site to build post-mining landforms and promote deep rooted vegetation. A solution to this problem, used in the United States, has been to extract gravel in shallow V's, which are then filled with silt pumped from wash plants or a diverted river (Carter, 1990a). Group Two mines are shallow pits with a lot of overburden or spoil. These are usually strip mined with the overburden dumped into worked out areas. Group Three mines are characterised by deep pits with little overburden. As backfilling would prevent utilisation of the resource, spoils and overburden are stored off site. The higher the grade of deposit, the less waste material is available to establish post mining landforms.

Post-mining land uses are limited by the quality as well as the quantity of soil and soil-like media (Miller and Mackintosh, 1987). Adverse soil physical properties associated with high compaction is one of the most common causes of revegetation failure. Adverse soil biological and physical properties are associated with rooting media which have low organic matter contents (Chapter 5.2.3). Excessive stoniness, an absence of fine soil forming material and absence of soil micro-organisms and soil fauna will also limit the establishment and growth of many species of plants.

The germination, establishment and persistence of vegetation are affected by the topography of an extraction site. Steep slopes, for example on pit sides, tend to have higher soil temperatures, greater extremes of soil temperature and poor water retention. Steep slopes are also difficult to work with machinery and may be visually incongruous in a landscape while steep slopes in a flooded pits limit colonisation by wetland plants and impede recreational access (Smale, 1985; Street and Kaye, 1989; Green and Salter, 1987).

#### 8.8.2 Landforms and uses of surrounding land

Landforms associated with mining can be masked or emphasised. Masking the sharp angles of an aggregate mine to integrate the sites with adjacent landscapes may involve backfilling, or copying of adjacent features. In Christchurch, for example, trucks returned to an aggregate mine with fill which was used to reconstruct river terraces characteristic of the surrounding area (Greenup, 1988). Sometimes landforms created by aggregate mining and quarrying can be utilised to produce dramatic landscaping. Hagan city hall in Germany, for example, was built on the front edge of a sloping quarry bottom to maximise the view of the city from the building and to utilise the visual impact of the 12 metre high quarry walls in the background (Dietrich, 1990).

A post-mining land use should generally be complementary with nearby land uses (Bradshaw and Chadwick, 1980; Miller and Mackintosh, 1987). This compatibility may be enforced by zoning, for example, often industrial, housing and rural land uses are separately zoned. Thus isolated pits in rural zones are appropriately returned to an agricultural after use, either as

productive land which is assimilated within adjoining farms or as agricultural storage or service buildings (Bennett *et al.*, 1982). Similarly in the United States and England aggregate mines adjacent to parks and reserves have either been reclaimed to park habitats or used as parking areas to reduce the impact of infrastructure associated with park visitors (Anon, 1990<sup>3</sup>). To be compatible with adjoining agricultural or natural areas reclaimed sites should not contain problem plant materials (Mackintosh and Hoffman, 1985) such as noxious weeds, shelter trees that are hosts to plant diseases or insects, or poisonous plants. Assessment of adjoining ecological resources may identify off site features, for example woodlands or wet areas, that can be extended into the mined site to help integrate the mined site and create wildlife corridors which aid colonisation of the site by flora and fauna (Green and Salter, 1987; Samuel, 1991).

An area may have a unique factor which encourages a particular restoration option, for example, the greater London area is very short of areas for landfills. Conversely, area-specific factors may limit reclamation options, for example a surrounding landform which funnels cold air into a site may prevent the establishment of frost-tender crops (Mackintosh and Hoffman, 1985).

### 8.8.3 National legislation

Central (national) government may influence the choice of post-mining land use through mechanisms which range from specification of minimum environmental standards to introduction of tax incentives or subsidies. In New Zealand the Resource Management Act (Section 8.3) specifies<sup>ations</sup> may be interpreted to promote reclamation which leads to sustainable use of land. Many countries have legislation which specifies minimum standards of reclamation. In the United Kingdom, for example, land must be restored to the pre-mining land use wherever possible, particularly where highly productive agricultural land is mined (McRae, 1985). In the United States the Surface Mining Control and Reclamation Act 1977 requires the complete restoration of land use capability after mining. Where prime agricultural land is disturbed this means crop yields on reclaimed land must meet or exceed the average yields of undisturbed soil under equivalent management practices for three years before reclamation bonds can be released (Nawrot *et al.*, 1987; Daniels *et al.*, 1991; Sweigard and Saperstein, 1991). Additionally, the Act requires a minimum 1.2 m depth of soil or replacement materials and one of the crops used for demonstration yields must be the crop in the area with the deepest rooting requirement (Sweigard and Saperstein, 1991).

Reclamation requirements may prohibit or promote certain post-mining land uses. For example, United States legislation requiring extensive grading and rapid establishment of vegetative cover has resulted in some areas in compacted soils and competition of ground-cover species with tree seedlings. The outcome of this legislation has been a minimal effort to establish forests on mined land (Davidson 1984a; 1984b). Where a detailed "recipe" for reclamation is put into legislation the range of post-mining uses is generally reduced to those which are prescribed by



the recipe (Davidson, 1985). Australian legislation requires a post-mining land use which is commensurate with the land use before mining. This has resulted in a predominance of reclamation to low density, low value uses such as pastoral agriculture and native revegetation (Perry and Thatcher, 1987).

Post-mining land use may be influenced by government funding or tax breaks for reclamation research and expenditure. In the United Kingdom the Derelict Land Grant is used by central government to reclaim "land so damaged by industrial or other development that it is incapable of beneficial use without treatment" and varies between 100% to 50%, depending on the net loss incurred in undertaking restoration work (Michael and Bradshaw, 1989). Government funding may promote certain reclamation types by preferentially funding specified types of reclamation. In the United Kingdom 'hard' reclamation to housing or intensive recreation have been favoured by funding bodies while in Ontario, Canada government incentives promote reclamation to fish and wildlife reserves (Michalski *et al.*, 1987). In Australia the government encourages restoration research by providing tax incentives for private companies contracting out or doing their own research. This may promote natural habitat reclamation which in New Zealand and Australia has required a high research input as generally little is known about indigenous ecosystems and their constituents.

#### 8.8.4 Regional and local government

In New Zealand regional authorities can influence post-mining land uses through their roles as landowner, investor with large capital assets, consultant, rule maker and enforcer of environmental conditions. Regional plans may specify desirable post-mining land uses. Effective monitoring and high penalties for non-compliance may influence a restoration choice by increasing the popularity of known technologies with low environmental impacts, such as agricultural reclamation. Conversely risky reclamation options such as landfills or reclamation to native habitats will be less popular. In the Waimea district council experiences of inadequate agricultural reclamation after gravel extraction caused stricter restoration provisions on subsequent ventures. In such circumstances the council may be less amenable to alternative post-mining land use proposals.

The size of bonds imposed by regional and local councils may deter some post-mining land uses. For example near Palmerston North a large bond was required where aggregate excavations planned to leave two permanent lakes beside a river. The bond covered potential damage if the river flooded into the area and undermined a road or stop banks were not constructed to an adequate standard. If the area had been backfilled with inert material the bond would probably have been much smaller. Similarly, sanitary landfills would be expected to attract higher bonds than agricultural restoration, deterring investment in that post-mining land use.

Regional government can influence post-mining land use in their role as consultants (Lawson, 1985). The philosophy and aims of regional government, reflected in the rules and conditions they set, will influence post mining land use options, with regions differing in their willingness to trade off costs to the environment for positive economic benefits of extraction. For example, in areas where employment and economic growth has a priority over environmental conditions, land uses requiring minimal reclamation would probably be more prevalent. Conditions and rules also reflect the knowledge and experience of Council employees. For example quality and effectiveness of the condition that "a restoration plan must be submitted to the district engineer's satisfaction" is largely determined by the knowledge and interest of the engineer. Local and national policy which promotes the preservation of highly productive agricultural land in New Zealand and Canada has meant reclamation to agriculture is popular (Mackintosh and Mozuraitis, 1982). In the United Kingdom an increased emphasis on visual, environmental and ecological factors is resulting in areas reclaimed to agriculture with smaller fields, hedgerows and copses, walls of local stone, ponds and hay meadows with traditional seed mixes rather than large fields with single species crops which are more productive (Proctor, 1990).

Development agreements and zoning have also been used to direct post-mining land uses. In the United States district councils have initiated development agreements which commit the aggregate extractor to develop the mine site in a specified way and commit the local government to appropriately zone, buy or maintain the property (Merrill, 1985). Development agreements and zoning enable councils to satisfy the specific requirements of an area, for example recreational space, flood control works or rubbish disposal. For example in dense residential areas of the United States, which have few recreation facilities or open space, planning authorities have been able to promote parks as a favoured reclamation option (Krohe, 1989).

#### 8.8.5 Local community

Community preferences may dictate the objectives of restoration (Merrill, 1985; Consedine, 1990; Skelton, 1990). Increased community participation required under the RMAct should mean that the preferences of a community near an aggregate mine should increasingly influence the post-mining land use. In Germany cultural preferences place a high value on recreation and enjoyment of nature; consequently parks and natural habitats are common uses for inactive sand and gravel pits (Carter, 1990). In some cases aggregate extraction can directly meet the needs of the surrounding community. For example, in America an aggregate company mined a hill, leaving a gentle topography suitable expansion of a Teachers College campus which was previously limited by steep topography (Carter, 1985). In other cases reclamation can compensate the affected community for disturbance associated with mining by providing parks, public amenities or conservation areas.

Community participation in a reclamation programme is enhanced where special interest groups are consulted and help form <sup>ulate</sup> reclamation and management plans for a site for example conservation groups like the Royal Forest and Bird Society, botanical groups and Ducks Unlimited. In Canada an anglers club guided development of a stream and lake for spawning purposes at an aggregate mine (Swanson, 1990) while in England an aggregate pit was reclaimed for nature conservation in partnership with the Otter Trust, a group of local environmentalists.

#### 8.8.6 Mine owners and managers

The attitude of mine owners and managers towards the environment and reclamation is a main factor determining the adopted post-mining land use and quality of reclamation. Negative attitudes may occur where the operators have a low level of interest or pride in reclamation, seeing it as a burden or unnecessary cost imposed on them by legislation with no return for the time and effort involved (Pulman, 1990). A focus on short term profitability means reclamation by these operators is often minimal or sites are abandoned (Merrill, 1985). Poor reclamation of West Coast coal and alluvial gold sites, for example, has been partly attributed to a negative attitude towards reclamation displayed by miners (Mackenzie and Cave, 1991). Poor reclamation limits the potential post-mining land uses and value of many workings and may result in additional costs for remedial works. Reclamation to pasture may occur where extractors do not recognise the monetary value of alternative post-mining land uses such as subdivisions or landfills (Gilroy, 1985).

Successful reclamation generally occurs where the mining operator appreciates the tangible and intangible benefits of high quality restoration. Intangible benefits include creating or maintaining a good reputation leading to better working relationships with local community and critics from environmental interests (Gilroy, 1985). In the United Kingdom only companies that have a proven record of good reputation are granted permits for future mining operations (McRae, 1985). Tangible benefits may include second profits from selling the land, interim uses (e.g. landfills) or business partnerships with developers.

Mine owners and managers may be motivated to reclaim land to particular land uses through personal interest and enjoyment, although these factors are usually only significant for smaller individual operators (Michalski *et al.*, 1987). Sites in New Zealand and Canada have been reclaimed because the land owner enjoys the creative aspect of trying to raise rare fish or game birds (Michalski *et al.*, 1987) or creating wildlife habitats. For example, the gardening and landscaping interests of an operator in Dunedin has led to a quarry being restored to a garden containing more than 1000 trees and shrubs including 250 rhododendrons and hanging, climbing and ground cover plants (Hunter, 1990).

## 8.9 Conclusion

Legislation controlling the environmental impacts of the aggregate mining industry in New Zealand was revised from 1987 to 1991 and resulted in enactment of the Resource Management Act 1991. The RMAct has integrated and standardised legislation controlling the resource use and developed planning principles based on ensuring the sustainable use of natural resources. Under the RMAct Regional Councils have responsibility for controlling effects of aggregate mining that may impact water quality and quantity, soil conservation values and natural hazards. Regional Councils, therefore, have primary responsibility for river-based operations, which includes land-based operations within the 100 year flood plain of a river and on intermediate terraces where mining could alter the flood flow of a river. Regional Councils should act, primarily through granting resource consents and developing regional rules, to ensure reclamation which minimises siltation of water-ways and erosion. District Councils are responsible for the effects of aggregate extraction on land. These include which include visual and noise impacts and land quality. District Councils control these effects in conditions attached to land use consents and district rules. As most aggregate is privately owned it is not controlled by a minerals programme so direct control of which aggregate resources are mined is not possible.

The full effects of the RMAct will be felt over the next three to five years as regional policy statements are written, district plans are revised, national policy statements and Crown minerals programmes are released and legal precedents and case law are established. A greater emphasis on defining and mitigating social and environmental impacts, stricter conditions and increased penalties should result in a higher standard of reclamation and reduction of adverse environmental impacts at aggregate extraction sites. Under the RMAct land based aggregate mining should be freer to exploit resources if developers can prove that land productivity is undiminished or implement alternative reclamation strategies which enrich the environment.

The economic feasibility of a specified reclamation option is largely dependant on the post-mining land use and the value placed on tangible and intangible benefits associated with reclamation. The main economic reasons for reclamation are intangible, such as improved public relations which may be indirectly measured by reduced planning costs for future mining proposals. Tangible benefits of reclamation may include reduced reclamation bonds and reduced monitoring costs by Regional and District Councils. Tangible economic benefits depend largely on the post-mining land use, residual land value and costs of reclamation.

The requirements for reclamation by society have varied over time and with the expectations of the community concerned. Over time society has demanded higher standards of reclamation and reduction of the environmental costs associated with resource exploitation. This has been reflected in tougher legislation controlling management of resources. Successive legislation has

required increased analysis and amelioration of potential and actual impacts of mining and increased penalties for non compliance with conditions associated with development. The social demand for reclamation is based on the premise that the value and capability of land, whether productive, wildlife or scenic, should be sustained. Reclamation fulfills social desires for intergenerational equity, maintenance of the quality of the environment and application of user-pays principles.

Many New Zealanders still see the function of reclamation as greening, disguising or screening abandoned sites or sites at the end of their productive lives. Mine abandonment and natural revegetation can, however, lead to the inadvertent creation of important biological refugia and geological sites or areas for informal recreation. Minimal reclamation has been used to speed up natural revegetation process, or reduce public danger of site and off-site impacts of run-off and sedimentation. Minimal reclamation may be cheap and effective for abandoned mines or mines nearing the end of their extraction life with few funds or isolated mines in remote areas. Reclamation to production forests is also suited to minimally reclaimed or abandoned sites containing media with low water holding and nutrient capacities and few restrictions to root growth. Reclamation to horticultural or agricultural or forestry use is commonly a condition of extraction in rural zones with fertile soils and usually required retention of soils on a mine site. In cities, where open space is a valuable resource, aggregate mine sites may be utilised for playing fields or parkland. Where mining exposes the water table the lakes produced can be utilised as a feature for developing residential or commercial developments. Sites on the edge of urban areas may be suited to reclamation to conservation parks. Such areas are particularly valuable where wetlands can be created and features allow separation of people and birds. Thus there is a diverse range of possible after-uses of mined-out aggregate extraction sites. In the future people may fully appreciate the potential of mining to transform landscapes to create a wide variety of beneficial uses for communities and regions.

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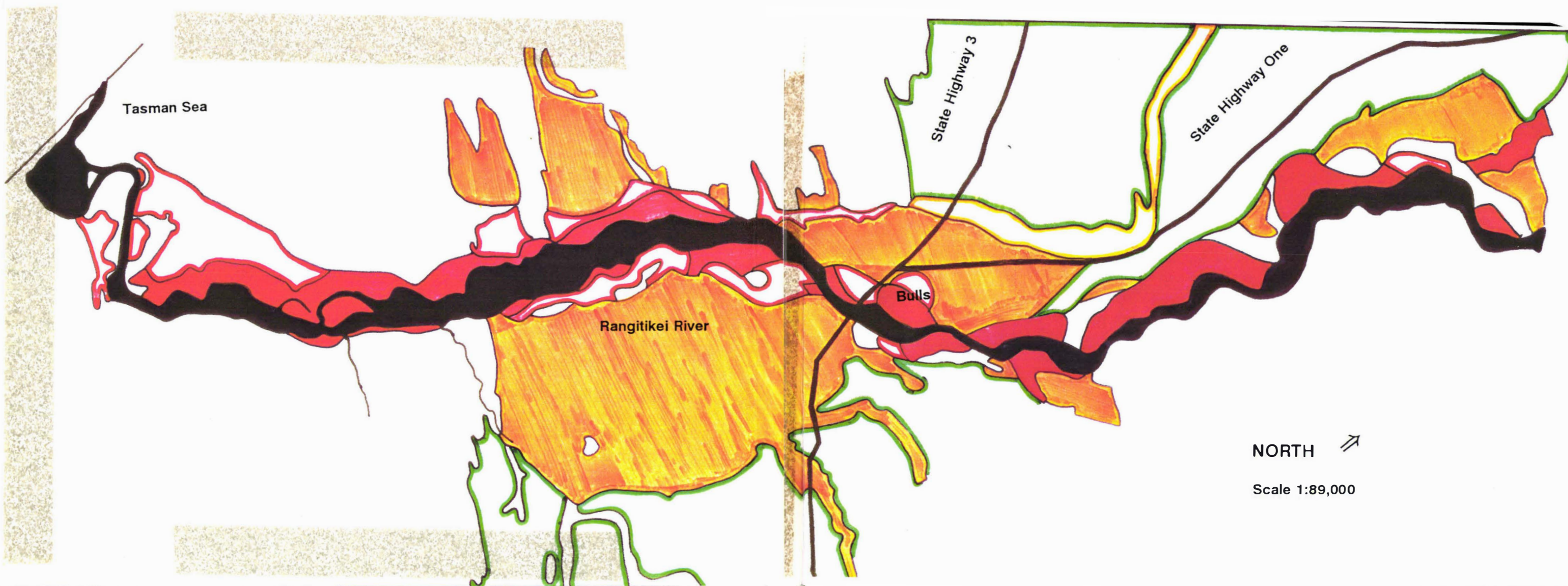
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Appendix 2

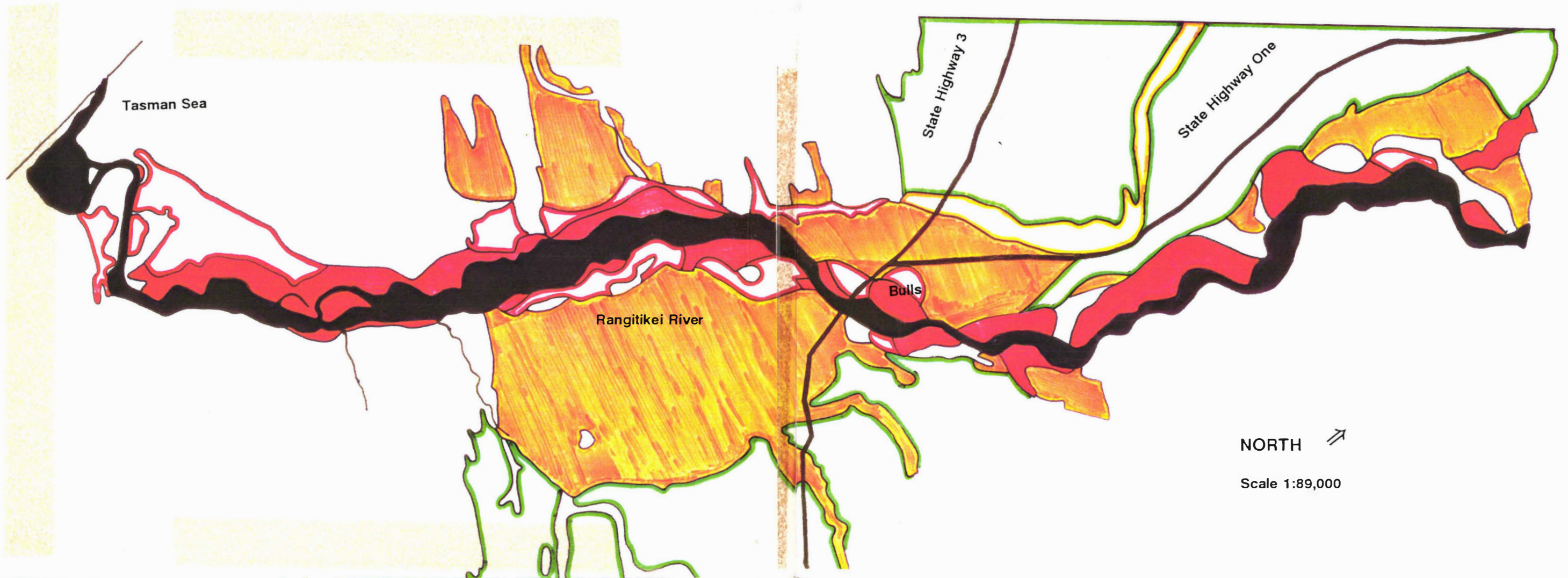


Class	Colour
1	red
2	yellow
3	clear (low terrace)
4&5	green outline

Appendix 2.1 Suitability classes of potential aggregate deposits in the Lower Rangitikei River, derived from overlying soil series and using the Soil Map of Rangitikei County, North Island, New Zealand. Part New Zealand Soil Survey Report 38 by Campbell and Aitken, 1979.



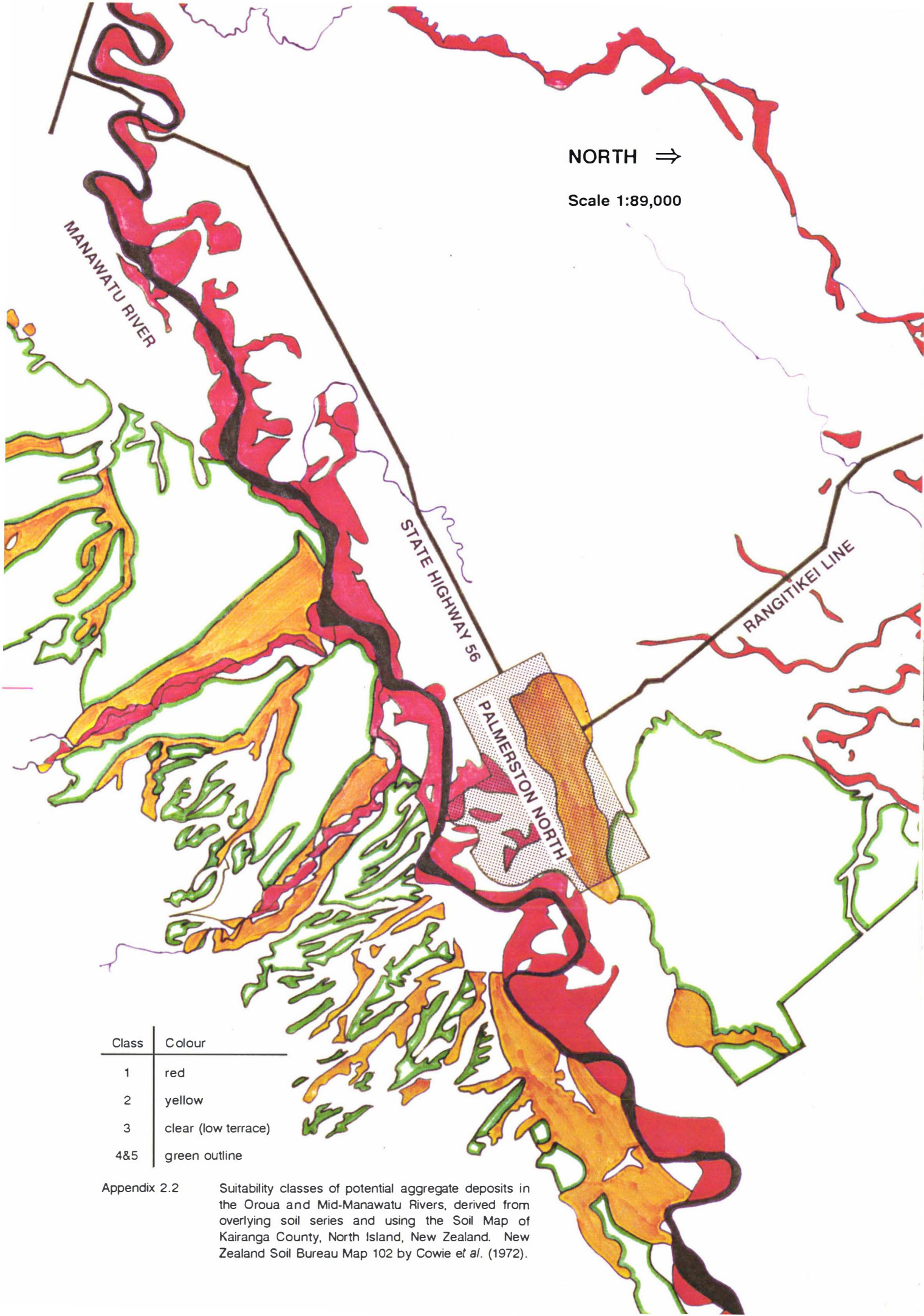
Appendix 2



Class	Colour
1	red
2	yellow
3	clear (low terrace)
4&5	green outline

Appendix 2.1 Suitability classes of potential aggregate deposits in the Lower Rangitikei River, derived from overlying soil series and using the Soil Map of Rangitikei County, North Island, New Zealand. Part New Zealand Soil Survey Report 38 by Campbell and Aitken, 1979.





NORTH ⇒

Scale 1:89,000

MANAWATU RIVER

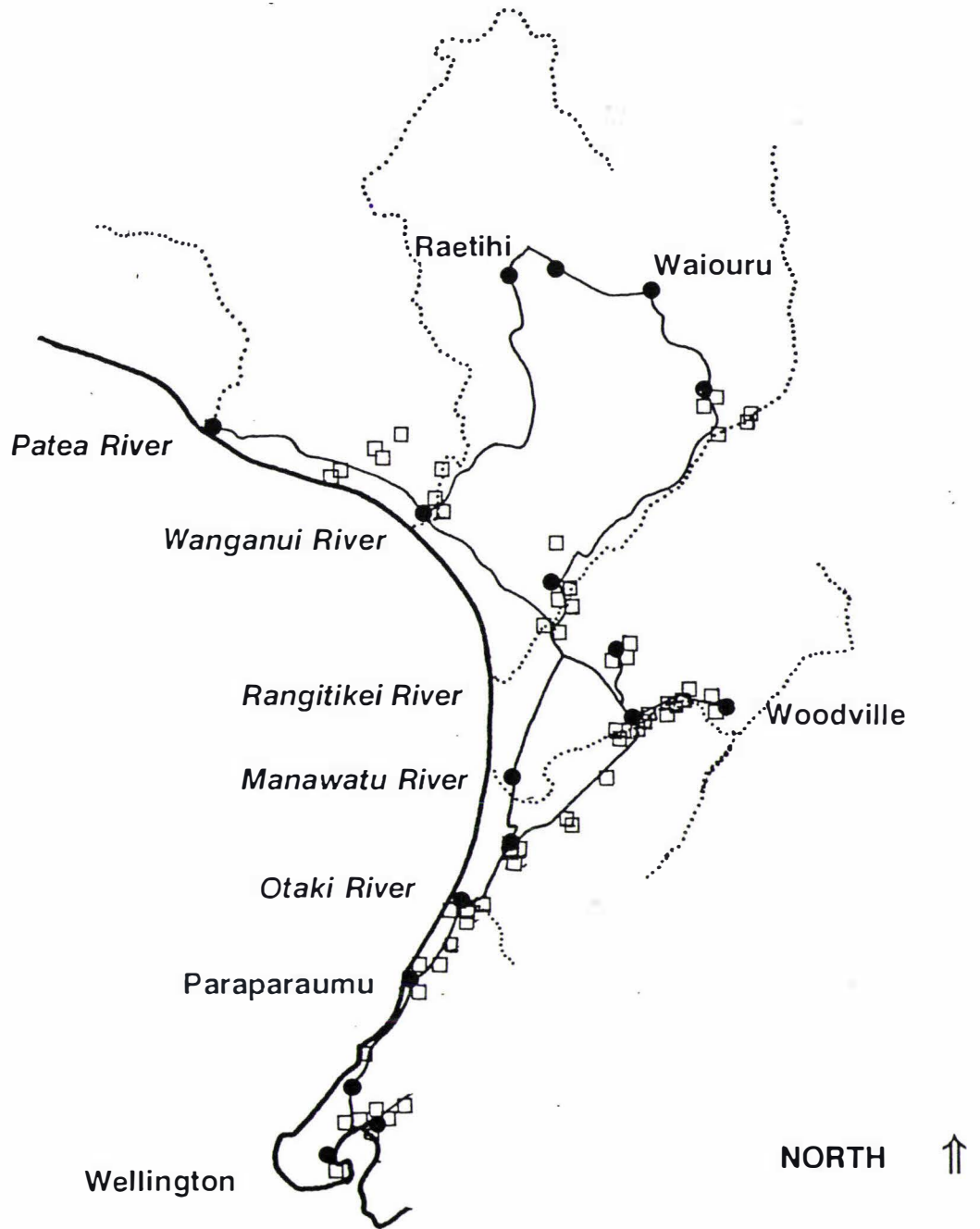
STATE HIGHWAY 56

RANGITIKEI LINE

PALMERSTON NORTH

Class	Colour
1	red
2	yellow
3	clear (low terrace)
4&5	green outline

Appendix 2.2 Suitability classes of potential aggregate deposits in the Oroua and Mid-Manawatu Rivers, derived from overlying soil series and using the Soil Map of Kairanga County, North Island, New Zealand. New Zealand Soil Bureau Map 102 by Cowie *et al.* (1972).



Appendix 2.3 Location of aggregate extraction companies, towns, major rivers, and major roads in the south-west of the North Island.

## Appendix 4.1. Type profiles

### Type profile of Ohakea silt loam (Cowie 1974)

<b>Ap</b>	0-23 cm dark brown to greyish brown silt loam, few reddish brown mottles, friable, moderate nut structure.
<b>Bgc</b>	23-41 cm greyish brown heavy silt loam, few to many yellowish brown mottles; abundant black concretions; friable; moderate nut structure.
<b>Bg</b>	41-71 cm light grey to olive grey clay loam; abundant yellowish brown mottles; firm; weak blocky structure.
<b>Bg2</b>	71-91 cm mottled light grey and yellowish brown heavy silt loam; few light grey vertical veins, very firm, massive.(may have many distinct strong brown mottles).
<b>2C</b>	on iron stained gravels and stones, cemented in upper parts but not below, average size of gravels 8-10 cm but a few up to 25 cm, gravels mixed with coarse sand and fine gravels.

### Profile of Ohakea silt loam, Ohakea trial site

<b>Ap</b>	0-18 cm dark yellowish brown 10YR 4/4 to dark brown 10YR 4/3 silt loam; few (5%) medium distinct brownish yellow 10YR 6/8 mottles; distinct boundary; many roots.
<b>Bgc1</b>	18-46 cm light yellowish brown 10YR 6/4 dense silt loam profuse 30%+ medium coarse distinct light grey 10YR 7/2, and brownish yellow 10YR 6/8 mottles with blurred edges; few to many black 10YR 2/1 medium sized iron nodules; few roots
<b>Bg2</b>	46-70 cm light grey 10YR 6/1 silt loam with many indistinct brownish yellow 10YR 6/8 and yellow 10YR 7/8 mottles, few gravels
<b>2C</b>	70 cm+ cemented iron stained gravels and stones in a stained sand matrix.

#### Key

c	accumulation in concretionary form
g	mottling or gleying reflecting variations in oxidation or reduction states of iron
p	disturbed by ploughing
w	weathered in situ as reflected by clay content, colour or structure

(definitions after FAO-UNESCO, 1984)

**Type profile of Ashhurst silt loam, stony phase profile (Cowie 1978)**

<b>Ah</b>	0-25 cm. brown (10YR 4/3) fine sandy loam; friable; moderately to strongly developed fine nut structure; few gravel and stones increasing with depth; many roots; distinct and wavy boundary.
<b>Bw1</b>	25-38 cm. dark yellowish brown (near 10YR 4/4) stony and gravelly silt loam; firm; weakly developed medium blocky breaking to nut structure; weakly developed brown (10YR 4/3) coatings on aggregate faces; few roots; distinct boundaries.
<b>Bw2</b>	38-58 cm. yellowish-brown (near 19YR 5/6) stony and gravelly heavy silt loam; many thin distinct brown (10YR 4/3) coatings; few distinct fine strong brown (7.5YR 5/8) mottles; firm; massive; few roots; distinct boundary
<b>C</b>	58 cm+ . gravel

**KEY**

u	undifferentiated
h	humic: addition of organic matter in mineral horizons
C	a mineral layer of unconsolidated, unaltered parent material

**Type soil profile of Rangitikei fine sandy loam (Cowie 1975)**

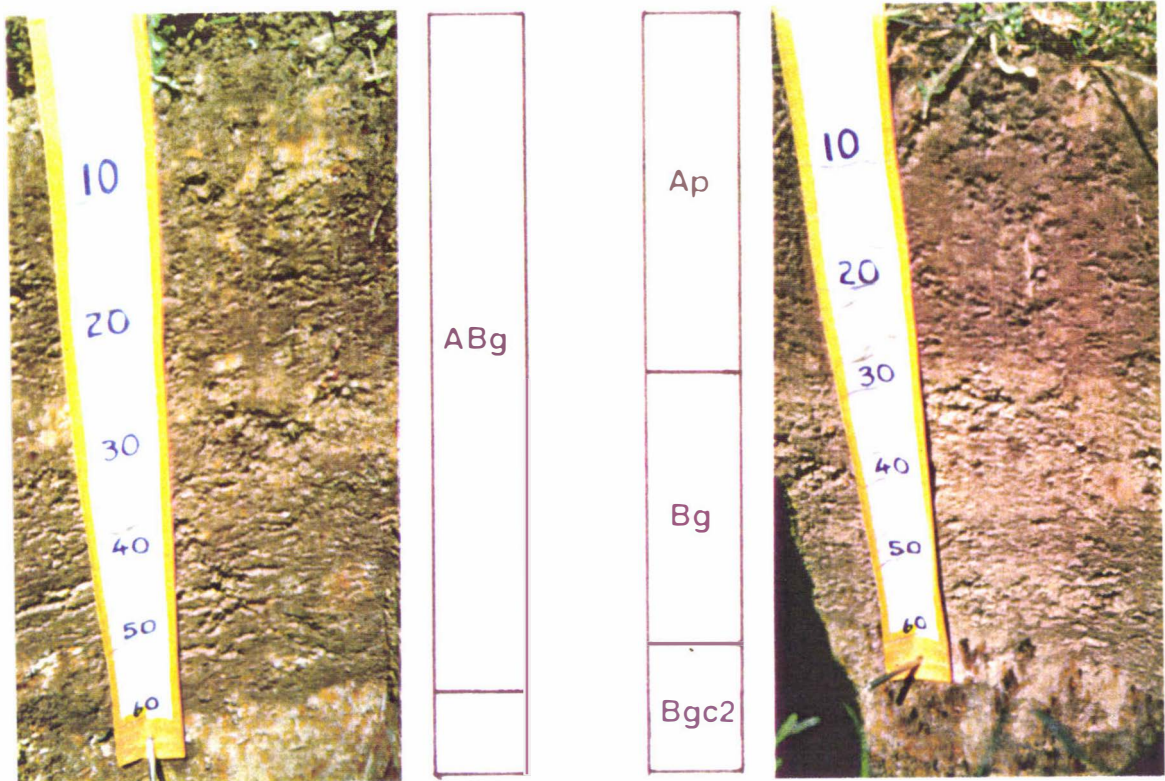
<b>A1</b>	0-6 cm dark greyish brown loamy sand; very friable; weak nut structure
<b>BC</b>	6-24 cm light olive brown sand loam or sand; very friable, weak blocky structure. (Flood banded silts and sands)
<b>D</b>	on grey gravels and stones with sand

**Profile of Rangitikei fine sandy loam, Spall's trial site.**

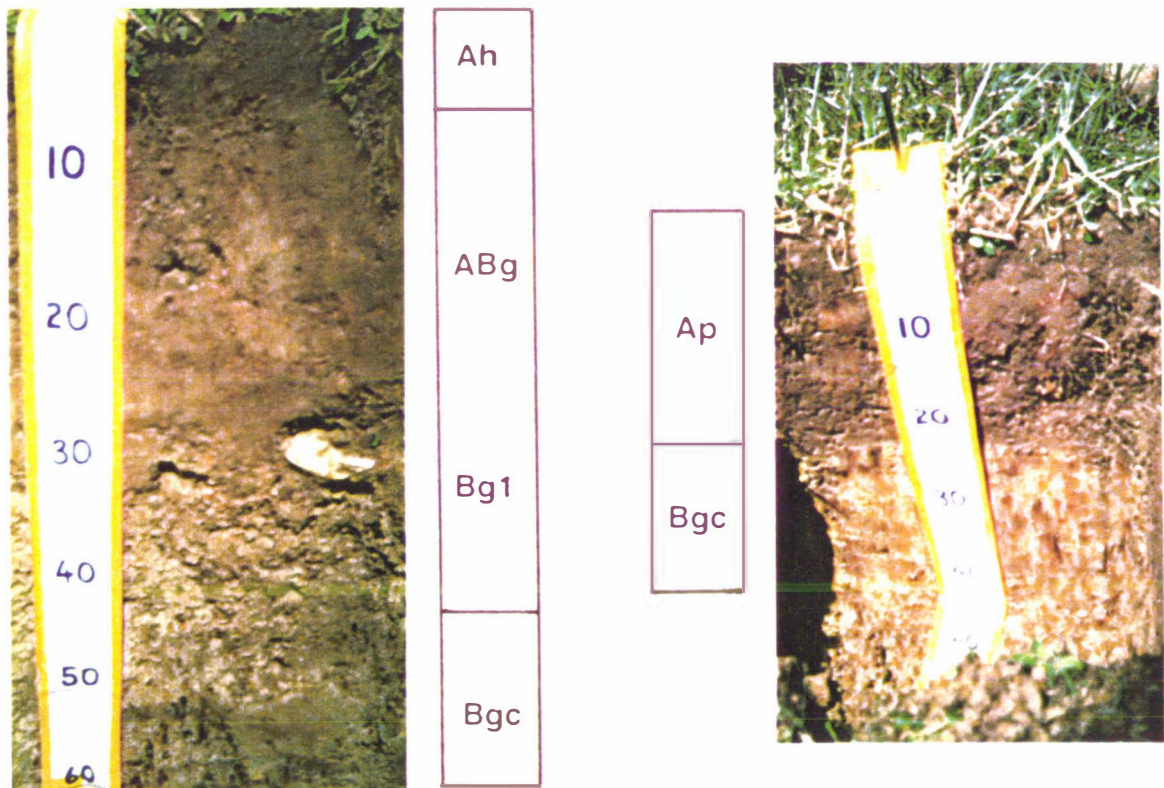
<b>Ah</b>	0-6 cm dark brown 10YR 3/3 fine sandy loam; weak nut structure; many roots and abundant thatch material; faint boundary.
<b>Cu</b>	6-20 cm olive brown 2.5YR 4/4 sand; abundant roots.
<b>2Cu</b>	20-37 cm light olive brown 2.5YR 5/4 sand; many roots.
<b>3Ahb</b>	37-40 cm olive brown 2.5YR 4/4; fine sand; denser horizon; few roots.
<b>3Cu</b>	40-57 cm light olive brown 2.5YR 5/4; coarse sand; few roots
<b>4Cu</b>	57-86 cm olive brown 2.5YR 4/4; fine sand; denser horizon; few roots to base of profile
<b>5Cu</b>	86 cm+ grey gravels and stones with sandy matrix



**Appendix 4.2: Ohakea trial. Profiles of soil replacement treatments.**



a. Profile of "ABmix" (LHS) and "AonB" (RHS) soil replacement treatments. Note the irregular distribution of gleyed material throughout the "ABmix" profile (LHS) and the clear change of colour in the "AonB" profile between the dark topsoil and light subsoil (RHS).



b. Profile of "undisturbed" (LHS) and "Aonly" (RHS) soil replacement treatments. Note the gradual change of soil colour from dark brown to light grey in the undisturbed, unploughed treatment (LHS) and the dark brown iron-manganese concretions at the base of both soil profiles.



### Appendix 4.3 Chemical analyses

#### Chemical analyses of undisturbed soils

Soil type	Chemical analyses					
	Ph	Olsen P	K	Ca	Mg	Na
Ohakea silt loam	5.8	16	0.52	8.0	1.3	0.25
Ashhurst silt loam	6.3	18	1.02	10.8	1.35	.35
Rangitikei loamy sand	6.2	19	1.2	4.1	0.96	0.14

#### Ratings for chemical properties of New Zealand soils (from Rijske, 1977)

Rating	Cation-Exchange Properties				
	CEC (me.%)	BS (%)	Ca (me.%)	Mg (me.%)	K (me.%)
Very high	>40	80-100	>20	>6	>1.2
High	25-40	60-80	10-20	3-6	0.8-1.2
Medium	15-25	40-60	5-10	1-3	0.5-0.8
Low	6-12	20-40	2-5	0.3-1	0.3-0.5
Very low	<6	<20	<2	<0.3	<0.3

## Ratings for chemical properties of New Zealand soils (cont.)

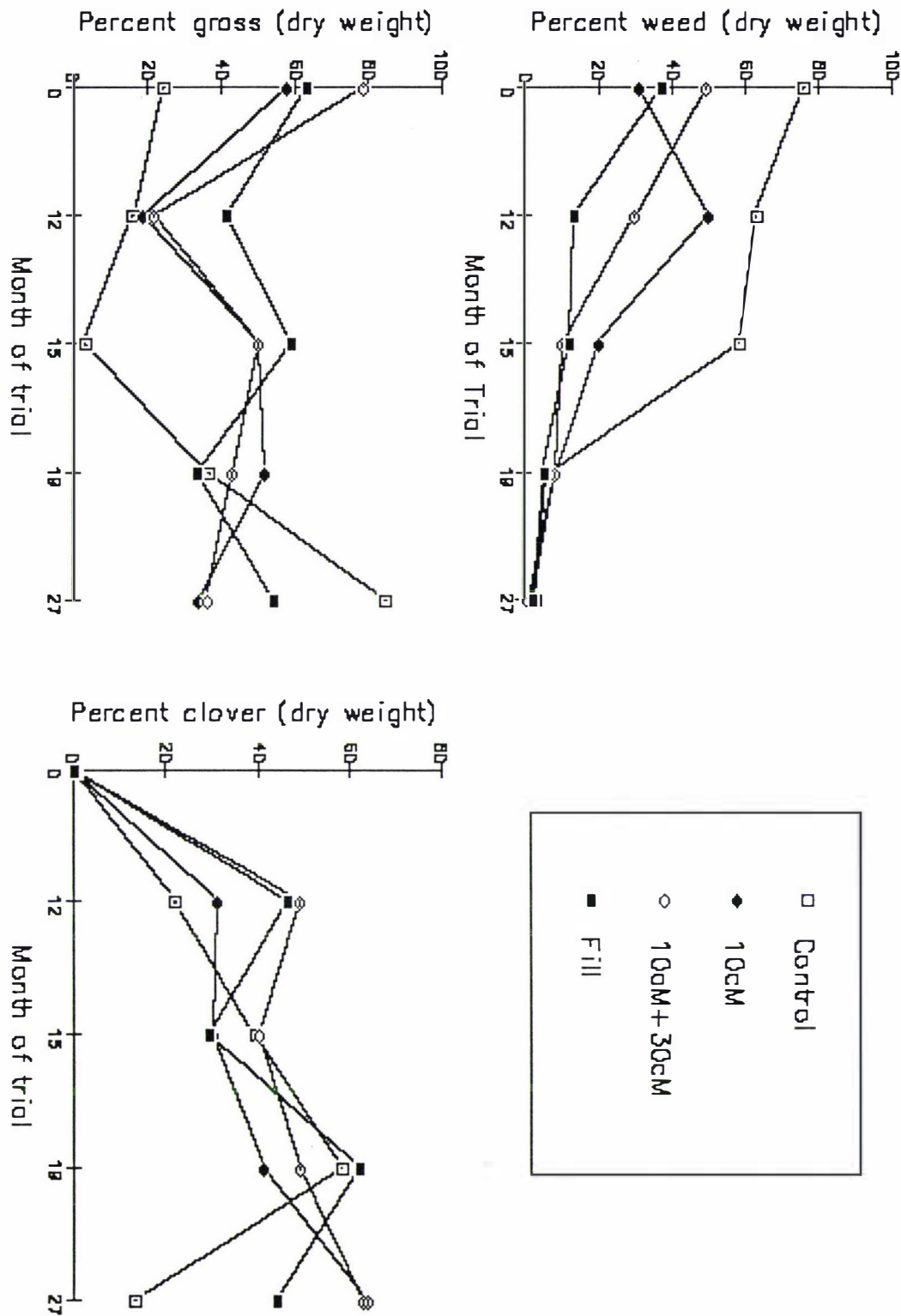
Rating	Chemical property			
	Organic Carbon (%)	P retention (%)	Phosphorus	
			0.5M H <sub>2</sub> SO <sub>4</sub> (mg%)	Troug (mg%)
Very high	>20	90-100	>40	>5
High	10-20	60-90	20-40	3-5
Medium	4-10	30-60	10-20	2-3
Low	2-4	10-30	5-10	1-2
Very low	<2	0-10	<5	<1

Ph (1:2.5 soil:water)	Rating
>9.0	extremely alkaline
8.4-9.0	strongly alkaline
7.6-8.3	moderately alkaline
7.1-7.5	slightly alkaline
6.6-7.0	near neutral
6.0-6.5	slightly acid
5.3-5.9	moderately acid
4.5-5.2	strongly acid
<4.5	extremely acid



Appendix 5.2.1:

Rangitikei trial. Herbage composition (% dry mass of weed, grass and clover) of topsoiled treatments and nil-soil (fill) treatment over five harvests. Note "grass" in harvest one is the percentage of barley+oats crop.



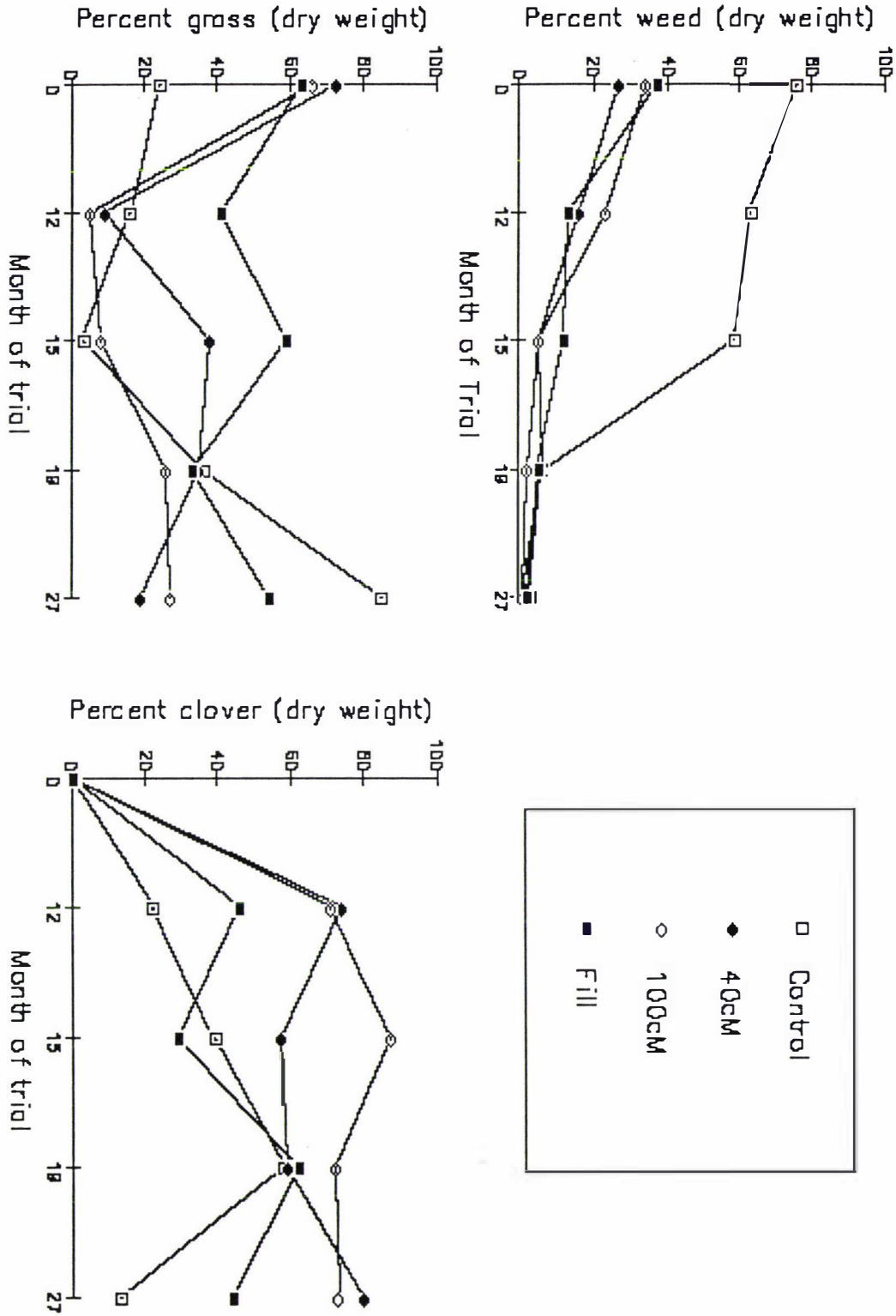
Appendix 5.2.2: Rangitikei trial. Herbage composition (% dry mass of clover, grass and weed) of pasture from topsoiled treatments of the Rangitikei trial. na = no clover dissected in harvest one, the barley+oats harvest.

Soil Treatment	Harvest				
	1	2	3	4	8
<b>Percent clover</b> Control	na	22	39	58 a	12 c
10A	na	31	30	41 b	64 a
10A+30C	na	49	40	49 ab	63 a
fill	na	46	29	62 a	44 b
<b>Percent grass</b> control	24 c	16 b	3 b	36 b	85 a
10A	58 b	19 b	50 a	52 a	34 c
10A+30C	79 a	22 b	50 a	43 ab	36 c
fill	63 b	41 a	59 a	33 b	54 b
<b>Percent weeds</b> control	22 a	63 a	58 a	6 a	3 a
10A	31 a	50 ab	20 b	8 a	2 ab
10A+30C	49 a	30 bc	10 b	8 a	1 b
fill	46 a	13 c	12 b	6 a	2 ab

Appendix 5.2.3: Rangitikei trial. Root length (m) and oven-dry root mass (g) per 1.2 l soil sample of topsoiled treatments. N = 2 for each treatment, each sample comprised two cores bulked together.

Soil Treatment	Root length (m) or mass (g) at specified soil depth (m)			
	0 to 0.05	0.10 to 0.15	0.20 to 0.25	0.30 to 0.35
Control	164	31 ± 12	13 ± 5	48
10A+30C	297 ± 163	81 ± 43	42 ± 20	30 ± 22
10A	188 ± 52	110 ± 62	60 ± 5	13 ± 13
Fill	412 ± 94	117 ± 71	52 ± 67	32 ± 42
<b>Root mass (g)</b>				
Control	1.06 ± .06	.10 ± .03	.07 ± .02	.24
10A+30C	2.05 ± 1.52	.30 ± .14	.14 ± .06	.09 ± .08
10A	1.27 ± .29	.62 ± .21	.30 ± .09	.08 ± .08
Fill	2.47 ± .50	.52 ± .34	.20 ± .23	.07 ± .08

Appendix 5.2.4: Rangitikei trial. Herbage composition (% dry mass of weed, grass and clover) of nil-topsoil treatments over five harvests. Note "grass" in harvest one is the percentage of barley+oats crop.



Appendix 5.2.5: Rangitikei trial. Herbage dissection (% dry mass of clover, grass and weed) of pasture from nil-topsoil treatments. na = no clover dissected in harvest one, the barley+oats harvest.

Soil Treatment	Harvest				
	1	2	3	4	8
<b>Percent clover Control</b>	na	22 c	39 c	58 b	13 c
100C	na	71 a	87 a	72 a	73 a
40C	na	74 a	57 b	59 b	80 a
fill	na	46 b	29 c	62 ab	44 b
<b>Percent grass control</b>	24 b	16 b	3 c	36 a	85 a
100C	66 a	5 c	8 c	26 a	27 c
40C	73 a	9 bc	38 b	35 a	19 d
fill	63 a	41 a	59 a	33 a	54 b
<b>Percent weeds control</b>	76 a	63 a	58 a	6 a	3 a
100C	34 b	23 b	5 b	2 a	1 b
40C	27 b	16 b	5 b	6 a	1 ab
fill	37 b	13 b	12 b	5 a	2 ab

Appendix 5.2.6: Rangitikei trial. Root length (m) and oven-dry root mass (g) per 1.2 l soil sample of nil-topsoil treatments. N = 2 for each treatment, each sample comprised two cores bulked together.

Soil Treatment	Root length (m) or mass (g) at specified soil depth (m)			
	0 to 0.05	0.10 to 0.15	0.20 to 0.25	0.30 to 0.35
Control	164	31 ± 12	13 ± 5	48
100C	125 ± 33	21 ± 15	18 ± 6	21 ± 18
40C	196 ± 85	56 ± 14	35 ± 20	32 ± 17
Fill	412 ±	117 ± 71	52 ± 67	32 ± 42
<b>Root mass (g)</b>				
Control	1.06 ± .06	.10 ± .03	.07 ± .02	.24
100C	1.07 ± .31	.09 ± .05	.10 ± .05	.07 ± .04
40C	1.46 ± .76	.20 ± .05	.21 ± .11	.11 ± .04
Fill	2.47 ± .50	.52 ± .34	.20 ± .23	.07 ± .08



**Appendix 5.3: Rangitikei trial: effect of mixing horizons and replacing topsoil**

Appendix 5.3.1: Rangitikei trial. Particle density of rooting media. Significance = 0.22. Treatments with different "Duncan's test" letters are significantly different at a significance level of 0.10.

Medium	N	Particle Density Mg m <sup>3</sup>	Duncan's (0.10)
		Mean and std. dev.	
A horizon	4	2.64 ± 0.04	a
C horizon	4	2.68 ± 0.02	a
Fill	4	2.63 ± 0.02	a

Appendix 5.3.2: Rangitikei trial. Soil moisture content at 1500 kPa suction (permanent wilting point) of rooting media. Specific soil replacement treatments measured are in brackets under "Medium" (NB: Sig = 0.0001).

Medium	N	Gravimetric water %	Duncan's(0.10)
		Mean and std. dev.	
A horizon (10A)	10	6.4 ± 1.3	a
C horizon (40C)	10	5.7 ± 0.6	b
Fill	10	8.0 ± 1.5	c

Appendix 5.3.3: Rangitikei trial. Gravimetric moisture content at 5 k Pa suction of soil replacement treatments. N = number of cores taken.

Treatment	Soil depth (m)			
	0	0.1	0.2	0.30
Undisturbed	35.0 abc	29.0 ab	26.7 a	26.3 b
Control	40.5 a	26.0 b	26.0 a	26.0 b
10A+30C	38.7 a	30.0 ab	29.3 a	31.5 a
40C	36.0 ab	30.5 ab	25.0 a	31.5 ab
100C	32.0 bc	32.3 a	25.8 a	27.3 b
N	20	17	14	13
Probability	0.11	0.44	0.34	0.16

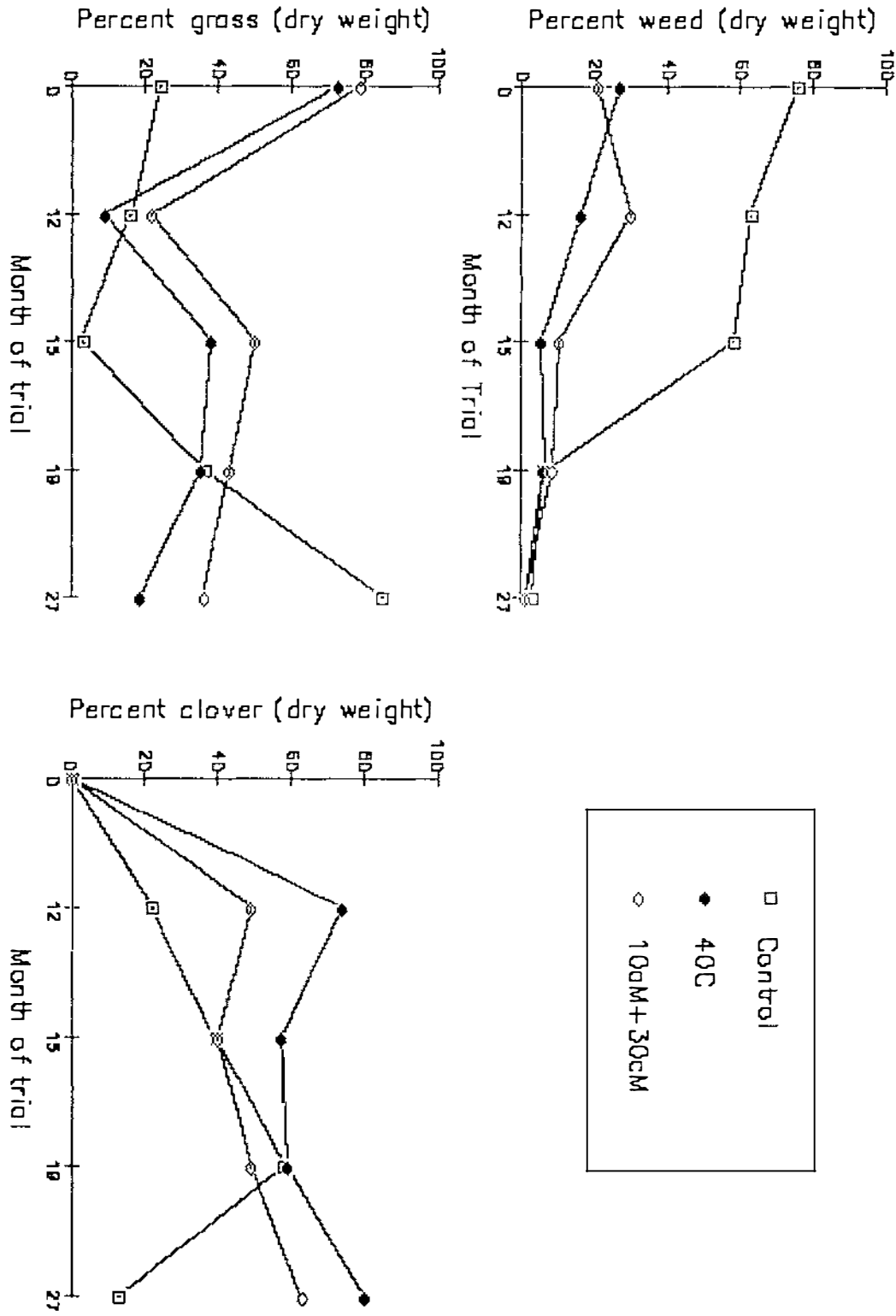
Appendix 5.3.4: Rangitikei trial. Gravimetric moisture content at 10 k Pa suction of soil replacement treatments. N = number of cores taken. Duncan's Test results are on the RHS of each column.

Treatment	Soil depth (m)			
	0	0.1	0.2	0.30
Undisturbed	31.7±0.6 ab	23.0±1.0 b	20.7±0.6 b	20.0±1.0 b
Control	37.0±0 a	21.0±1.4 b	20.5±0.7 b	18.0±0 b
10A+30C	36.0±1.0 a	27.0±3.6 a	25.3±1.2 a	28.0±1.4 a
40C	32.0±3.0 ab	26.5±0.7 a	23.0±5.7 ab	27.5±0.7 a
100C	30.3±1.3 b	26.3±2.9 a	23.5±0.6 ab	25.5±3.1 a
10A	32.3±6.2 ab	28.3±1.5 a	na	na
N	38	34	28	26
Probability	0.09	0.01	0.20	0.02

Appendix 5.3.5: Rangitikei trial. Gravimetric moisture content of topsoiled and nil-topsoil replacement treatments at 5 and 10 k Pa suction. N = number of cores taken.

Soil Treatment	Soil depth (m)		
	0	0.1	0.2
<b>5 k Pa suction</b>			
10A+30C	38.7	30.0	29.3
40C	37.8	28.3	25.5
N	16	14	14
Probability	0.21	0.36	0.30
<b>10 kPa suction</b>			
10A+30C	36.0	27.0	25.3
40C	34.0	23.8	21.8
N	16	14	14
Probability	0.09	0.09	0.27

Appendix 5.3.6: Rangitikei trial. Herbage composition (% dry mass of weed, grass and clover) of nil-topsoil and topsoiled treatments showing the effect of mixing soil A and C horizons over five harvests. Note "grass" in harvest one is the percentage of barley+oats crop.



Appendix 5.3.7: Rangitikei trial. Herbage dissection (% dry mass of clover, grass and weed) of pasture from nil-topsoil and topsoiled treatments showing the effect of mixing A and C horizons over five harvests. na = no clover dissected in harvest 1 (barley and oats harvest).

Soil Treatment	Harvest				
	1	2	3	4	8
<b>Percent clover</b> Control	na	22 c	39 b	58 a	13 c
40C	na	74 a	57 a	59 a	80 a
10A+30C	na	49 b	40 b	49 a	63 b
<b>Percent grass</b> control	24 b	16 bc	3 c	36 a	85 a
40C	73 a	9 c	38 b	35 a	19 c
10A+30C	79 a	22 b	50 a	43 a	36 b
<b>Percent weeds</b> control	76 a	63 a	58 a	6 a	3 a
40C	27 b	16 b	5 b	6 a	1 b
10A+30C	21 b	30 b	10 b	8 a	1 b

#### Appendix 5.4: Ohakea trial soil replacement treatments

Appendix 5.4.1: SAS programme used to analyse the significance of soil replacement treatments of the Ohakea trial.

```

/* file h:\pdata\*.dat text input */
data robyn;
infile 'h:\pdata\oh100-0.dat';
do soil = 1 to 8;
do drainage = 1 to 2;
do block = 1 to 2;
input d1 d2 d3;
output;
end; end; end; run;
data new; set robyn;
if soil=3 or soil=5 or soil=7 then delete;
proc format;
value drainage 1 = 'drained' 2 = 'undrained';
value soil 1 = 'original' 2 = 'control' 3 = 'ABmix' 4 = 'x' 5 = 'A' 6 = 'y' 7 = 'AonB' 8 = 'z';
run;
proc print;
run;
proc glm;
class drainage block soil;

model d1 d2 d3 = block drainage block*drainage
            soil soil*block soil*drainage soil*block*drainage / ss1;
test h = soil soil*drainage e = soil*block*drainage / htype=1 etype=1;
run;
means soil soil*drainage / duncan e = soil*block*drainage etype=1 alpha=.05;
means soil soil*drainage / duncan e = soil*block*drainage etype=1 alpha=.1;
run;

```

Appendix 5.4.2: Ohakea trial. Particle density of Ohakea soil horizons. Significance = 0.24.

Medium	N	Particle Density Mg m <sup>3</sup>	Duncan's (10%)
		Mean and std. dev.	
A horizon	4	2.61 ± 0.07	a
AB mixed	4	2.66 ± 0.03	a
B horizon	6	2.66 ± 0.04	a

Appendix 5.4.3: Ohakea trial. Soil gravimetric moisture content at 1500 k Pa suction (permanent wilting point) of Ohakea soil horizons. Significance = 0.0001

Medium	N	Gravimetric water %	Duncan's(10%)
		Mean and std. dev.	
A horizon	10	20.7 ± 4.0	a
AB mixed	10	14.8 ± 1.0	b
B horizon	10	14.6 ± 0.8	b

Appendix 5.4.4: Ohakea trial. Total carbon content of Ohakea soil replacement treatments. Specific treatments sampled are given in brackets in the left hand column (Significance = 0.0001).

Medium	N	Total carbon %	Duncan's Test (10%)
		Mean Std Dev	
A horizon (control)	4	3.75 ± 0.27	a
A horizon (AonB)	4	3.26 ± 0.37	b
A horizon (Aonly)	4	3.07 ± 0.16	b
AB mixed	4	1.87 ± 0.24	c
B horizon	4	1.20 ± 0.08	d



Appendix 5.4.5: Ohakea trial. Bulk density ( $\text{Mg m}^{-3}$ ) of soil replacement treatments at specified soil depths. Duncan's Test letters, applied at a significance of 0.10 are given on the RHS of each column.

Treatment	Soil Depth (m)			
	0	0.1	0.2	0.3
A on B	1.31 a	1.27 a	1.36 a	1.44 a
AB mix	1.24 ab	1.26 a	1.38 a	1.43 a
A only	1.26 ab	1.23 a	1.28 a	1.51 a
Control	1.22 ab	1.22 a	1.46 a	1.46 a
Original	1.16 b	1.21 a	1.44 a	1.51 a
Significance	.30	.84	.67	.38
Number of samples	20	20	19	18

Appendix 5.4.6: Ohakea trial. Gravimetric moisture content (%) at 10 k Pa suction of soil replacement treatments at specified soil depths. Duncan's Test letters, applied at a significance of 0.10 are given on the RHS of each column.

Treatment	Soil Depth (m)			
	0	0.1	0.2	0.3
A on B	.14 a	.20 a	.22 a	.19 a
AB mix	.19 a	.19 a	.19 a	.20 a
A only	.18 a	.24 ab	.19 a	.20 a
Control	.18 a	.24 b	.19 a	.20 a
Original	.18 a	.23 b	.20 a	.17 a
Significance	.75	.11	.41	.68
Number of samples	20	18	19	17

Appendix 5.4.7: Ohakea trial. Pasture dry matter production (kg ha<sup>-1</sup>) for soil replacement treatments. Duncan's test applied at 0.10 level of significance. Means with the same letter are not significantly different, \* indicates results are significantly different at a 0.05 significance level.

	Harvest Number						
	1	2	3	4	5	6	7
<b>A on B</b>	1790 a*	957 ab	1151 ab	708 a*	1202 a	875 c*	1277 b*
<b>AB mixed</b>	543 c*	708 c*	1147 ab	760 a*	1145 ab	848 c*	977 c
<b>A only</b>	508 c*	699 c*	942 b*	299 b*	850 b	897 c*	769 c*
<b>Control</b>	674 c	812 bc	1348 a	723 a*	1264 a	998 b*	1231 b*
<b>Original</b>	1094 b*	1027 a*	1289 ab	747 a*	1144 ab	1082 a*	1584 a*
<b>Significance</b>	0.01	.05	.33	.05	.21	.003	.001

	Pasture Harvest Number						
	8	9	10	11	12	13	14
<b>(8) A on B</b>	1187 a*	1860 ab*	1320 a*	2510 a*	1219 b	1618 a*	587 a*
<b>(4) AB mix</b>	587 c*	1671 b	1416 a*	2539 a*	1234 b	1612 a*	378 c*
<b>(6) A only</b>	631 c*	1462 c*	1376 a*	2191 a*	1496 a	1589 a*	485 b*
<b>(2) Control</b>	1107 ab*	1703 b	1447 a*	2285 a*	1244 b	1649 a*	530 ab*
<b>(1) Original</b>	1036 b*	2029 a*	1400 a*	2429 a*	1402 ab	1707 a*	527 ab*
<b>Significance</b>	.001	.02	.74	.79	.18	.86	.02

Appendix 5.4.8: Ohakea trial. Herbage dissection of pasture by weed, clover and grass (% dry matter) for Harvests one and two. Duncan's Test letters are on the RHS of each column.

Treatment	Harvest 1			Harvest 2		
	clover	grass	weed	clover	grass	weed
<b>(8) A on B</b>	3 d	78 bc	20 a	7 b	75 ab	18 b
<b>(4) AB mix</b>	4 cd	83 b	12 b	18 a	67 bc	15 c
<b>(6) A only</b>	9 a	77 bc	14 ab	21 a	65 c	15 c
<b>(2) Control</b>	6 bc	71 c	22 a	14 ab	63 c	23 a
<b>(1) Original</b>	9 ab	90 a	2 c	17 ab	76 a	7 d
<b>Significance</b>	.03	.02	.03	.24	.08	.01

Appendix 5.4.9: Ohakea trial. Oven dry root mass (g) of pasture for soil replacement treatments. Duncan's Test results at  $p=0.10$  are given on the RHS of each column.

Treatment	Soil Depth (m)				
	0	0.1	0.2	0.3	Total
A on B	1.65 a	.46 a	.21 a	.13 a	2.45 a
AB mix	1.40 a	.37 a	.16 a	.14 a	2.52 a
A only	2.49 a	.29 a	.19 a	.22 a	3.16 a
Control	2.15 a	.39 a	.27 a	.12 a	2.86 a
Original	2.17 a	.20 a	.22 a	.11 a	2.64 a
Significance	.24	.80	.32	.27	.62
Number of samples	18	18	18	18	17

Appendix 5.4.10: Ohakea trial. Root length (m) of pasture for soil replacement treatments. Duncan's Test results at  $p=0.10$  are given on the RHS of each column. \* = Duncan's Test letters significant at  $p=0.05$ .

	Soil Depth				
	0	0.1	0.2	0.3	Total
(8) A on B	425 a	88 a	59 ab	38 ab	612 a
(4) AB mix	455 a	119 a	39 bc	42 a	690 a
(6) A only	673 a	103 a	74 a	41 a	809 a
(2) Control	657 a	136 a	83 a*	26 ab	888 a
(1) Original	489 a	81 a	28 c*	20 b	600 a
Significance	.49	.62	.08	.22	.60
Number of samples	17	17	18	18	17

Appendix 5.4.11: Ohakea trial. Total N and total P concentrations ( $\text{gm}^{-3}$ ) in grass and clover of soil replacement treatments.

Soil Replacement Method	N	Concentration of nutrient ( $\text{g m}^{-3}$ )			
		Nitrogen		Phosphorus	
		Ryegrass	Clover	Ryegrass	Clover
Undisturbed	4	625 $\pm$ 15	884 $\pm$ 24	9.7 $\pm$ 0.7	6.4 $\pm$ 0.4
AB mixed	4	589 $\pm$ 18	860 $\pm$ 36	8.9 $\pm$ 1.4	6.6 $\pm$ 0.7
A only	4	577 $\pm$ 42	849 $\pm$ 29	9.7 $\pm$ 2.1	6.7 $\pm$ 0.4
A on B	4	593 $\pm$ 11	832 $\pm$ 43	10.6 $\pm$ 1.2	5.9 $\pm$ 0.3
Control	4	596 $\pm$ 19	853 $\pm$ 37	10.0 $\pm$ 1.5	6.3 $\pm$ 0.3

Appendix 5.5: Ashhurst trial soil replacement treatments

Appendix 5.5.1: Ashhurst trial. Soil replacement treatments placed in order of pasture dry matter production. The highest producing treatment is on the top of each column. c = control, un = undisturbed, A = Aonly, AB = AB mix and AonB = Aon B.

Harvest number								
1	2	3	4	5	6	7	8	9
c	un	un	c	AB	un	c	c	AB
un	c	AonB	A	c	AB	AonB	AonB	un
A	AonB	AB	AonB	AonB	AonB	AB	un	c
AB	AB	c	AB	un	A	A	AB	A
AonB	A	A	un	A	c	un	A	AonB

Appendix 5.5.2: Ashhurst trial. Significant correlation analyses of soil volumetric moisture content with pasture dry matter production.

Harvest	Significance	Correlation Coefficient
1	0.07	0.37
4	0.07	0.38
6	0.08	0.37

### Appendix 5.6: Results from the acetate peel experiment

The upper surfaces of Ohakea and Rangitikei topsoil and subsoil samples was prepared for suction plate analysis using either an acetate peel or a sharp knife (Chapter 5.2: Methods). The method of sample preparation was found to have no significant effect on the amount of moisture contained in the samples at 0.1 k Pa suction (Appendix 5.6.1). On the basis of these results peeling soil cores before placing them on suction apparatus was not adopted.

The surface horizon of the Rangitikei soil was the sample most sensitive to the method of core preparation. This horizon contained a large number of roots. Removal of some of these roots by peeling would have increased the volume of pores drained, giving a slightly elevated but not significant reading.

Appendix 5.6.1: Mean gravimetric water content of peeled and unpeeled soil cores from surface and subsoil horizons of Rangitikei and Ohakea soils. N = the number of samples analyzed, P = the probability that  $H_0$  is true.

	Gravimetric water content at -0.1 k Pa (%)		N	P
	Peeled cores	Unpeeled cores		
Rangitikei A	40.7 ± 4.8	37.6 ± 3.4	12	.32
Rangitikei C	21.2 ± 4.4	20.5 ± 3.5	16	.80
Ohakea A (1)	19.2 ± 0.5	19.8 ± 0.8	28	.28
Ohakea A (2)	42.0 ± 2.3	42.1 ± 1.9	24	.87
Ohakea B	27.0 ± 1.4	26.9 ± 1.6	24	.82

## Appendix 6.1: Effect of Ohakea trial compaction treatments

6.1.1 SAS Statistical Programme for analyzing significance of high and low compaction treatments in the Ohakea Trial.

```

/* file h:\pdata\oh100-0.dat text input */
data robyn;
infile 'h:\pdata\oh100-0.dat';
do trt=1 to 8;
do drain=1 to 2;
do block=1 to 2;
input d1 d2 d3;
output;
end; end; end; run;
proc format;
value drain 1='drained' 2='undrained';
run;
data new; set robyn;
if trt=1 or trt=2 then delete;
if trt=3 or trt=5 or trt=7 then comp='high';
else if trt=4 or trt=6 or trt=8 then comp='low';
if trt=3 or trt=4 then soil='ABmix';
if trt=5 or trt=6 then soil='A';
else if trt=7 or trt=8 then soil='AonB';
proc print;
run;
proc glm;
class drain block comp soil;

model d1 d2 d3 = block drain block*drain comp soil comp*soil comp*block
soil*block comp*drain soil*drain comp*block*drain soil*block*drain
comp*soil*drain comp*soil*block*drain / ss1;
test h= block drain e=block*drain / htype=1 etype=1;
test h= soil comp soil*comp comp*drain soil*drain
e= soil*comp*block*drain / htype=1 etype=1;
run;
means drain / duncan e=block*drain etype=1 alpha=.1;
means drain / duncan e=block*drain etype=1 alpha=.05;
means comp comp*drain / duncan e=soil*comp*block*drain etype=1 alpha=.1;
means comp comp*drain / duncan e=soil*comp*block*drain etype=1 alpha=.05;
means soil soil*drain / duncan e=soil*comp*block*drain etype=1 alpha=.1;
means soil soil*drain / duncan e=soil*comp*block*drain etype=1 alpha=.05;
run;
endsas;

```

6.1.2 Ohakea trial. Correlation of dry matter production with bulk density. Correlation of root mass with dry matter production. Within each box the Pearson Correlation Coefficient is given on the LHS where the probability (RHS number) that the correlation is due entirely to chance is  $< 0.10$ . Samples were taken at soil depths of 0 to 0.05 m, 0.10 to 0.15 m, 0.20 to 0.25 m and 0.30 to 0.35 m. The dates of each harvest are given in Chapter 5.6.

Harvest Number	Soil depth (m)			
	0	0.10	0.20	0.30
1	(.31) 0.09	0.15	(.39) .03	.68
2	(.32) 0.08	0.20	.15	.86
3	0.63	0.33	(.33) .07	.2
4	0.76	0.71	(.36) .05	.78
5	0.67	0.60	.99	.68
6	(.37) 0.04	(.36) 0.04	.74	0.67 .001
7	(.42) 0.02	.17	.60	.14
8	(.61) 0.001	(.41) 0.02	.90	.62
9	0.53	0.11	0.31 .09	.85
10	0.62	0.86	.36	.65
11	0.22	0.23	.71	.52
12	0.41	0.25	.17	0.42 .03
13	0.19	0.21	.95	.61
14	(.33) 0.06	0.16	.66	.18



6.1.3 Ohakea trial. Correlation of dry matter production with macroporosity. Within each box the Pearson Correlation Coefficient is given on the LHS where the probability (RHS number) that the correlation is due entirely to chance is  $< 0.10$ . Samples were taken at soil depths of **0** to 0.05 m, **0.10** to 0.15 m, **0.20** to 0.25 m and **0.30** to 0.35 m.

Harvest Number	Soil depth (m)				
	0	0.10	0.20	0.30	
1	.45	.26	.34	.06	.91
2	.64	.51		.22	.40
3	.51	.84		.70	.11
4	.95	.11		.63	.31
5	.53	.23		.25	.57
6	.43	.32		.89	(.61) .001
7	(.45) .01	.43		.83	.20
8	.47	.40		.82	.54
9	.51	.74	(.31)	.10	.88
10	.86	.92		.25	.13
11	(.31) .08	.33		.84	.96
12	.25	.58		.46	.21
13	.80	.84		.42	.96
14	.56	0.31 .09	(.31)	.10	.20

6.1.4 Ohakea trial. Interaction of soil replacement treatments and compaction treatments for harvests 1 to 14, showing means of dry matter production (LHS of boxes) and standard deviations (RHS of boxes) in kg ha<sup>-1</sup>. High = high compaction treatment, low = low compaction treatment. A key explaining soil replacement treatments is given in Chapter 4.3.1)

Harvest Number	Soil replacement treatment							
	AB high		AB low		AonB high		AonB low	
1	565 ±	258	543 ±	202	626 ±	331	1790±	242
2	760 ±	249	708 ±	139	800 ±	124	957±	66
3	1167±	200	1147±	230	1042±	259	1151±	192
4	772 ±	175	760 ±	109	646 ±	196	708±	180
5	1362±	187	1145±	204	1249±	214	1202±	240
6	948 ±	77	848 ±	38	979 ±	147	875±	86
7	888 ±	308	977 ±	179	1258±	282	1277±	273
8	797 ±	287	587 ±	153	1007±	222	1187±	377
9	1824±	352	1671±	68	1848±	276	1860±	230
10	1514±	254	1416±	157	1346±	214	1320±	242
11	3005±	228	2539±	584	2478±	256	2510±	326
12	1274±	53	1234±	87	1182±	98	1219±	85
13	1565±	106	1616±	124	1628±	193	1618±	87
14	464 ±	99	378 ±	59	454 ±	45	587 ±	116

6.1.5 Ohakea trial. Pasture composition of high and low compaction treatments (as % dry mass) in Harvests 1 and 2. Four sub samples from each of 24 plots were used in the herbage analysis. Total clover, grass and weed percentages do not add up to exactly 100% because means of herbage analyses are used.

Treatment	Harvest 1			Harvest 2		
	clover	grass	weed	clover	grass	weed
Low compaction	5 ± 4	79 ± 9	15 ± 7	15 ± 10	69 ± 9	18 ± 5
High compaction	9 ± 6	73 ± 10	18 ± 9	20 ± 9	63 ± 10	19 ± 9
Significance	.26	.08	.19	.35	.14	.21

- 6.1.6 Ohakea trial. Effect of high and low compaction treatments on bulk density ( $\text{Mg m}^{-3}$ ). Brackets indicate negative values. Samples were taken at soil depths of 0 to 0.05 m, 0.10 to 0.15 m, 0.20 to 0.25 m and 0.30 to 0.35 m. "Significance" is the probability that  $H_0$  holds, i.e. that differences between high and low compaction treatments are due to chance alone.

Treatment	$\rho_b$ ( $\text{Mg m}^{-3}$ ) at specified soil depth (m)			
	0	0.1	0.2	0.3
Low compaction	1.27 ± 0.11	1.25 ± 0.09	1.34 ± 0.12	1.46 ± 0.11
High compaction	1.22 ± 0.08	1.22 ± 0.11	1.48 ± 0.15	1.43 ± 0.14
Significance	.29	.40	.15	.58
Number of samples	48	48	48	46
Effect of compaction	(.05)	(.03)	.14	(.03)

- 6.1.7 Ohakea trial. Mean (LHS) and standard deviation (RHS) bulk density ( $\text{Mg m}^{-3}$ ) associated with soil replacement and compaction interaction. N = number of samples. "High" = high compaction treatment, "Low" = low compaction treatment.

Soil depth (m)	Treatment AB		Treatment Aonly		Treatment AonB		N
	$\rho_b$ High	$\rho_b$ Low	$\rho_b$ High	$\rho_b$ Low	$\rho_b$ High	$\rho_b$ Low	
0	1.20± 0.08	1.24± 0.07	1.27± 0.04	1.26±0.14	1.19±0.11	1.31±0.11	48
0.10	1.20± 0.08	1.26± 0.06	1.30± 0.12	1.23±0.13	1.14±0.06	1.27±0.06	48
0.20	1.51± 0.16	1.37± 0.12	1.54± 0.13	1.28±0.12	1.38±0.13	1.36±0.12	48
0.30	1.34± 0.03	1.43± 0.06	1.49± 0.20	1.51±0.11	1.45±0.13	1.44±0.16	44

- 6.1.8 Ohakea trial. Effect of high and low compaction treatments on soil gravimetric moisture content at 10 k Pa suction (%; no units). Samples were taken at soil depths of 0 to 0.05 m, 0.10 to 0.15 m, 0.20 to 0.25 m and 0.30 to 0.35 m. Brackets represent a negative value.

Treatment	Macroporosity at specified soil depth (m)			
	0.0	0.10	0.20	0.30
Low compaction	.17 ± 0.05	.20 ± 0.06	.21 ± 0.04	.18 ± 0.04
High compaction	.21 ± 0.04	.24 ± 0.05	.20 ± 0.05	.22 ± 0.06
Significance	.18	.31	.14	.12
Number of samples	24	23	23	20
Effect of compaction	(.03)	(.04)	.01	(.04)

6.1.9 Ohakea trial. Effect of soil compaction treatment on root length (m per 0.5 l of soil). Samples were taken at soil depths of 0 to 0.05 m, 0.10 to 0.15 m, 0.20 to 0.25 m and 0.30 to 0.35 m. Brackets represent a negative effect of compaction (difference between high and low compaction treatments in m).

Treatment	Root length (m) at specified soil depth (m)			
	0.0	0.10	0.20	0.30
Low compaction	508 ± 227	104 ± 47	57 ± 23	40 ± 22
High compaction	490 ± 172	150 ± 95	37 ± 23	24 ± 15
Significance	.88	.26	.12	.13
Number of samples	21	21	24	23
Effect of compaction	18	(46)	20	16

6.1.10 Ohakea trial. Interaction between soil replacement and soil compaction treatments with respect to root mass means (LHS) and standard deviations (RHS). "high" = high compaction treatment, "low" = low compaction treatment, P = probability, N = number of samples.

Soil Depth (m)	ABmix		Aonly		AonB		N
	high	low	high	low	high	low	
0	3.05	1.40	3.18	2.49	2.08	1.65	22
0.10	.34	.37	.511	.29	.41	.46	22
0.20	.17	.16	.14	.19	.13	.21	24
0.30	.09	.14	.08	.22	.07	.13	23
Total	3.66	2.52	3.78	3.16	2.71	2.45	21

6.1.11 Correlation analysis of root length with bulk density. Within each box the RHS number is the probability that the correlation is due entirely to chance. The Correlation Coefficient is on the LHS. Brackets indicate a negative value. Significant correlations are bolded. Samples were taken at soil depths of 0 to 0.05 m, 0.10 to 0.15 m, 0.20 to 0.25 m and 0.30 to 0.35 m.

Root length at specified soil depth	Bulk density at specified soil depth							
	0		0.10		0.20		0.30	
0	0.07	0.74	0.21	0.29	0.29	0.15	0.06	0.79
0.1	(0.06)	0.76	(0.29)	0.14	0.13	0.53	<b>0.56</b>	<b>0.01</b>
0.2	0.15	0.41	(0.02)	0.90	<b>(0.39)</b>	<b>0.03</b>	<b>0.37</b>	<b>0.06</b>
0.3	<b>0.63</b>	<b>0.01</b>	<b>0.58</b>	<b>0.01</b>	(0.14)	0.48	<b>(0.33)</b>	<b>0.10</b>
Total	0.14	0.46	0.12	0.52	0.24	0.21	0.21	0.30

6.1.12 Correlation analysis of root mass with bulk density. Within each box the RHS number is the probability that the correlation is due entirely to chance. The Correlation Coefficient is on the LHS. Brackets indicate a negative value. Significant correlations are bolded. Samples were taken at soil depths of 0 to 0.05 m, 0.10 to 0.15 m, 0.20 to 0.25 m and 0.30 to 0.35 m.

Root mass at specified soil depth	Bulk density at specified soil depth							
	0		0.10		0.20		0.30	
0	(0.01)	0.98	0.03	0.86	0.45	0.02	0.08	0.71
0.1	(0.04)	0.85	(0.14)	0.49	0.15	0.46	0.28	0.18
0.2	(0.05)	0.78	(0.09)	0.63	<b>(0.39)</b>	<b>0.03</b>	0.26	0.20
0.3	<b>0.46</b>	<b>0.01</b>	<b>0.52</b>	<b>0.01</b>	0.02	0.92	(0.28)	0.17
Total	0.13	0.48	0.10	0.59	<b>0.43</b>	<b>0.02</b>	0.10	0.62

6.1.13 Ohakea trial. Effect of compaction treatment on soil volumetric water content (%), measured with a TDR. Brackets signify a negative effect of compaction.

*Effect of compaction treatment on soil volumetric water content measured on 30-10-90.*

Treatment	$\theta$ at specified soil depth (m)			
	0-0.15	0.15-0.3	0.3-0.4	0.4-0.6
Low compaction	27.5	37.3	47.5	33.6
High compaction	27.0	34.6	45.7	32.7
Significance	0.57	0.04	0.53	0.91
Number of samples	24	24	23	20
Effect of compaction	(0.5)	(2.7)	(1.8)	0.9

*Effect of compaction treatment on soil volumetric water content measured on 13-11-90.*

Treatment	$\theta$ at specified soil depth (m)			
	0-0.15	0.15-0.3	0.3-0.4	0.4-0.6
Low compaction	20.0	32.5	37.0	39.1
High compaction	19.0	33.6	36.2	38.4
Significance	0.14	0.27	0.68	0.99
Number of samples	24	23	23	19
Effect of compaction	(1.0)	1.1	(0.8)	(0.7)

*Effect of compaction treatment on soil volumetric water content measured on 27-11-90.*

Treatment	$\theta$ at specified soil depth (m)			
	0-0.15	0.15-0.3	0.3-0.4	0.4-0.6
Low compaction	13.3	24.9	27.7	28.3
High compaction	14.5	26.2	29.2	29.0
Significance	0.24	0.47	0.61	0.86
Number of samples	24	24	24	21
Effect of compaction	1.2	1.3	1.5	0.7

*Effect of compaction treatment on soil volumetric water content measured on 12-5-91.*

Treatment	$\theta$ at specified soil depth (m)			
	0-0.15	0.15-0.3	0.3-0.4	0.4-0.6
Low compaction	24.8	35.1	37.9	36.8
High compaction	23.3	39.9	39.3	38.0
Significance	0.02	0.31	0.73	0.54
Number of samples	24	24	22	21
Effect of compaction	(1.5)	4.8	2.6	1.2

## Appendix 6.2: Ashhurst trial compaction treatments

6.2.1: Ashhurst trial. Pasture dry matter production means (LHS) and standard deviations (RHS) ( $\text{kg ha}^{-1}$ ) of high and low compaction treatments. Dates of harvests are given in Chapter 5.6.

Treatment	Harvest yield ( $\text{kg ha}^{-1}$ )				
	Total	1	2	3	4
High compaction	17,010	1309±205	1248±242	1021±137	1807±264
Low compaction	13,900	1308±438	1187±351	935±64	1786±260
Significance	na	.98	.83	.24	.87
No. of samples	12	16	12	16	16

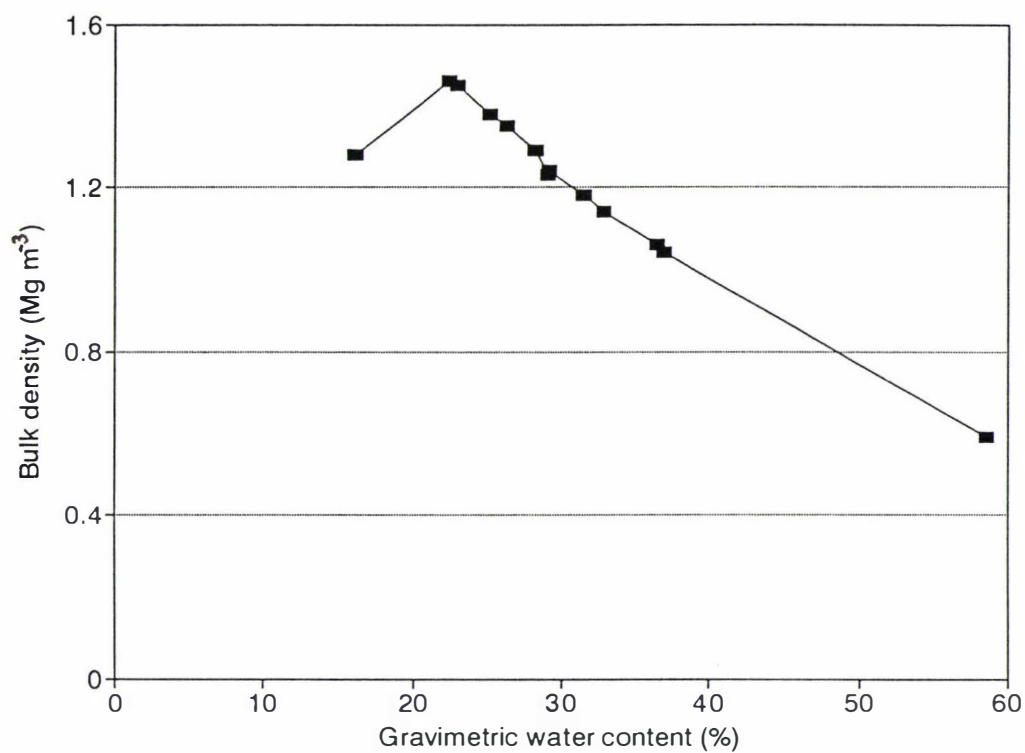
Treatment	Harvest yield ( $\text{kg ha}^{-1}$ )				
	5	6	7	8	9
High compaction	2113±581	1793±548	3026±326	1822±615	476±81
Low compaction	2061±339	1823±383	2663±550	1730±625	454±107
Significance	.85	.94	.12	.81	.79
No. of samples	16	16	16	16	16

6.2.2 Ashhurst trial. Soil volumetric water content from compacted and uncompacted plots, measured by TDR.

Characteristic	Level of compaction	
	High	Low
Water content (volumetric)	29.3 ± 3.4	29.4 ± 3.9
Significance	0.96	
Number of samples	8	8



- 6.2.3 Ashhurst trial. Proctor compaction curve for the A horizon of an Ashhurst soil. More points are needed to characterise the drier end of the curve.



### Appendix 6.3: Rangitikei trial compaction treatments

6.3.1: Rangitikei trial. Means (LHS) and standard deviations (RHS) of bulk density in "high" and "low" compaction areas ( $\text{Mg m}^{-3}$ ). Different letters indicate statistically significant differences at a level of significance = 0.05.

Bulk density ( $\text{Mg m}^{-3}$ )	Depth of sample (m)			
	0-0.05	0.10-0.15	0.20-0.25	0.30-0.35
High compaction	1.53±0.12 a	1.63±0.10 a	1.59±0.06 a	1.54±0.08 a
Low compaction	1.49±0.06 a	1.48±0.05 b	1.37±0.06 b	1.35±0.06 b
Control	1.39±0.05 b	1.45±0.04 b	1.44±0.04 c	1.40±0.04 b
Significance	.04	.0001	.0001	.0001

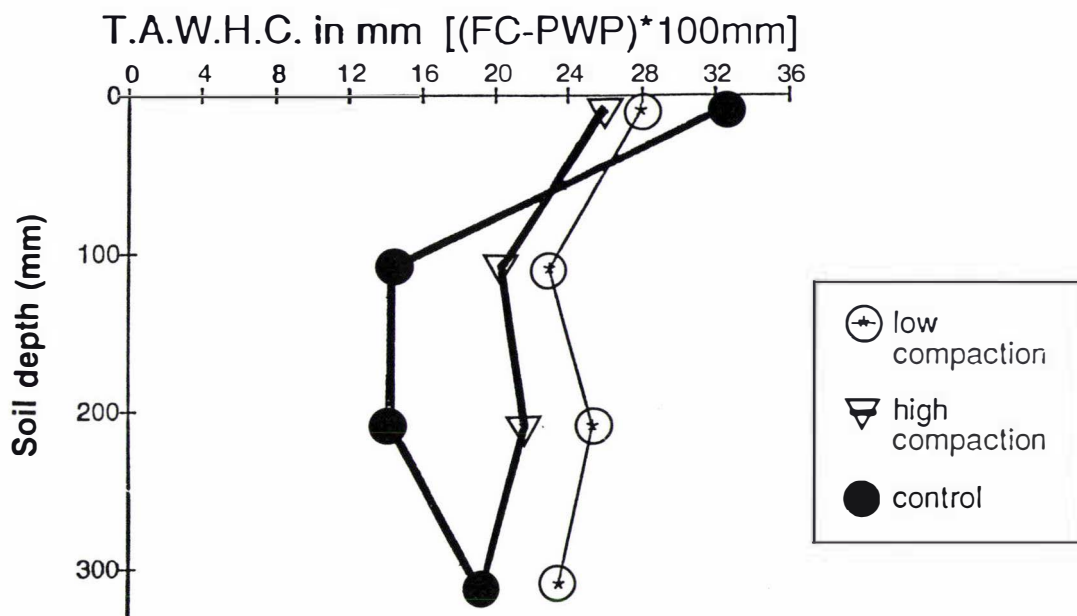
6.3.2 Rangitikei commercially reclaimed area. Mean penetration resistance of "high" and "low" compaction areas using a flat-tipped scalar penetrometer. Note: measurements are not adjusted for soil moisture content, which was c.2% higher in highly compacted plots so differences are likely to be greater than measured (Volumetric water content at 0 to 0.10 m depth was  $10.4 \pm 1.1\%$  ( $n=16$ ) in the compacted area and  $7.9 \pm 2.3\%$  ( $n=16$ ) in the low compaction area).

Penetration resistance (no units)	Depth of sample (m)			
	0	0.06	0.15	0.25
High compaction	67	4163	481	413
Low compaction	64	68	60	50
Significance	.47	.007	.0001	.0001
No of samples	48	48	48	48

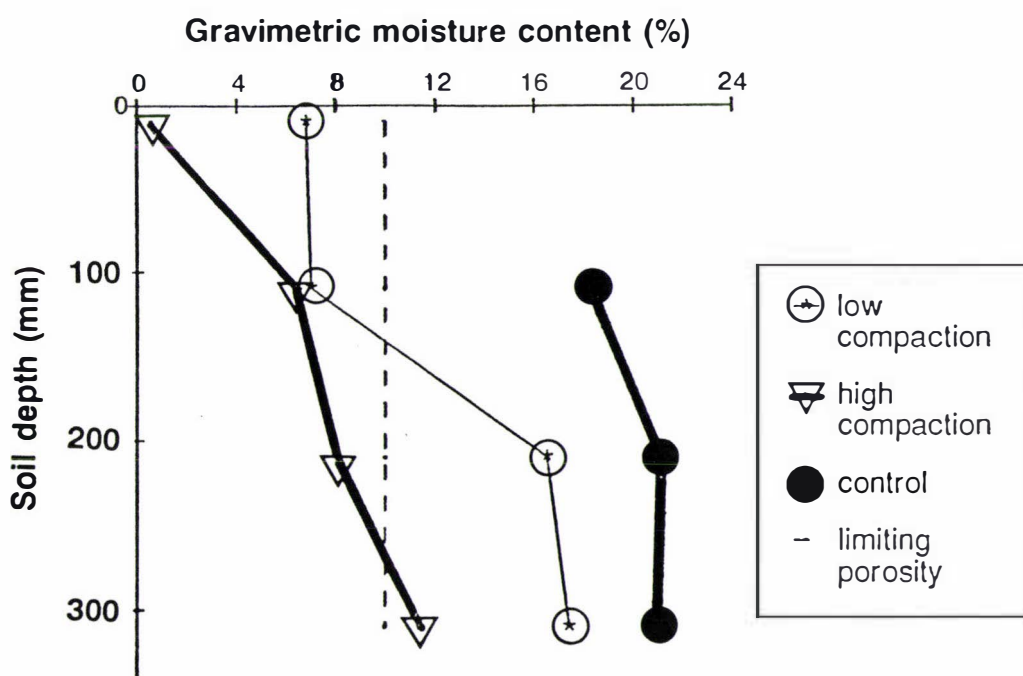
6.3.3: Rangitikei commercially reclaimed area. Total soil available water holding capacity to 0.4 m depth calculated from:

$$(\text{Field capacity} - \text{Permanent wilting point}) \times 400$$

Field capacity was taken to equal volumetric soil water content at 10 k Pa suction (1 m head).



6.3.4 Rangitikei commercially reclaimed area. Soil gravimetric moisture content at 10 k Pa suction.



6.3.5: Rangitikei commercially reclaimed area. Means (LHS) and standard deviation (RHS) dry matter production for harvest one on 28 November 1989 from "high" and "low" compaction areas (8 samples were taken from each area).

Treatment	Herbage Dissection (%)			Total dry matter (kg ha <sup>-1</sup> )
	grasses	clovers	weeds	
High compaction	44 ± 12	23 ± 16	34 ± 23	810 ± 580
Low compaction	70 ± 10	20 ± 10	10 ± 3.5	2770 ± 580
Significance	.007	.75	.03	.0001

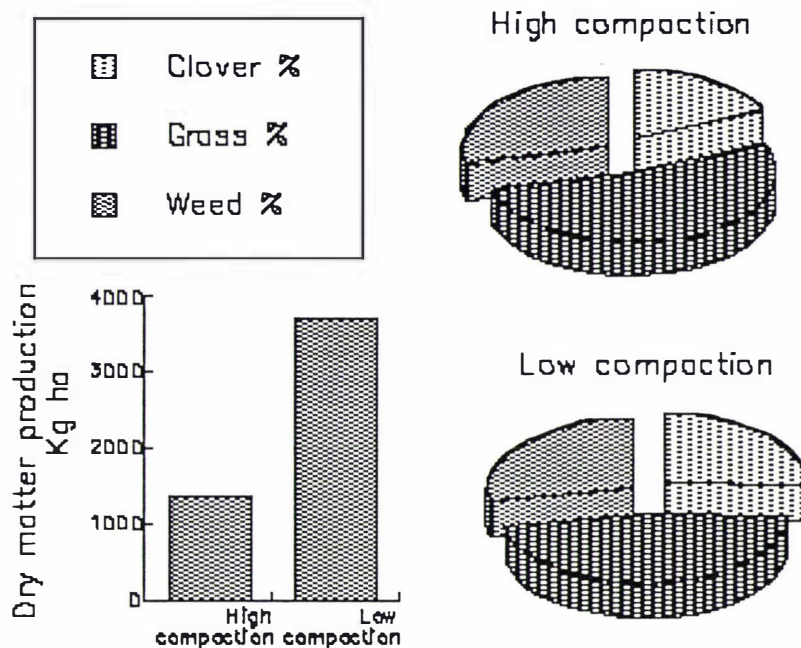
6.3.6 Rangitikei commercially reclaimed area. Means (LHS) and standard deviation (RHS) of reproductive and vegetative clover (% by dry mass) for harvest one from "high" and "low" compaction areas (8 samples were taken from each area).

Treatment	Herbage dissection (%)	
	Vegetative clover	Reproductive clover
High compaction	10 ± 9	13 ± 15
Low compaction	20 ± 10	0 ± 0
Significance	.006	.05

6.3.7: a) Rangitikei commercially reclaimed area. Means (LHS) and standard deviations (RHS) of pasture dry matter production for harvest two, February 1990 from "high" and "low" compaction areas (8 samples were taken from each area).

Treatment	Herbage Dissection (%)			Total dry matter (kg ha <sup>-1</sup> )
	grasses	clovers	weeds	
High compaction	53 ± 14	18 ± 13	29 ± 11	1490 ± 430
Low compaction	46 ± 11	26 ± 16	28 ± 9	3740 ± 600
Significance	.34	.26	.90	.0001

b) Rangitikei commercially reclaimed area. Bar graph of pasture dry matter production (LHS) and pie graph of herbage composition (RHS) for harvest two, February 1990 from "high" and "low" compaction areas (8 samples were taken from each area).



6.3.8 Rangitikei trial. Mean (LHS) and standard deviation (RHS) Pasture composition as (% dry mass) of high compaction and low compaction fill treatments in Harvest Four and Harvest Eight.

Harvest	Level of compaction		Significance
	High	Low	
<b>Harvest Four</b>			
Clover	9 ± 10	62 ± 9	0.008
Grass	23 ± 14	33 ± 10	0.47
Weed	68 ± 24	5 ± 3	0.05
<b>Harvest Eight</b>			
Clover	33 ± 27	44 ± 16	0.53
Grass	54 ± 28	54 ± 8	0.99
Weed	14 ± 5.6	2 ± 2	0.03

#### Appendix 6.4: Ohakea trial drainage treatments

6.4.1 Ohakea trial. Volumetric water contents of drained and undrained treatments.

*Soil volumetric water contents (%) on November 13 1990*

Treatment	Soil Depth (m)			
	0-0.15	0.15-0.3	0.3-0.4	0.4-0.6
Drained	18.0 ± 2.3	24.7 ± 2.8	29.0 ± 12.1	42.5 ± 8.0
Undrained	20.6 ± 3.9	29.6 ± 3.8	37.4 ± 3.7	50.0 ± 4.5
Significance	.11	.03	.03	.07
Number of samples	32	31	30	27
Advantage of drainage	2.6	4.8	5.3	2.1

*Soil volumetric water contents (%) on November 27 1990*

Treatment	Soil Depth (m)			
	0-0.15	0.15-0.3	0.3-0.4	0.4-0.6
Drained	13.0 ± 2.1	18.0 ± 2.3	25.6 ± 3.7	33.1 ± 7.3
Undrained	14 ± 2.5	20.6 ± 2.5	30.9 ± 7.9	36.1 ± 14.1
Significance	.12	.11	.26	.31
Number of samples	32	32	31	29
Advantage of drainage	1	2.6	5.3	3.1

*Soil volumetric water contents (%) on December 5 1990*

Treatment	Soil Depth (m)		
	0-0.15	0.15-0.3	0.3-0.4
Drained	22.8 ± 2.7	35.8 ± 10.9	37.6 ± 11.6
Undrained	25.9 ± 2.7	37.5 ± 4.5	40.7 ± 5.9
Significance	.04	.79	.44
Number of samples	32	32	29
Advantage of drainage	3.1	1.7	3.1

Soil volumetric water contents (%) on 22 January and 7 and 20 February 1991.

Treatment	Measurement		
	TDR 5	TDR 6	TDR 7
Drained	29.7 ± 2.5	28.4 ± 1.5	31.7 ± 2.0
Undrained	31.2 ± 2.5	30.3 ± 2.4	37.7 ± 6.4
Significance	.14	.09	.16
Number of samples	32	32	32
Advantage of drainage	1.5	1.9	6

6.4.2 Ohakea trial. Effect of drainage treatment on depth to water table (m) at Ohakea trial. WT 1 = First water table measurement. Each reading comprises 32 measurements (1 per plot).

Treatment	WT 1	WT 2
Drained	.33 ± 0.05	.40 ± 0.05
Undrained	.18 ± 0.11	.25 ± 0.12
Significance	.003	.02

6.4.3 Ohakea trial. Mean soil bulk density ( $\text{Mg m}^{-3}$ ) of drained and undrained treatments at 0 to 0.05, 0.10 to 0.15, 0.20 to 0.25 and 0.30 to 0.35 m depths.

	Soil Depth (m)			
	0	0.1	0.2	0.3
Drained treatment	1.26	1.24	1.46	1.47
Undrained treatment	1.20	1.22	1.37	1.44
Significance	.21	.17	.24	.04
Number of samples	32	32	32	28

6.4.4 Ohakea trial. Soil gravimetric moisture content (%; no units) at 10 k Pa suction of drained and undrained treatments at 0 to 0.05, 0.10 to 0.15, 0.20 to 0.25 and 0.30 to 0.35 m depths.

Treatment	Soil Depth (m)			
	0	0.1	0.2	0.3
Drained	.19	.24	.19	.19
Undrained	.18	.21	.21	.20
Significance	.77	.38	.31	.86
Number of samples	32	32	30	26



6.4.5 Ohakea trial. Effect of drainage treatment on pasture dry matter production ( $\text{kg ha}^{-1}$ ) from September 1989 to June 1991.

	Pasture Harvest Number						
	1	2	3	4	5	6	7
<b>Drained</b>	1748	847	1044	553	1068	909	1088
<b>Undrained</b>	2813	741	1179	710	1244	991	1128
<b>Significance</b>	.68	.31	.14	.35	.15	<u>.06</u>	.83
<b>Advantage of Drainage (%)</b>	(38)	13	(11)	(22)	(14)	<u>(8)</u>	(4)
	8	9	10	11	12	13	14
	<b>Drained</b>	1004	1785	1356	2293	1304	1676
<b>Undrained</b>	791	1740	1427	2729	1318	1563	397
<b>Significance</b>	.05	.55	.56	.09	.62	.03	.10
<b>Advantage of Drainage</b>	21	3	(5)	(16)	(1)	7	31

6.4.6 Ohakea trial. Root mass (g) and root length (m) of pasture taken from drained and undrained treatments. Samples taken at 0 to 0.05, 0.10 to 0.15, 0.20 to 0.25 and 0.30 to 0.35 m depths.

Treatment Root mass (g)	Soil Depth (m)			
	0	0.1	0.2	0.3
<b>Drained</b>	2.47	0.35	0.14	0.14
<b>Undrained</b>	2.08	0.41	0.22	0.10
<b>Significance</b>	0.09	0.52	0.18	0.58
<b>No. of samples</b>	29	28	30	32
Root length (m)				
<b>Drained</b>	506	113	44	35
<b>Undrained</b>	534	138	54	25
<b>Significance</b>	0.81	0.25	0.49	0.20
<b>Number of samples</b>	28	27	30	30

6.4.7 Ohakea trial. Correlation of volumetric water content with dry matter production. Within each TDR measurement the bottom number is the Probability  $> |R|$  under  $H_0: \rho=0$  (where  $H_0$ =Null hypothesis). The Pearson Correlation Coefficient is given on the top line where the probability value is less than 0.10. The number of observations used in each correlation varies from 26 to 32.

Harvest Number	TDR 4				TDR 5	TDR 6	TDR 7
	Volumetric water content at specified soil depth						
	15	15-30	30-40	40-60	15	20	20
1	22	.78	.86	62	.86	.50	36
2	-.34 06	20	.37	54	-.43 .01	-.51 .003	-.46 .01
3	26	.95	.45	20	.43	19	25
4	28	.84	.91	.41 .03	.41	29	35
5	15	25	.98	31 10	.94	.70	86
6	.35 05	27	.90	16	.71	28	15
7	33	.17	.67	.26	-.32 .08	.26	18
8	-.43 .01	.18	.91	.90	-.41 02	-.32 .08	-.45 01
9	.38	60	.11	.36 .05	28	49	-.34 06
10	86	.33	.93	.89	28	32	56
11	23	31 08	27	14	58 .001	37 .04	45 01
12	46 .01	.40	.97	.32	33 07	.66 0001	62 0002
13	52	29	.82	82	44	.56	40
14	-.5 003	14	-.34 .07	15	-.55 001	-.46 01	-.55 001

### Appendix 6.5 Results of muffle furnace experiment

This experiment was carried out to find out if there was any change in the fraction of mineral soil which was attached to washed root samples taken from 0, 0.1, 0.2 and 0.3 m depths. I concluded that there was no significant difference in the % mineral fraction (by mass) attached to roots in samples taken from 0.1 to 0.3 m depths.

Soil depth (mm)	N	% Mineral Fraction
0 to 0.10	7	17.9 ± 3.5 a
0.10 to 0.20	7	23.1 ± 3.0 b
0.20 to 0.30	7	24.3 ± 6.3 b
0.30 to 0.35	7	27.8 ± 5.4 b

### APPENDIX 8.1: Definition of sustainable management

Resource Management Act 1991, Section 5(2). Sustainable management means:

"managing the use, development and protection of natural and physical resources in a way or at a rate which enables people and communities to provide for their social, economic, cultural wellbeing and for their health and safety while-

- a) sustaining the potential of natural and physical resources (excluding minerals) to meet the reasonably foreseeable needs of future generations; and
- b) safeguarding the life-supporting capacity of air, water, soil, and ecosystems; and
- c) avoiding, remedying, or mitigating any adverse affects of activities on the environment"

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**APPENDIX 8.2: Fourth Schedule of the Resource Management Act 1991 (Section 88(6)(b)).**

**Assessment of Effects on the Environment**

**1. Matters that should be included in an assessment of effects on the environment-**

Subject to the provisions of any policy statement or plan, an assessment of effects on the environment for the purposes of Section 88(6)(b) should include-

- (a) A description of the proposal:
- (b) Where it is likely that an activity will result in any significant adverse effect on the environment a description of any possible alternative locations or methods for undertaking the activity:
- (c) Where an application is made for a discharge permit, a demonstration of how the proposed option is the best practicable option:
- (d) An assessment of the potential or actual effect on the environment of the proposed activity:
- (e) Where the activity includes the use of hazardous substances and installations, an assessment of any risks to the environment which are likely to arise from such use:
- (f) Where the activity includes the discharge of any contaminant, a description of
  - (i) The nature of the discharge and the sensitivity of the proposed receiving environment to adverse effects; and
  - (ii) Any possible alternative methods of discharge, including discharge into any other receiving environment:
- (g) A description of the mitigation measures (safeguards and contingency plans where relevant) to be undertaken to help prevent or reduce the actual or potential effect:
- (h) An identification of those persons interested in or affected by the proposal, the consultation undertaken, and any response to the views of those consulted:
- (i) Where the scale or significance of the activity's effect are such that monitoring is required, a description of how, once the proposal is approved, effects will be monitored and by whom.

**2. Matters that should be considered when preparing an assessment of effects on the environment-**

Subject to the provisions of any policy statement or plan, any person preparing an assessment of the effects on the environment should consider the following matters:

- (a) Any affect on those in the neighbourhood and, where relevant, the wider community including any socio-economic and cultural effects:
- (b) Any physical effect on the locality, including any landscape and visual effects:

- (c) Any effect on ecosystems, including effects on plants or animals and any physical disturbance of habitats in the vicinity:
- (d) Any effect on natural and physical resources having aesthetic, recreational, scientific, historical, spiritual, or cultural, or other special value for present or future generations:
- (e) Any discharge of contaminants into the environment, including any unreasonable emission of noise and options for the treatment and disposal of contaminants:
- (f) Any risk to the neighbourhood, the wider community, or the environment through natural hazards or the use of hazardous substances or hazardous installations.

**Appendix 8.3: Survey of aggregate extraction sites.**

**Survey : Lower North Island Aggregate Producers**

Please use a separate sheet for each extraction site

Company :

Address :

1. Location of extraction site (road and/or town)
  
2. Where is your aggregate sourced? (tick the correct box)

	now	in the future
river bed and/or banks		
land - river terraces		
hard rock quarry		
sea foreshore		
  
3. Who owns the land?

extraction company
private owner
the Crown
local or regional government
State owned enterprise
  
4. What size are the extraction and processing areas (1 acre = 0.4 hectares) **Please circle the measurement units you are using**

processing (plant) area	extraction area
hectares/acres	hectares/acres/km riverbed
1-5	
6-10	
11-15	
16-20	
>20	
  
5. How many years has the site operated?  
or in what year did extraction begin?
  
6. Were there any conditions imposed by the leasee?

yes	no	don't know
-----	----	------------

7. Was a licence or permit required?  
yes                      no                      don't know

**If you answered YES to question 7 please answer questions 8-10. If you answered NO to question 7 please go to question 11.**

8. Who was the licensing body? (Please tick the applicable box)  
local or district council  
regional council  
government department or State Owned Enterprise  
catchment board

9. What conditions were attached to mining?  
Please tick the applicable boxes or attach a photocopy of the planning or leasee's conditions.

a) general requirements

maximum extraction depth  
fencing  
maximum face heights and gradients  
sealing of access road  
infilling of mined areas  
silt traps or settling ponds

b) restoration or rehabilitation requirements

planting of trees and shrubs as screens  
spreading of imported soil  
spreading of stripped and stockpiled soil  
ripping  
sowing pasture  
preparation of a restoration plan  
other (please specify)

10. Who monitors these conditions?



**Questions 11-15 for land based aggregate sites and quarries only.**

11. What was the land used for before extraction began?  
cropping  
pasture  
horticulture  
unutilised land  
other (please specify)
  
12. What will the extraction area be used for when extraction has finished?
  
13. What will the plant area be used for when extraction has finished?
  
14. What determines what happens after extraction is completed?
  
15. Who would you use for advice on site restoration?  
yourself  
Mines Inspector  
District or regional council  
MAF (Ministry of Agriculture and Fisheries)  
private agricultural consultants  
other (please specify)

I am very interested in any further comments you have about land restoration or mining controls, monitoring, etc...

Thankyou very much for answering this survey.

The survey of aggregate sites was sent with a covering letter:

Dear Sir

**Survey : Lower North Island Aggregate Producers**

I am writing to ask if you would fill out the enclosed survey about your aggregate extraction site.

I am studying the restoration and the aggregate industry at Massey university, and gave a talk about compaction at last year's joint AA&IQ conference in Palmerston North.

Your answers will help my research project on restoration of aggregate mines.

A summary of the survey replies will be printed in the Quarry Institute and Aggregates Association newsletters in 1992. Your answers are confidential and no individual sites will be described.

Please fill in the survey and post it in the addressed envelope.

If you have any queries, please ring me. Thankyou very much for your help.

Yours sincerely

Robyn Simcock

Appendix 8.4 Alluvial Mining Standard Conditions and Restoration Schedule  
(Macleod and Rouse, 1991)

Schedule and plan at a scale of 1:10 000 giving restoration requirements for the licence:

A The areas marked A on the attached plan shall be rehabilitated to pasture as specified below unless an alternative vegetation type and standards are mutually agreed upon between the Inspector of Mines, licensee and landowner/occupier.

Where practical, all merchantable timber that has to be cleared for mining shall be stacked at a suitable pick-up point for the use of the owner of the timber.

Other logs and stumps shall be buried in the tailings or otherwise disposed of.

All soil shall be stripped and stockpiled in a secure manner ahead of mining operations.

If required by the Inspector of Mines after consultation with the landowner/occupier the soils shall be stripped, stockpiled and replaced in a specified order.

Fines are to be mixed with coarse tailings either before or during contouring.

Soil replacement on contoured tailings and all other disturbed areas must consist of sufficient suitable topsoil, subsoil or alternative material to support a productive vegetative cover that meets the intended post-development land capability and use.

All disturbed areas must be graded to contours that are compatible with the post mining land use and generally conform with surrounding topography, unless otherwise agreed upon between the landowner/occupier and the Inspector of Mines.

Where farming is the intended land use, the licensee shall take appropriate steps to prevent stones hindering farm operations and ensure adequate drainage is installed to prevent ponding.

The maximum slope of restored ground shall in general not exceed 12 degrees from the horizontal and the contours of the restored land shall permit proper drainage free from erosion.

As soon as practicable after soil replacement a vegetative cover may be required to be established that is compatible with the post mining land use to the satisfaction of the Inspector of Mines.

Any maintenance shall include such fertilisation, grazing control, erosion control, weed control, revegetation or other management as may be required by the Inspector of Mines.

Area Aa: [ ] stock units / hectare

Area Ab: [ ] stock units / hectare

Area Ac: [ ] stock units / hectare

B The areas marked B on the attached plan shall be rehabilitated to exotic tree plantation as specified below unless an alternative vegetation type and standards are mutually agreed upon between the Inspector of Mines, licensee and landowner/occupier.

Where practical, all merchantable timber that has to be cleared for mining shall be stacked at a suitable site for removal for the owner of the timber.

Other logs and stumps shall be buried in the tailings or otherwise disposed of.

All soil shall be stripped and stockpiled in a secure manner ahead of mining operations.

Fines are to be mixed with coarse tailings either before or during contouring.

Soil replacement on the contoured tailings and all other disturbed areas must consist of sufficient suitable soils or alternative material to support a productive vegetative cover that meets the intended post development land use.

All disturbed areas must be graded to contours that are compatible with the post mining land use and generally conform with surrounding topography, unless otherwise agreed upon between the landowner/occupier and the Inspector of Mines.

The maximum slope of restored ground shall in general not exceed 12 degrees from the horizontal, and the contours of the restored land shall permit proper drainage free from erosion.

As soon as practicable after soil replacement a vegetative cover may be required to be established that is compatible with the post mining land use to the satisfaction of the Inspector of Mines.

Any maintenance shall include such fertilisation, erosion control, weed control, revegetation or other management as may be required by the Inspector of Mines.

Area Ba:           Sowing with a cover crop of \_\_\_\_\_ or similar vegetation type, to prevent erosion, followed by planting with certified seedlings at \_\_\_\_\_ stems/hectare, with an 85% survival rate of trees with healthy vigour at one year after planting.

Area Bb:           Sowing with a cover crop of \_\_\_\_\_ to prevent erosion; followed by planting with certified seedlings at \_\_\_\_\_ stems/hectare, with an 85% survival rate of trees with healthy vigour at one year after planting.

C   The areas marked C on the attached plan shall be rehabilitated to indigenous forest as specified below unless an alternative vegetation type and standards are mutually agreed upon between the Inspector of Mines, licensee and landowner/occupier.

Where practical, all merchantable timber that has to be cleared for mining shall be stacked at a suitable site for removal for the owner of the timber.

Other logs and any stumps shall be buried in the tailings or otherwise disposed of.

All vegetation, forest debris and duff shall be stacked and respread with the topsoil.

All soil shall be stripped and stockpiled in a secure manner ahead of mining operations.

Fines are to be mixed with coarse tailings either before or during contouring.

Soil replacement on the contoured tailings and all other disturbed areas must consist of sufficient soils or alternative material to support a productive vegetative cover that meets the intended post development land use.

Tailings and overburden shall be returned to worked out areas and contoured to match surrounding ground levels. The top 1 metre shall consist of a mix of size fractions that will ensure free drainage with maximum fertility.

The maximum slope of restored ground shall in general not exceed 12 degrees from the horizontal, and the contours of the restored land shall permit proper drainage free from erosion.

As soon as practicable after soil replacement a vegetative cover must be established that is compatible with the post mining land use to the satisfaction of the Inspector of Mines.

Any maintenance shall include such fertilisation, erosion control, weed control, revegetation or other management as may be required by the Inspector of Mines.

Area Ca: (a) If required by the Inspector of Mines after consultation with the landowner/occupier all disturbed areas shall be sown with a cover/nurse crop of \_\_\_\_\_ or a similar vegetation type.

(b) Plant with \_\_\_\_\_ seedlings at \_\_\_\_\_ stems/hectare with an 85% survival rate of trees with healthy vigour at one year after planting.

Area Cb: (a) If required by the Inspector of Mines after consultation with the landowner/occupier all disturbed areas shall be sown with a cover/nurse crop of \_\_\_\_\_ or a similar vegetation type.

(b) Plant with \_\_\_\_\_ seedlings at \_\_\_\_\_ stems/hectare with an 85% survival rate of trees with healthy vigour at one year after planting.

D: The areas marked D on the attached plan shall be rehabilitated to ...

E The improvements shown on the attached plan shall be restored to the following standards: