WIND EROSION IN HAWKE'S BAY: THE INFLUENCE OF SOIL AGGREGATE SIZE AND CULTIVATION MANAGEMENT ON SEDIMENT FLUX

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"What now remains compared to what existed is like the skeleton of a sick man, all the fat and soft earth having wasted away, and only the bare framework of the land being left."

Plato describing effects of erosion in classical Greece (cited in Clark et al., 1985).

Abstract

The influence of soil aggregate size and cultivation management on sediment flux of two Hawke's Bay soils was investigated. Hawke's Bay Regional Council initiated, and partially funded, the project after they identified wind erosion as a significant land management issue in their region.

Wind erosion was simulated on Pakipaki sandy loam (Typic Sandy Recent Soil) and Takapau silt loam (Typic Orthic Allophanic Soil) soil types using a portable wind tunnel. Three different cultivation treatments were applied to research sites on each soil, with eight replicates of each treatment positioned via a split-plot, randomised block trial design. Treatments were designed to produce a range of soil aggregate size distributions. A minimum tillage treatment was also simulated. At each plot, surface (10 mm depth) soil samples were collected for gravimetric moisture content, soil aggregate size and aggregate stability tests. Surface roughness and vegetative cover were measured only on Takapau plots.

The Takapau silt loam plots were very susceptible to aggregate breakdown under cultivation, with only a quarter of soil aggregates over 0.85 mm in size after one pass with the cultivator. Two additional passes did not cause a significant change in aggregate size. Minimum tillage on the Takapau plots lead to markedly lower mean sediment flux rates (0.2 $gm^{-1}s^{-1}$) compared to one pass with a cultivator (3.4 $gm^{-1}s^{-1}$).

The Pakipaki sandy loam exhibited higher resistance to aggregate breakdown compared to Takapau silt loam. After one pass of the cultivator 50 percent of aggregates measured were over 0.85 mm in size, reducing to 45 and 43.3 percent after two and three passes respectively. Data collected from Pakipaki plots suggest decreasing soil aggregate size leads to increasing erosion rates. The relationship was not significant ($P<0.05$) primarily due to a high variance in results within treatments. Minimum tillage on the Pakipaki sandy loam also resulted in considerably lower mean sediment flux (0.03 $gm^{-1}s^{-1}$) than the least cultivated plots (1.8 $gm^{-1}s^{-1}$).

The results highlighted some important implications for cultivation management in Hawke's Bay. Use of conventional cultivation techniques on Takapau silt loam soils should be avoided due to the high risk of aggregate breakdown and the subsequent wind erosion risk. Minimum or no-tillage with maximum retention of vegetative residue is the most appropriate for continued arable farming on such soils. In comparison, soil structural characteristics of the Pakipaki sandy loam soil allow for greater manipulation of aggregate size through cultivation. However, the sediment flux measured off Pakipaki plots indicates other wind erosion control techniques, such as windbreaks and stubble retention, should be utilised in conjunction with maintenance of large aggregate size to adequately control soil wind erosion.

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1. INTRODUCTION

Wind erosion of soil is a natural event, which has influenced landscape formation in many parts of the world and across the ages. Movement of soil by the wind, particularly during arid climate phases, has contributed not only to 'loss' of soil in sediment source areas but also to soil formation in more humid downwind deposition zones (McTainsh & Leys, 1993). As with other soil erosion forms, wind erosion rates and spatial distribution have been influenced by anthropogenic land use activities. This somewhat diffuse form of land degradation is currently recognised as a major problem in the United States, Canada, Australia, India, Africa and the former USSR (Fryrear, 1990; Potter *et al.*, 1998).

Soil is an extremely important global resource, and effectively finite on a human time scale. Rates of soil formation vary depending upon climate and geology in particular, and the rate of 0.08mm/year constitutes rapid formation (McTainsh & Leys, 1993). When compared to wind erosion rates of up to 10mm/year in some areas (*ibid.*), the potential severity of wind erosion-induced land degradation is graphically illustrated.

Although small in comparison with arid areas of the world, wind erosion is a significant land degradation issue in specific regions of New Zealand. However, little research has been carried out on the topic in this country when compared to work into the rates, impacts, and control of water erosion, particularly in hill country pastoral systems. Previous investigations into wind erosion have primarily centred on the Canterbury Plains (Painter, 1977; Hunter & Lynn, 1988; Cresswell *et al.*, 1991). Hamish McGowan of Victoria University (pers. comm., 1999) is currently undertaking work into natural sediment flux in Central Otago.

The relative lack of wind erosion investigations reflects the proportionally lower land area affected by accelerated wind erosion. However, the smaller land area belies the true economic cost of the degradation, with predominantly high value arable areas being affected in Canterbury, Wairarapa and Hawke's Bay. In a review of wind erosion in New Zealand, Basher & Painter (1997) identified the need for research quantifying wind erosion rates and impacts in this country, in addition to investigations in to the importance of resultant nutrient and productivity losses.

There is limited quantitative information concerning wind erosion in Hawke's Bay. In order to implement effective wind erosion control methods a more detailed understanding of the processes involved is required. This is particularly pertinent for the Hawke's Bay Regional Council (HBRC) who, through their policy approaches, are responsible for promoting sustainable land management in the Hawke's Bay region. Policy decisions are often based on imperfect knowledge of both societal and biophysical factors, and this holds true for many regional authorities who lack the financial base to fund numerous, sometimes expensive, research initiatives. The HBRC has identified wind erosion as an issue, which they require detailed scientific information on. While they have been, and still are, making policy decisions in this area, they have undertaken to improve the current level of information that exists on specific aspects of wind erosion in the region.

The purpose of this research is to provide the HBRC with sound scientific information on an aspect of wind erosion in their region, to aid in the Council's decision making and policy formulation process. The importance of obtaining such information will be outlined in the following literature review. While similar studies have been carried out internationally, the site specific nature of wind erosion means that results found in such previous reports are not directly applicable to Hawke's Bay, and therefore this project is extremely relevant and worthwhile.

1.1 PROBLEM STATEMENT

The Hawke's Bay Regional Council lacks sound scientific data on which to base its recommendations for appropriate management of soils prone to wind erosion.

1.2 OBJECTIVES

Objective 1: Investigate the effect of different cultivation practices on wind erodibility of selected Hawke's Bay soils.

Objective 2: Investigate the specific influence of soil aggregate size on sediment flux of cultivated soils.

Objective 3: Discuss implications for management of cultivation to reduce wind erosion in Hawke's Bay.

1.3 IMPORTANCE OF RESEARCH

The findings and implications of this project will be of primary importance to the HBRC and to land users on fine-textured, low-density soils in Hawke's Bay. The data will add to information held by the Council on the subject, and therefore aid in the formulation and implementation of sustainable land management policy and advice to land users. Practical implications discussed in this thesis will be of direct relevance to specific land use practices of arable land users in the region.

The recommendations drawn from this research will also be useful in other wind erosion-prone areas of New Zealand, and for the respective Regional Councils responsible for sustainable land management in those areas.

1.4 OUTLINE OF THESIS

This thesis will follow the a standard report writing structure:

1. Introduction – will provide the reader with a background into the subject, defining the problem statement and research objectives.

2. Literature review – building on the knowledge base of previous work on this subject by the author, the review will outline why wind erosion is a concern, internationally, nationally and specifically in Hawke's Bay. The processes and impacts of wind erosion will be described, as will the importance of soil aggregate size and cultivation management. A review of relevant prior research approaches in this topic will explain the adoption of the methodology in the next section. Possible erosion control techniques, encountered via the literature review process, will be integrated into the later discussion section.

3. Methodology – from the literature review, knowledge of available time, money and equipment, and requirements of the research objectives, the methods adopted will be outlined.

4. Results – the pertinent results from the research will be presented.

5. Discussion – results will be discussed in relation to previous findings and their implications for land users in Hawke's Bay. The effectiveness of the methods used will also be discussed.

6. Conclusions – the main conclusions drawn from the research will be stated.

2. LITERATURE REVIEW

2.1 INTRODUCTION

The following section outlines why the influence of soil aggregate size on wind erosion rates in Hawke's Bay is a topic worthy of a Masterate investigation. Initially, the importance of wind erosion internationally, nationally, and in Hawke's Bay itself is summarised. The possible impacts of this form of erosion are identified and the physical processes involved are explained. The roles of cultivation and soil aggregate size are addressed and previous research approaches relevant to this work are specified.

This project constitutes the final year of a two-year investigation, which began with an Honours research project. Some of the information addressed in this review is also discussed in the 1998 project, for example the processes involved in wind erosion. However, to ensure this thesis is a stand-alone document it has been summarised again to provide the reader with the appropriate background knowledge to be able to understand the remainder of this section and the subsequent methodology adopted. As would be expected, this years work is in more detail and explores new aspects of the wind erosion issue, for example the role of cultivation.

Note: (a) See glossary for explanation of technical terms.
(b) Unless otherwise stated, *erosion* refers to *wind erosion*.

2.2 THE WIND EROSION ISSUE

2.2.1 Wind erosion globally

The geomorphologic process of wind erosion affects the entire globe (Pietersma *et al.*, 1996; Lopez, 1998). It is a natural phenomenon which can greatly reduce the life-supporting capacity of sediment source areas, act to form new landscapes, enhance aquatic life in the worlds ocean through deposition of nutrient-rich dust, and even influence global weather patterns (Fryrear, 1990). The sediment transport capacity of wind is less than that of water, but the relentless movement of air over the earth's surface and the potential ability of wind to erode soil on any slope highlight the degradation potential of wind erosion. In the United States, soil moved by wind erosion is approximately equivalent to one-quarter the annual sediment load of water erosion, but its impact on cropland is intensified because its impact on semiarid regions is proportionally more severe (Fryrear, 1984).

Arid soils are most vulnerable to wind erosion, and comprise 31.5 percent of earth's total land area (Fryrear, 1990). The distribution of the worlds arid regions is shown in Table 2.2.1. Australia has the highest percentage of arid soils by landmass, with Europe having the least. Arid land is not exclusively affected by wind erosion, as high winds in humid regions can also cause soil movement.

Table 2.2.1: Distribution of arid-region soils by continent (excluding Polar Regions)

	Arid-region soils	
Continent	Area in sq. km	Percent of continent
Africa	17,660	59.2
Asia	14,405	33.0
Australia	6,250	82.1
Europe	644	6.6
North America	4,355	18.0
South America	2,835	16.2
Total	46,149	

Source: Dregne, 1976 (cited in Fryrear, 1990)

Wind erosion has been recognised as an issue for centuries. In the 1790s Deane published the first accounts of the wind erosion problem in the United States (cited in Fryrear, 1990). Pioneering work into the actual wind erosion processes was carried out between the 1930s and 1950s, stimulated by the extensive wind erosion problems suffered on the Great Plains of the U.S. in the 1930s (Pietersma *et al.*, 1996). The dramatic 'dust-bowl' conditions seen in the mid-West U.S. during this decade produced enduring images of devastated crops, buried houses and ruined farms (*ibid.*).

Early wind erosion research was concentrated on the movement of sand sized particles, and it wasn't until major drought conditions in the US and Canada in the 1970s induced significant wind erosion that the focus shifted to mechanics of suspended sediment transport (Nickling, 1978).

2.2.2 Wind erosion in New Zealand

Wind erosion in New Zealand might not be as dramatic and widespread as in arid-regions of the world, but it has played an important role in the formation of soils and landscapes in this country (McLaren & Cameron, 1990). Prior to human deforestation, it predominantly took the form of loess derived from riverbeds and coastal plains (Basher & Painter, 1997). Human activities have induced accelerated erosion on dry pastoral land and arable areas.

Wind erosion differs in form and significance throughout New Zealand. According to Eyles (1983) wind erosion is very localised in the North Island and occurs in three main areas:

- Areas of dune sands (32 percent of wind erosion in the North Island);
- Ash covered slopes over 700 metres above sea level;
- Argillite hill and terrace country on the eastern side of southern Hawke's Bay (including the Heretaunga Plains) and Wairarapa.

In the South Island wind erosion is more widely distributed in lower rainfall areas with dominant rock types of loess, alluvium, schist and greywacke. Salter (1984: cited in Basher and Painter, 1997) identified the following areas commonly associated with South Island wind erosion:

- Alluvial plains in Canterbury, Marlborough and Southland – most vulnerable when cultivated;
- Loess-covered Canterbury and North Otago downlands – vulnerable when cultivated;
- Inland loess-covered basins of Canterbury, Otago and Southland – exacerbated by poor vegetation cover due to sheep and rabbit grazing;
- Mountain land, with summer moisture deficiency, in Canterbury, Otago, and Marlborough – also exacerbated by low vegetation cover;
- Shallow hill country soils with severe moisture deficiencies in summer in North Canterbury;
- Exposed rolling uplands of Otago after significant vegetation removal.

Extreme wind erosion potential exists in the coastal sand dunes areas and the Rangipo Desert (*ibid.*). In total, the Land Resource Inventory worksheets identify approximately wind erosion to be present on 4.6 percent of land in the North Island, compared to 19 percent in the South Island.

Wind erosion on arable land occurs when a dry, disturbed soil surface coincides with strong winds. Although most of New Zealand's cropping soils are susceptible in this condition (Basher & Painter,

1997) wind erosion is primarily significant in two regions, Canterbury and Hawke's Bay. Although occurring on significantly different soil types, the common thread between the two vulnerable areas is the fact that cultivation techniques and whole-farm management is the key to reducing erosion rates.

The Hawke's Bay Regional Council (HBRC) have signalled their intent to address the issue in their region, instigating a broad wind erosion management program, of which this project forms a part. In Canterbury, the Regional Council have also undertaken to increase their knowledge, and therefore improve their quality of advice provision, with a commitment to research similar to this project in the coming year.

2.2.3 Wind erosion in Hawke's Bay

a) History

Wind erosion has been recognised as a regionally significant issue for many decades, and is identified as a significant issue in the Hawke's Bay state of the environment report (HBRC, 1997). Incidences of accelerated erosion occurred soon after European settlement, however there are few historical records of wind erosion events, with knowledge predominantly held in the memory of local residents (Bayliss, 1975; Hilson, 1976; Boyd, 1984).

The magnitude of the few recorded examples of wind erosion in Hawke's Bay provide a testament to the vulnerability of some soils in the region. Pohlen *et al.*, (1947) observed wind erosion strip the topsoil from a bare, cultivated field in the Willowford/Blowhard area. At this site wind and sheet erosion combined to remove 90 cm of topsoil, down to the parent material. In the Esk Valley, Campbell (1948) recorded removal of up to 60 cm of sandy silt in a one-year period. Such mass of movement is verified by a local pedologist who estimates that wheat growing practices on the Ruataniwha Plains in the 1860s initiated the erosion of up to 60 cm of topsoil (Griffiths pers. comm., 1998). The Takapau soils in that district, similar to those investigated in this study, can have as little as 30 cm regolith before the gravel base is uncovered (Griffiths, 1997).

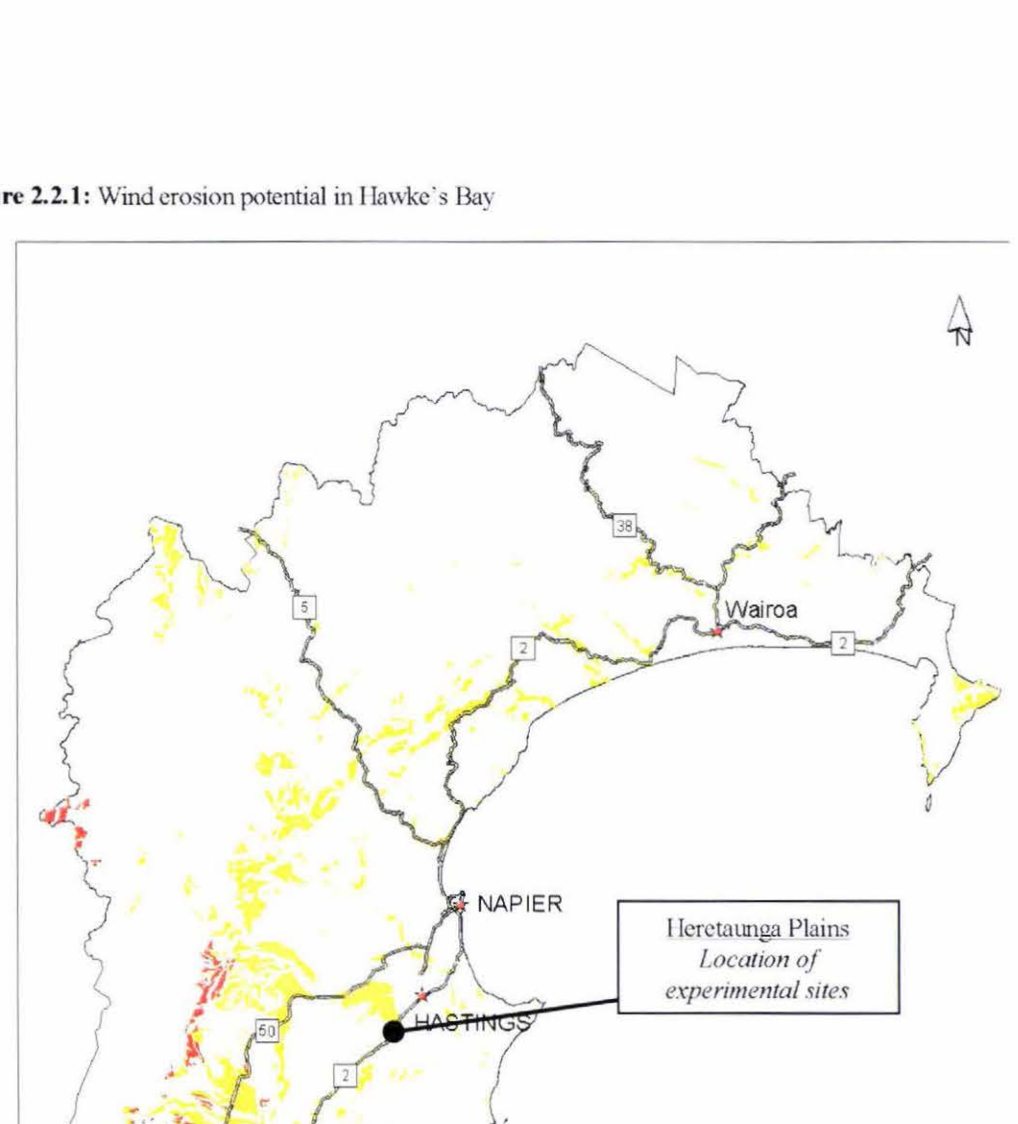
The alluvial sand, pumice, volcanic ash and peat-based soils have been classified as the most vulnerable to wind erosion in Hawke's Bay. They occur predominantly on the Heretaunga and Ruataniwha Plains, and in the foothills on the regions western boundary. Over 112,000 ha of arable land in Hawke's Bay is considered susceptible to erosion when cultivated (Figure 2.2.1). Current intensive land use practices on the Heretaunga Plains have focussed attention on the potential for wind erosion. Soil characteristics on these Plains have been strongly influenced by the Tutaekuri and Ngaruroro Rivers which used to flood regularly, depositing greywacke alluvium and redistributing volcanic materials (Molloy, 1988). The depth and fineness of alluvium deposited determines soil physical properties, and is consequently a factor determining the erodibility of soils throughout the Plains.

The Heretaunga Plains commonly experience strong winds during the spring equinoxal period of October to December. This timing coincides with the spring cultivation period, when bare soil surfaces are left exposed, often for a period of over 4 weeks. Winds from the north to northwest are the most erosive, because they are hot and dry and have high evaporative energy to remove moisture from the soil surface (Faulknor, 1985). During the 1996 equinox, gales reached speeds of 125 kmh^{-1}, causing widespread soil loss from recently cultivated land (Brennan pers. comm., 1998). At Napier airport, northeast of the Heretaunga Plains, gusts of 95 kmh^{-1} are recorded on average one day every two and a half years (Ministry of Works, 1971).

The erosivity of wind run in the region has long been recognised. Seven separate wind erosion control schemes operated in the 1980s, focussing on shelterbelt plantings and administered by the former Hawke's Bay Catchment Board. A scheme in the Mangleton-Kereru area covered 18,000 ha, encompassing 30 properties and comprising over 47 km of windbreaks. Prior to 1983 'Wind erosion hazard zones' were defined and assistance limited to these areas (Cairns *et al.*, 1983). The HBRC currently operates a windbreak-planting scheme, which includes some financial assistance. The grant is up to 50 percent of total cost and must be on a soil identified as having severe or extreme risk of wind erosion under cultivation, and applies only to shelterbelt plantings (Bloomer pers. comm., 2000)

Land use change in the Heretaunga Plains has amplified the risk of wind erosion. Vulnerable soils were predominantly in pastoral agriculture up to two decades ago, with organic matter return and maintenance of a vegetative cover minimising erosion rates. Recently, the combined pressures of urban expansion in Hastings and Havelock North, the growth of permanent horticulture, and economic requirements for intensive land use have lead to increased arable production on the previously pastoral areas (Brennan pers. comm., 1998). Economic factors have also affected crop rotation patterns, with land experiencing less time in a restorative pastoral phase, if in fact it occurs at all.

Figure 2.2.1: Wind erosion potential in Hawke's Bay



DATA FROM: Wind erosion information derived from Landcare Research NZ Ltd, New Zealand Land Resource Inventory computer archive. Landcare Research NZ Ltd New Zealand Ltd, Private Bag 11052, Palmerston North.

ARABLE LAND (LUC 1 - 4) PRONE TO WIND EROSION IN THE HAWKE'S BAY REGION WHEN UNDER CULTIVATION

b) Wind erosion management roles

The impacts from wind erosion are of concern to not only individual landusers but also to the community as a whole. While the HBRC may have the statutory obligation to promote sustainable use of natural and physical resources in the region, organisations such as landuser associations and arable industries also have a role to play in researching and promoting wind erosion processes and control.

The existence of a problem must be recognised by individual land users before wind erosion control methods will be successfully implemented. A small study by Eastwood (1998) investigated the perceptions of Hawke's Bay land users toward wind erosion and found that although land users might admit to wind erosion being an issue regionally, they did not consider it a problem on their own properties. Such a dichotomy has been noted in international studies where landusers may not know or want to acknowledge that they have a problem, and that 'the other guy down the road has a problem, I don't' (Nowak, 1982: cited in Parminter, 1994).

Increasing awareness of the issue requires a community-wide approach. A current community initiative, LandWise, aims to improve the sustainability of cropping in Hawke's Bay by addressing specific arable land management issues, including wind erosion, through facilitation of research and technology transfer. It encourages and facilitates links between growers, industry, government, researchers and other organisations. Participants currently include growers, food processors, researchers and the HBRC (HortNet, 2000). While the initiative was primarily instigated by the HBRC, the Council intends to take a 'back seat' in the direction of the group, providing some financial and administrative support.

The HBRC currently employs a non-regulatory approach to wind erosion control. Advice provision and information dissemination forms the basis of this approach, with field days and trials commonly utilised. Reliance on non-regulatory methods requires a sound knowledge of the specific processes involved with wind erosion and its control as they pertain to the region, in addition to a favourable community attitude toward land management staff.

2.3 WIND EROSION PROCESSES

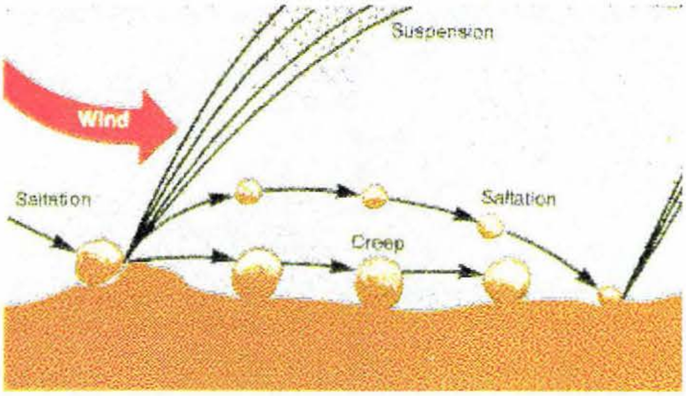
Given that land degradation on a large scale can occur due to wind erosion, what are the processes by which it operates, and what are the factors that exacerbate its impact? Wind velocity and air turbulence provide the necessary energy to initiate and maintain movement of soil particles (Nickling, 1978). The amount of energy required to entrain the soil particles will depend on the specific nature of the soil-air interface, therefore entrainment will begin when the force of the wind exceeds the combined effect of particle weight and cohesion between adjacent particles (Lancaster *et al.*, 1994).

Wind erosion has important spatial and temporal characteristics. Spatially, in an open field of similar soil characteristics, erosion increases in the direction of the wind. This is predominantly caused by the cascading effect of saltating particles described in section 2.3.2. Soil surface conditions also change over time *during* a wind erosion event through processes such as abrasion and breakdown of surface crusts and aggregates.

2.3.1 Transport modes

Soil entrained by wind is moved in one of three modes, creep, saltation or suspension, depending upon particle size and density. In general the particle diameters of soil in each transport mode is 0.5 to 2mm for creep, 0.05 to 0.5 mm for saltation, and less than 0.1 mm for suspension (Sterk & Raats, 1996; McTainsh & Leys, 1993). At the transition of two modes some particles may be moved by both transport forms, depending on the wind velocity and particle density (Sterk *et al.*, 1996). The overlap in size range for saltation and suspension recognises that such a categorisation is only arbitrary because the vertical distribution of eroded soil resembles a continuum. Supporting this statement, Scott (1995) suggests that there is no distinct saltation layer, and that saltation is not distinctly different from suspension. However, international literature predominantly uses a particle size distinction as listed above.

Figure 2.3.1: Wind erosion transport modes.



Source: http://soils.ecn.purdue.edu/~wepphtml/wepp/wepptut/jhtml/wndersn.html

Saltation is generally recognised as being the primary mode of soil movement, accounting for 50 to 75 percent of wind eroded mass (Haynes, 1995). Particles move via this mode are lifted vertically (10 to 50 cm height) by wind gusts, moving horizontally up to one metre (Painter, 1978). Each saltating grain impacting the surface supplies enough energy to break cohesive forces between stationary particles on the surface, ejecting between three to ten additional grains or aggregates into the air (Shao *et al.*, 1993). A subsequent cascading effect is produced, with erosion increasing across a field until the carrying capacity of the airflow is reached (Nicholas & Kemp, 1995). The bombardment of surface aggregates by saltating particles can also cause abrasion, where the impacting grains break off pieces of the surface aggregates increasing the proportion of fine, erodible particles in the surface layer. The importance of saltation as a component of wind erosion is acknowledged by Shao *et al.* (1993) who identify bombardment of the surface by saltating sand grains as the primary mechanism responsible for suspended sediment entrainment.

Small particles move via *suspension* in the wind stream and can be carried for considerable distances (Wethey, 1984). This form of transport may account for approximately 15 percent of total wind erosion but can be of higher relative significance due to the high nutrient holding capacity of such small particles, and the fact that they are generally moved off-site. There are three major sources of the suspended wind erosion component: direct emission of loose suspension-size material, abrasion from clods or surface crusts, and breakdown of saltating aggregates (Mirzamostafa, 1998).

Surface creep involves particles rolling or sliding across a surface, with the potential to 'burn' or bruise crop seedlings. This transport mode represents between 2 to 25 percent of total wind erosion (Haynes, 1995; Nickling, 1978).

2.3.2 Effect of field length

There are two mechanisms that influence the development of erosion as wind moves across a field. The first is an aerodynamic feedback mechanism, where some of the wind energy is transferred to saltating particles (Gillette *et al.*, 1988). This energy transfer lowers the wind velocity at the soil surface, also lowering the erosivity of the wind. The wind velocity and eroding soil interact until at some point downwind equilibrium is reached (*ibid.*). The second mechanism was alluded to above, where sandblasting by upwind saltation acts to lower the erosion threshold further downwind by transfer of energy on impact (*ibid.*).

2.3.3 Vertical distribution

Sterk *et al.* (1996) found that the horizontal mass flux of wind eroded soil decreases strongly with height. From ground level to 0.15 m height saltation is the dominant sediment transport mode, from 0.15 to 0.85 m saltation and suspension both play a significant role, and from 0.85 to 1 m suspension is dominant (*ibid.*). Overall, the majority of sediment flux occurs relatively close to the soil surface, below 0.3 metre Fryrear *et al.* (1991).

2.3.4 Factors influencing vulnerability

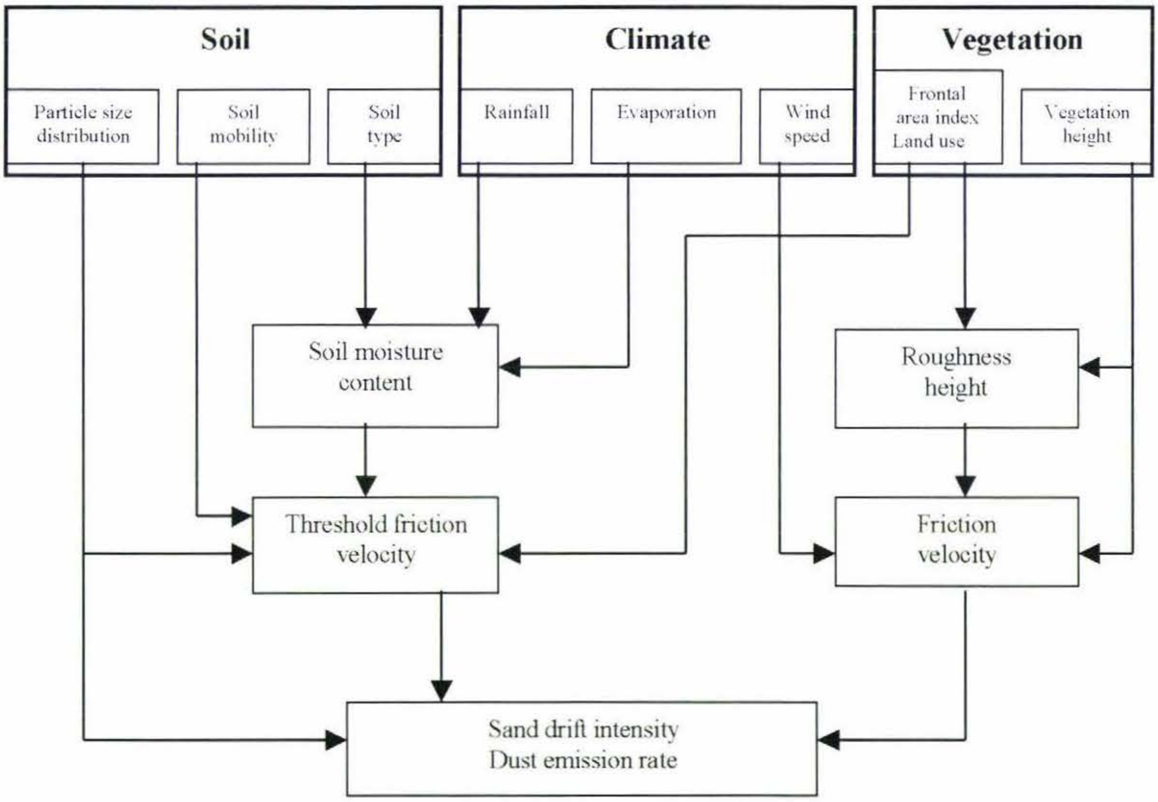
Climatic, soil physical, topographical, and managerial factors all influence wind erosion vulnerability of soil. A good understanding of these aspects is integral in aiding development and adoption of on-farm erosion control techniques. Wind is the major climatic factor to consider but the bombarding effect of rain upon an exposed soil surface also plays a role, as does freeze-thaw and wet-dry cycles in some regions. Important soil properties include aggregate size distribution and aggregate stability, surface roughness, and soil moisture content. Land management can act to exacerbate or diminish the risk of wind erosion, through manipulation of the climatic and soil physical aspects.

Leys & Raupach (1991) summarised the key factors in the following general relationship:

> Wind erosion = spatial location (erosion, transport, or deposition zone) + previous management + climatic and erosion processes.

Shao *et al.* (1994) also summed up the processes involved in wind erosion in a wind erosion assessment model. It shows the influences that soil, climate and vegetation have over erosion. When combined with GIS, and input of sufficiently detailed data, the model allows for quantitative and spatially detailed assessment of wind erosion.

Figure 2.3.2: Australian wind erosion assessment model.



Adapted from Shao *et al.* (1994).

a) Wind flow characteristics

Wind is obviously a primary contributing factor in the wind erosion process, providing the energy to move soil particles. Velocity and turbulence of the wind flow across a soil surface act to define the critical point at which entrainment begins. Frictional interactions at the soil surface/air interface modify the wind speed and turbulent structure in a dynamic fashion, changing throughout the erosion event (McTainsh & Leys, 1993). 'Friction velocity' is a measure of the drag produced as wind passes over the soil surface (*ibid.*). Both wind speed and surface roughness influence friction velocity, for example as surface roughness increases there is also an increase in the friction velocity.

Painter (1978) calculated the erosivity values for regions throughout New Zealand. Hawke's Bay was not covered due to lack of appropriate recording sites. Average erosivity was significantly higher than values calculated for the U.S.. However, wind erosion is less significant in scale and frequency in this country. This is due to the greater influence of soil moisture in New Zealand's temperate climate (Basher & Painter, 1997). The evaporative energy supply of the wind is therefore important because it acts to remove the surface moisture from the soil. Northwesterly foehn winds, common in Canterbury and Hawke's Bay, have high evaporative potential and can rapidly change a soil from a moist erosion-resistant state to a vulnerable dry surface.

When air moves over a rough surface, a turbulent flow is created. The surface creates a frictional drag, slowing the wind speed moving across it, forming what is termed the boundary layer. Where the drag effects with the surface become negligible and velocity is constant with height it is termed the freestream (Nickling, 1995). Once erosion begins, the entrained particles extract momentum from the airflow, transferring it to the surface on impact. This significantly alters the wind profile near the soil surface, slowing the wind velocity and influencing boundary layer development. The subsequent effect on wind tunnel operation is discussed in section 2.6.1 below.

b) Threshold velocity

The energy required to initiate and maintain soil movement is greatly influenced by soil physical characteristics and land management practices, which combine to produce specific soil surfaces. Soil entrainment begins when the drag and lift forces of the wind exceed the gravity and cohesion forces at the soil surface, known as the *threshold velocity* (McTainsh & Leys, 1993). Nicholas & Kemp (1995) identify the threshold for erodible soils to be from 19.3 to 24.1 kmh^{-1} (5.4 - 6.7 ms^{-1}). In contrast McLaren & Cameron (1990) state that velocities must exceed 30 kmh^{-1} (8.3 ms^{-1}) for particle movement to begin. Threshold velocity is soil and site specific, with many factors able to influence the actual point of entrainment and therefore no single wind velocity can be quoted as a definitive threshold for all soil types. Achieving a detailed knowledge of wind erosion in any region, including Hawke's Bay requires adaptation of previous research findings to integrate the specific characteristics of the region.

c) Soil moisture

Soil moisture levels of the erodible layer have a large effect on the susceptibility of a soil to wind erosion (Saleh & Fryrear, 1995). Generally, as soil water content increases there is an associated decrease in erosion potential (*ibid.*). This is because when a film of water surrounds soil particles, the cohesive forces between particles are strengthened and more energy is required to begin entrainment (Cresswell, 1990). A 'critical water content' exists above which erosion is very unlikely to occur, similar in theory to the critical particle size discussed below. This critical value is determined by the specific characteristics of an area. Such dependence on site specific factors has meant that little definitive research is available to determine the actual water content at which soils will not erode. Gravimetric moisture contents of approximately 0.6 percent can more than double the threshold velocity of medium sized sand grains when compared the dry state (Lancaster *et al.*, 1994). At moisture contents exceeding five percent such sand grains become very resistant to erosion by most natural winds (*ibid.*). It is not possible to extrapolate such findings to aggregated mineral soils such as in Hawke's Bay. Although wind tunnel experiments on agricultural soils have indicated an exponential relationship between increases in moisture content and threshold velocity (Azizov, 1977: cited in Lancaster *et al.*, 1994) research is still required in this area before specific values can be stated.

The moisture content of the erodible layer, less than 30 mm depth, is of primary importance for wind erosion. The ability to measure the moisture content of this layer would be very useful for classification of real-time erosion vulnerability. However, due to the shallow depth, rapid soil moisture measurement using Time Delay Reflectometry or neutron probe methods is not applicable and more time-consuming gravimetric and volumetric sampling is required (Scotter pers. comm., 1998; Nickling, 1978). Subsequently, using moisture content as an indicator to guide wind erosion management techniques, for example when to safely cultivate, is largely impractical with current technology.

Rain often carries some of the fine particles downward, leaving coarse particles at the top (Hagen *et al.*, 1988). However, small rain showers can accelerate erosion rates by smoothing the soil surface and loosening some of the aggregates making the field more vulnerable when it dries again (*ibid.*). Dust storm frequencies increase with decreasing rainfall to about 200mm/year then decrease below that because those areas have already been stripped of their sediment supply, however alluvial areas such as on the Heretaunga Plains do not follow this rule because their sediment supply is replenished (McTainsh & Leys, 1993).

d) Soil aggregate size

The influence of soil aggregate size on wind erosion rates has been the focus of many international studies (Chepil 1950, 1951; Leys & Raupach, 1991). Soil structure is probably one of the most important influences on soil erodibility (Leys & Raupach, 1991; Larney & Bullock, 1994). Logically, increasing aggregate size and mass relates to an increasing energy requirement to move individual aggregates. Researchers have identified a critical particle diameter of 0.84 mm, greater than which aggregates are generally considered non-erodible by wind (Chepil, 1950; Zobeck, 1991). The usefulness of such a threshold occurs at a field scale, rather than in relation to individual particles. Depending upon specific soil characteristics, the proportion of aggregates greater than the threshold size can provide a guide to a fields erodibility. For example Davies & Payne (1988: cited in Haynes, 1995) suggest that soils with >60 percent of particles in the 0.1 to 0.5 mm diameter range are very susceptible to wind erosion, while those with <40 percent of particles in the same range do not erode easily.

The low density of the volcanic soils most vulnerable to wind erosion in Hawke's Bay influences the critical aggregate size. The erosion threshold velocity will be lower on such soils when compared to mineral soils of similar structure, or alternatively, aggregates need to be comparatively larger in size to have the same resistance to entrainment. Many New Zealand soils have a low proportion of aggregates larger than 0.84 mm, due to low clay content and weak soil structure (Basher & Painter, 1997).

Soil aggregation can be influenced by many factors. Soil texture, $CaCO_3$ content, and organic matter content have an effect on aggregate size distribution (Zobeck *et al.*, 1990). Although not directly applicable to Hawke's Bay, weather-related phenomena such as freezing and thawing and snow depth can lead to temporal variations in aggregate sizes (*ibid.*). Cultivation can also have a significant effect on soil aggregation levels, as discussed in section 2.5.

Aggregate size distribution of the soil surface is pertinent when discussing the influence that aggregate size has on wind erosion rates, because it is the immediate topsoil that interacts with the wind flow.

Therefore, when attempting to relate sediment flux to aggregate size the top 10 to 25 mm is the relevant depth to sample (Nickling, 1978; Lopez *et al.*, 1997; Mirzamostafa., 1998).

e) Vegetation

The presence of roughness elements, such as vegetation and crop residues, acts to absorb some of the force of the wind and slow its velocity over a soil surface, in addition to acting to bind soil aggregates (McTainsh & Leys, 1993). On a larger scale, wind breaks and barriers can obstruct the path of the wind flow reducing the erosive energy of the wind through frictional losses (*ibid.*). Wind erosion control through use of vegetation can therefore take the form of windbreaks, stubble mulches and surface residues, or strip crops (Nicholas & Kemp, 1995).

f) Additional factors

Stability of soil aggregates influences their resistance to structural breakdown through abrasion and crushing. Soils with weak aggregates are generally most susceptible to wind erosion because the aggregates fracture easily and break into small sizes (Hagen *et al.*, 1988). Rainfall or irrigation can act to break down weak aggregates near the soil surface, sometimes resulting in the formation of a crust. This is important in Hawke's Bay where the peat, pumice and ash-based soil types of the Heretaunga Plains are of low structural strength (Eastwood, 1999). Soil stability is derived from both cohesive strength and internal friction (McLaren & Cameron, 1990). Soils formed in volcanic ash, such as the Takapau silt loam have lower cohesion than soils with predominantly crystalline clay, leading to a greater susceptibility to aggregate breakdown through inappropriate tillage techniques. Saltating particles bouncing along a soil surface during erosion can cause abrasion of other aggregates, leading to a cumulative increase in erosion rates across a field (Painter, 1972; Zobeck, 1991).

Soil texture can also be an important factor determining wind erodibility. For example, Chepil (1955: cited in Skidmore & Layton, 1992) found that soils containing 20 to 35 percent clay were least erodible, and that erosion rates increased in soils with clay content higher and lower than this range. Soil density also effects erodibility, but varies between soils less than factors such as aggregate stability and size distribution (*ibid.*).

Surface roughness as a component of wind erosion vulnerability presents a double-edged sword situation. The smoother the surface is, the less turbulence will be created, reducing erosion potential. However, the smoother the surface is, the less resistance the wind travelling near the surface faces due to lower friction therefore maintains a higher velocity and relative erosivity. Roughening the surface by tillage will usually reduce soil erosion (Saleh, 1994). Roughness is influenced by the size of soil aggregates, the presence of vegetation, the presence of other friction-creating elements – all of which can be influence by management techniques.

2.4 IMPACTS OF WIND EROSION

2.4.1 Physical

Wind erosion can have wide-ranging and irreversible effects on the soil resource, and therefore on soil productivity, depending on the size and frequency of events. As previously discussed, wind erosion can cause global impacts but the most significant effects are on a more localised scale. Removal of the immediate topsoil carries away the more fertile soil fraction (McTainsh & Leys, 1993). The soil remaining also has depleted nutrient content, infiltration rates, aggregate structure, water holding capacity, and potential rooting depth. Crops can be damaged through saltating particles in particular and suspended particles can be adverse to human and animal health, permeating buildings and machinery and also potentially carrying pesticides for long distances (Nanney *et al.*, 1993).

In comparison to water erosion, the wind erosion process is more 'particle selective' and causes a winnowing effect, primarily removing fine particles and organic matter (Cresswell, 1990). Miles & McTainsh (1994) showed that the particle sizes of wind eroded sediments are finer than the source soil. Therefore, if wind erosion continues to occur on that site the soil will become increasingly sandier, with a related reduction in water and nutrient holding capacity. Water-eroded sediments do not show this trend, with similar particle sizes in the eroded sediment and source soil.

Nutrient loss from wind erosion is predominantly attributed to losses through suspension of fine particles (Zobeck & Fryrear, 1986; Leys & McTainsh, 1994; Sterk *et al.*, 1996). Suspension carries the soil beyond property boundaries resulting in a net loss, also removing relatively high concentrations of nutrients since the nutrients are preferentially attached to fine particles (approximately <100 μm diameter) (Young *et al.*, 1985; Shao *et al.*, 1994). Similarly, wind erosion preferentially removes the nutrient-rich organic matter and clay due to their low particle density and small particle size respectively (Lal, 1988).

In a sandy, silicious Nigerian soil, Sterk *et al.* (1996) observed differences in the total element contents (K, C, N, and P) of vertically distributed wind-blown particles. Soil trapped 0.05 m above the surface had a nutrient content similar to that of the topsoil, whereas at 0.50 m the nutrient content was three times richer. Sediment deposited at 2 m height was found to be 17 times richer. In terms of total mass flux, the amount of nutrients moved in the saltation layer was an order of magnitude greater than that of the suspended flux measured. The suspension layer extends to greater heights, and while saltation only results in a local redistribution of soil (often against a fence or windbreak!) suspended dust can move thousands of kilometres, resulting in a regional, or in New Zealand's case national, nutrient loss (*ibid.*). An illustration of such movement is the example quoted by Knight *et al.* (1995) where traces of soil from an Australian dust storm was deposited on the Southern Alps in New Zealand!

2.4.2 Economic

Wind erosion creates two types of costs: on-site and off-site. On-site costs primarily concern impacts on soil and crop productivity (Piper, 1989). Particulate-related damages constitute the off-site component, and include increased cleaning and maintenance costs for downwind businesses and households, damages to non-farm machinery, and adverse health impacts (*ibid.*). The off-site damages are larger than on-site in the United States, however this may not be the case in New Zealand where dust clouds are smaller in size and are often isolated to individual paddocks.

Many of the impacts from wind erosion are of a long-term nature and involve complicated non-market values, for example the loss of actual soil volume, that are difficult to assign a monetary value to. In contemporary society justification for implementing wind erosion mitigation techniques is primarily required in monetary terms, rarely undertaken in New Zealand (Basher & Painter, 1997). The most common valuation approach used to measure the damage resulting from wind erosion is to simply value the loss of nutrients in the eroded fraction. Shearer (1982: cited in Cresswell, 1990) provided the value of nutrients moved in 100 tonnes of eroded soil, based on Hakataramea Valley (South Island, NZ) soil types. The cost of restoring the nutrient loss was estimated to be in excess of $1100 per hectare, in 1990 terms.

In New Zealand there is limited information on wind erosion rates. Painter (1978) measured actual erosion rates from a cultivated paddock in Canterbury, NZ, with mast-mounted traps. Background losses amounted to 200 $kgha^{-1}yr^{-1}$, with up to 40 $kgha^{-1}min^{-1}$ being lost in single events. Hunter and Lynn

(1988: cited in Basher & Painter, 1997) measured sediment deposited on a paddock edge after an erosion event. At least 70 tha^{-1} was lost during a two-day period where a fine tilth and low soil moisture combined with strong winds. Similar conditions existed during a 1945 wind erosion event, where wind gusted to over 144 kmh^{-1} (40ms^{-1}) (*ibid.*). The average depth lost from a 6.1 ha paddock analysed was 25 cm, equivalent to 3125 tha^{-1} of soil eroded. Caesium-137 has been utilised in several studies to provide indirect estimates of historical erosion rates (*ibid.*).

2.5 CULTIVATION AND WIND EROSION

Intensive cultivation can induce degradation of physical soil characteristics, causing associated land management problems, including increased wind erosion potential. In a Canterbury, New Zealand, study on a silt loam susceptible to wind erosion, Cresswell (1991) found that multiple pass tillage operations can significantly affect soil aggregate size distribution, aggregate stability index, random surface roughness and dry bulk density. When dry soil conditions coincide with erosive winds most of New Zealand's arable soils are susceptible to wind erosion (Basher & Painter, 1997).

Tillage operations that remove vegetative cover can have an immediate impact on the wind erosion potential by exposing soil aggregates to wind and rain. Agricultural soils are largely immune to erosion by wind when adequate vegetative cover exists. Additionally, rainfall tends to decrease the mean aggregate size of the surface soil, potentially increasing erosion risk upon drying (Zobeck & Popham, 1990).

Cultivation management practices adopted by a land user are a key factor in determining the aggregate size distribution of the seedbed produced. For any particular soil, the water content at the time of tillage, soil density, and the tillage characteristics of the machinery used are major influences on the outcome of the cultivation with respect to soil aggregation (Zobeck & Popham, 1990). Intensive cultivation produces a greater proportion of fine particles, while also weakening aggregate strength (McLaren & Cameron, 1990). Soil with unstable aggregates have less resistance to bombardment by raindrops, and therefore are more likely to form a crust (*ibid.*). Structural degradation can also lead to a greater proportion of micropores, decreasing infiltration and hydraulic conductivity rates.

Conventional cultivation of pastoral land can result in the rapid decline of soil organic matter (Haynes, 1995; Gupta *et al.*, 1988). Continuous cultivation acts to reduce the organic matter levels from between

3 to 4 percent organic carbon to a lower equilibrium of 1 to 2 percent in many New Zealand soils (Haynes, 1995). The decline is due to lower root biomass under arable crops, removal of organic matter at harvesting, and exposure of previously inaccessible organic matter to microbial attack – hastening decomposition (*ibid.*). Organic matter has two important functions in a productive soil system, it aids aggregate stability through binding and cementing individual particles together through production of organic glues, and it is also an important sink for soil nutrients (McLaren & Cameron, 1990). Organic matter decline can lead to nutrient loss in two forms, decomposition of organic matter related to mechanical disturbance, and/or via transportation of organic matter through wind erosion, in the form of suspension (Lorentz, 1996).

Timing of cultivation is vital because soil aggregate size is influenced by soil moisture, implement choice, speed and depth of operation (Fryrear, 1984). Tillage conducted when the soil moisture content is near the plastic limit produces aggregates that are less stable than formed at lower moisture contents (Cresswell *et al.*, 1991).

Emergency tillage is often used in North America and Canada to produce a rough soil surface, more resistant to erosion (Larney *et al.*, 1994). However, suitable soil conditions for production of non-erodible aggregates must exist at the time of cultivation, and the optimum condition will vary with soil texture and implement used (Lyles, 1982). Intense tillage can actually act to produce a smoother soil surface, therefore increasing susceptibility of the soil to wind erosion (Cresswell *et al.*, 1991). Under good management, cultivation techniques can be used to decrease the risk of wind erosion. Some tillage operations can result in soil clod and aggregate production, creating a random roughness, other methods tillage are directly aimed at producing soil ridges (Saleh, 1994). Both methods act to trap saltating particles, and thus prevent increase of erosion across a paddock due to the avalanching effect.

Cultivation can influence the stability of soil aggregates through the increased decomposition of organic matter. Long-term arable soils exhibit aggregates with lower organic matter, and lower stability than those under long-term pasture. Arable aggregates, partly because of their low organic matter content, are weakly bound together and drying causes small fracture faults to develop (Haynes & Swift, 1990). During re-wetting after rain, energy release from rapid rehydration can cause slaking effects along the faults. In comparison, pastoral soil aggregates are more strongly held together by organic compounds, fine plant roots and associated fungal hyphae (all of which are rapidly broken down after cultivation). Additionally, the partial hydrophobic properties of the organic component of pastoral aggregates resist rapid rehydration, and less slaking occurs because the energy release is spread over a longer time period (*ibid.*).

Soils with unstable aggregates have less resistance to bombardment by raindrops, and therefore are more likely to form a crust (*ibid.*). Structural degradation can also lead to a greater proportion of micropores, decreasing infiltration and hydraulic conductivity rates.

The cultivation technique adopted is determined primarily by seedbed requirements of the crop to be sown. Cereals establish satisfactorily in a moderately coarse tilth, as do peas, field beans and squash (McLaren & Cameron, 1990). Grass, clover and root crops such as carrots, parsnips and swedes all require a fine seedbed (Haynes, 1995). The optimum tilth for seed germination may therefore conflict with a goal of preparing a erosion-resistant soil surface.

Traditional cultivation involves using a mouldboard plough to turn over the soil, followed by use of discs, harrows and rollers to work the soil into a suitable tilth (Haynes, 1995).

2.6 WIND EROSION RESEARCH

2.6.1 Portable wind machines and wind erosion research

Wind erosion research on agricultural soils has been predominantly carried out using portable wind tunnel, with one of the first models used in 1939 (Fryrear *et al.*, 1991; Nickling, 1995; Lopez, 1998). Wind tunnels allow for in situ testing of the relationship between wind velocity and sediment flux, in relation to site specific characteristics such as soil texture and aggregate size distribution. They provide a more controlled environment, with increased repeatability of experiments than possible in open field trials, and the ability to simulate a variety of wind speeds (Lopez, 1998). Direct field observations allow assessment of natural erosive processes, for example equilibrium saltation, but are time consuming and rely upon suitable climate conditions to obtain useful data. However, portable wind tunnels can incur significant aerodynamic constraints. The ability of a tunnel to accurately model natural wind mechanics and erosion is directly related to its design and size, as discussed below.

Fixed laboratory wind tunnels can create the most controlled conditions for wind erosion research, but require soil samples to be collected and moved to the tunnel often resulting in structural or textural differences between the tested samples and soils they are intended to replicate (Nickling, 1995). Portable wind tunnels have several advantages over fixed laboratory tunnels (*ibid.*):

- They enable the rapid collection of wind erosion data, on a wide range of soil types.
- Trials can be undertaken fairly independent of climatic conditions, in comparison to open field trials which require natural wind to initiate soil particle movement.
- There can be minimal disturbance to the soil surface.
- Surface soil conditions, for example crusting, moisture content, and vegetation, can be specifically evaluated in relation to erosion rates.

In order to represent erosion processes under natural conditions, the flow characteristics in the tunnel must correspond to the natural atmospheric boundary layer. Edge effects occur along the sides of the tunnel where wind velocity is slowed by friction. Where the frictional effects cease to influence the flow in the tunnel is termed the free stream. Size and shape of a tunnel will determine how large the free stream zone is, or whether it is developed at all. Short wind tunnels with small cross sections may not develop suitable boundary layers (section 2.3.5), or an atmospheric boundary layer that mirrors natural flow (Nickling, 1995). Natural boundary layers can be from a few meters to several hundred meters high, while the boundary layer in a portable wind tunnel is usually relatively thin and depends on the length, height and width of the tunnel (*ibid.*).

Successful modelling of the erosion process relies heavily on tunnel design and the flow characteristics in the working section. The short working section in most portable wind machines does not allow the erosive mechanisms to fully develop and cannot account for soil and vegetative variability across a field (Lopez, 1998). Additionally, the relatively short time period that a machine operates on any one plot, for example one minute, does not allow for full development of aggregate abrasion and saltation avalanching effects (*ibid.*). Raupach & Leys (1990) identified the most important aspects of a well-designed wind tunnel:

1. Produces a flow of known and steady characteristics.
2. The wind speed can be varied easily and accurately.
3. It is durable and safe.
4. Large enough to enable representative sampling of the soil surface.

5. Easily portable for quick sampling of adjacent plots.
6. Easily transportable in a disassembled form.

2.6.2 Lincoln University portable wind machine

The wind machine used for this research project is described fully in Eastwood (1998). A brief summation of the important tunnel features is outlined below (Figure 2.6.1).

Figure 2.6.1: The Lincoln University Wind Tunnel (LUWT) set up on a Pakipaki plot

The Lincoln University portable wind machine (LUWM) was built in 1990 and has since been used primarily for demonstration purposes. No detailed calibration or investigation of flow characteristics had been completed on the tunnel prior to its use in this project. It is similar in design to the tunnel used by Raupach & Leys (1990) for erosion research in Australia. Mounted to the three-point linkage of a tractor, the LUWM is powered through the power-take-off (PTO) (Figure 2.6.1, 2.6.2). Wind velocity in the working section is manipulated by adjusting the tractor revs per minute (rpm), or by altering the pitch on the fan blades. The fan forces air through a flexible transition funnel, which accommodates the difference in height between the fan assembly and the ground. The tunnel section consists of a series of five, 1.2 m rectangular sub-tunnels able to be transported separately and connected in the field. The first sub-section contains conditioning elements designed to straighten the axial wind flow produced by the rotating fan blades. Air passes from the transition section, through anti-swirl vanes, then passing through honeycomb sections constructed with 300 mm long, 60 mm diameter PVC pipes. The flow then moves over a 1 m board with a 40 mm high tripping fence.

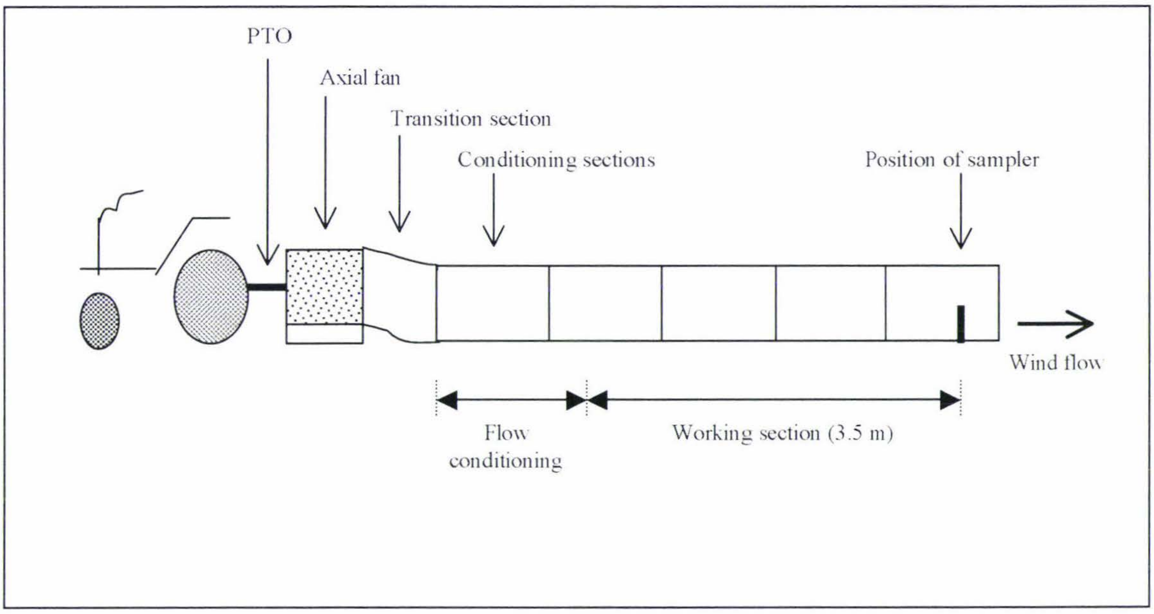


Figure 2.6.2: Schematic of the Lincoln University wind machine.

2.6.3 Wind erosion sediment samplers

There are many different methods employed to measure sediment flux in wind erosion studies internationally. Vertically integrating sediment samplers are most commonly used, with rectangular inlets ranging in size from 10 to 20 mm width and 100 to 300 mm height (Nickling, 1995). Samplers can be either active or passive in design. The former are equipped with pumping devices that actively maintain a flow through the intake similar to the ambient wind velocity, and are generally more accurate than passive samplers, which rely on the ambient wind to maintain internal flow (Shao *et al.*, 1993).

The backs of most passive traps are covered with a fine mesh, to allow airflow through the trap while also preventing sediment from exiting. To allow sufficient airflow through passive samplers the mesh must be coarser (>40 μm) than that used in active samplers (<2 μm) (*ibid.*). Despite their lower collection efficiency, passive traps are used most frequently because they are relatively inexpensive and portable, and do not require an electric pump.

The desired design criteria of an accurate and versatile sampler are identified by Nickling *et al.* (1997):

1. Samplers should be isokinetic (where the wind flow through the sampler intake is equal to the wind flow in the surrounding environment. A non-isokinetic sampler will deflect some of the airflow around the trap, carrying finer particles away from the inlet.
2. The efficiency of the trap should remain constant over a wide range of incident wind angles.
3. The sampler should be compact and streamlined to cause the least disturbance to ambient wind flow.
4. Scouring should be inhibited around the base of the trap.
5. The trap should be inexpensive and portable.

Nickling *et al.* (1997) designed a vertically integrating aeolian sediment trap, constructed of thin sheet aluminium with a wedge shape (32° frontal angle). It is a passive trap with a 20 by 500 mm sampling orifice extending 40 mm beyond the wedge form (Figure 2.6.3). The back of the trap is covered with 62.5 μm stainless steel mesh, allowing for efficient wind flow, and collecting creep, saltation, and some suspended particles. A hole in the base allows trapped sediment to fall into a 60 mm diameter pipe fixed below. A plastic bag slipped over the pipe collects sediment samples. More detailed specifications are described in the paper by Nickling *et al.* (1997). The sampler had near isokinetic flow characteristics with a sampling efficiency of at least 90 percent over a wide range of wind speeds.

Leys & Raupach (1991) observed that most of the airborne material in their wind tunnel-based experiments occurred below a height of 0.5m. Therefore a trap of 500 mm height, such as the Nickling model, should sample the majority of the erosion cloud. The particles possibly lost will be those in suspension, and potentially negligible in relative mass.

Figure 2.6.3: The Nickling sediment sampler used for the Hawke's Bay research

2.6.4 1998 Research

The project carried out by Eastwood (1999) identified several opportunities for improvement. These included:

- Installation of a tripping board to prevent scouring at the top of the working section and to improve wind flow characteristics in the tunnel.
- Using a vertically integrating sediment sampler suitable for use in a wind tunnel.
- Implementing a field trial design that allows for a high level of control over timing and type of cultivation.
- Introducing replicates to improve statistical significance of results.

2.7 SUMMARY

This literature review has outlined the issue of wind erosion both internationally and in New Zealand and exhibited the need for research into the specific characteristics of erosion in the Hawke's Bay region. Information presented in the literature review, surrounding the processes of wind erosion and possible research approaches, will be drawn upon to formulate the methodology adopted for this Masterate investigation, as outlined in the next section.

3. RESEARCH METHODOLOGY

3.1 INTRODUCTION

Development of a sensible, robust, scientifically sound, and yet simple method of fulfilling the stated research objectives is the key to successful research. Issues and options identified in the literature review process are drawn upon in this development process. The methods used to fulfil the stated project objectives are also based on previous work completed by the author in 1998, and through consultation with wind erosion experts in Australia and the United States. This section outlines the methods adopted to fulfil the research objectives.

3.2 FIELDWORK PREPARATION

3.2.1 Australian research trip

An integral part of the experimental design involved a week spent with John Leys in Adelaide, Australia during September of 1999. The trip was undertaken to observe the New South Wales Department of Land and Water portable wind tunnel, and to discuss the Masters objectives and methods with a widely-published wind erosion researcher. It proved to be extremely worthwhile, not only for the new ideas that came from the trip, but also through confirmation of methodology already developed at the time.

3.2.2 Wind machine calibration

Eastwood (1999) carried out the only known investigation of the Lincoln University Wind Tunnel (LUWT) wind flow characteristics with small cup anemometers. Proportionally large edge effects were found, and are probably due to the relatively small size of the tunnel. Such edge effects are found in tunnels used internationally (Raupach & Leys, 1990; Nickling, 1995) and are to be expected in a tunnel of this size. The analysis also showed that obtaining a general relationship between fan speed and subsequent wind speed in the tunnel is hindered by variability in cross-sectional and long axis velocities. The lack of highly accurate anemometers also prevented the formulation of a strong relationship.

Nickling (1995) states that a wind machine should be fully calibrated prior to use in a research capacity to ensure its flow characteristics are representative of the natural boundary layer. Without equipment such as pitot tubes this could not be completed. Therefore, relatively little is known about the wind flow characteristics of the LUWT. Following advice from John Leys (pers. comm., 1999) a visual assessment of flow characteristics was carried out by spreading sand on a smooth surface and running the wind machine at a set speed over the sand. This exercise didn't appear to show any major deficiencies in the tunnel aerodynamics, although there was one area that preferentially scoured near the front of the tunnel. This scouring may indicate a continuance of axial flow after the air has exited the conditioning sections.

The experimental objectives require the wind speed in the tunnel during each run to be known. It was not possible to fit the cup anemometer and sediment sampler in the tunnel at the same time, without interfering with either the wind flow around the trap or anemometer, or placing one of the items out of the freestream zone. Therefore, the wind velocity in the tunnel was calibrated to the speed of the axial fan on the wind machine. A range of velocities were measured every second, averaged over one minute, with a data-logging cup anemometer. Wind velocity was measured at 0.25 m height, equidistant from each side wall of the tunnel, and 0.5 m from the exhaust of the tunnel, assumed to be in the free stream after last years calibrations. This position also corresponds with the sampler position, and at half its total height of 0.5 m.

International wind tunnel studies convert the measured wind velocity in the tunnel to a velocity at 10 m height (Leys & Raupach, 1991; Leys *et al.*, 1996). This is in order to allow comparison between soil types, studies of similar design, and to relate the tunnel simulation to wind velocities at a height often used by meteorological services. The conversion requires detailed information on tunnel wind velocities during each run in order to calculate friction velocity (u_*) and surface roughness length (z_0). Appropriate equipment was not available for this project to enable such information to be collected. Although surface roughness has a very site-specific effect on the velocity profile, it is possible to estimate surface roughness length from values found in previous studies on similar surfaces. Pye (1987) recommended z_0 values of 0.0003 m for flat sand and 0.04 to 0.1 m for grass 0.25 m tall. Leys (pers comm., 2000) found that soils cultivated with a rotary hoe had z_0 values ranging between 0.0001 m for sandy soils to 0.004 m for soils with high clay contents. Surface roughness length is used to carry out the velocity conversion through use of the following equation:

(Eqn. 3.1) $U_1/U_2 = \ln(z_1/z_0) / \ln(z_2/z_0)$

U_1/U_2 equals the ratio of wind speed at 0.25 m in the tunnel (z_2) to 10 m height (z_1). If an estimated value for z_0 of 0.025 mm for the cultivated treatments is used (Leys pers comm., 2000), U_1/U_2 equals 1.40. Therefore, if the velocity measured in the tunnel is 35 kmh^{-1}, extrapolated to 10 m height the velocity would be approximately 50 kmh^{-1}.

The use of an estimated z_0 introduces a potential source of error and therefore the velocity conversion factor will only be utilised to place the tunnel speeds in context, not to make direct comparison with other studies.

There are some limitations in the basic LUWT design, as discussed in section 2.6.5. Through consultation with John Leys (pers. comm., 1999) it was decided that the current flow conditioning sections may be ineffective due to their diameter-length ratio, and that axial flow may still occur in the working section. In an attempt to address this problem, the 60 mm internal diameter, 300 mm length PVC pipes in one flow conditioning section were replaced with 5 mm diameter straws of the same length. The modification was not successful and the reasons are discussed further in section 5.1.2.

One of the recommendations drawn from previous work by Eastwood (1999) with the LUWT was that the tunnel would benefit from the addition of a 'tripping board'. Several international studies using wind tunnels included such a device, often a thin, roughened board with a vertical 'fence' to encourage rapid boundary layer development (Pietersma *et al.*, 1996; Leys & Raupach, 1991; Leys *et al.*, 1996). Pietersma *et al.* used a 0.25 m long roughened plywood board, while the tunnel used by Leys has a 2 m long board with a tripping fence 0.5 m from the upwind edge. The tripping board was positioned downwind of the flow conditioning section, which included an anti-swirl vane section and a honeycomb pipe section.

The length of a tunnel is also important for boundary layer development, as discussed in section 2.6.1. The addition of the tripping board acted to reduce the length of the working section in the LUWT by approximately 0.75 m. To rectify this, an additional 2.4 m section of the tunnel was requested from Lincoln University. However, it was not delivered before trials began on the first site and a decision was made not to use the equipment once it arrived due to the effect this would have on results.

3.2.3 Sediment sampler construction

A passive, vertically integrating, slot sampler, based upon designs specified in Nickling *et al.* (1997) (section 2.6.3), was used to collect eroding soil. The trap was selected due to its ease of construction and low cost, high sampling efficiency and ability to operate in a variety of wind speeds. It was constructed of light industrial steel, with stainless steel 63-micron mesh. Modifications of the trap were required to prevent 'wobble' during simulated wind events and involved attaching a plate to the base of the sampler and pegging the plate to the ground during each run. The flow characteristics of the sampler were not investigated due to lack of appropriate equipment, however the design closely follows that described by Nickling *et al.* (1997) and therefore its characteristics and sampling efficiency is assumed to be similar. No adjustment has been made to sediment flux measurements to account for sampling losses.

Prior to placement in the tunnel, a plastic bag was placed over the pipe section attached to the base of the trap, and sealed with a rubber band. A short length of stainless steel pipe, with a larger internal diameter than the external diameter of the trap-mounted pipe and bag combined, was pushed into the soil flush approximately 10mm below the surface. The use of this larger pipe section reduces the time taken at each plot as it eliminates the need to dig a hole every time the trap is installed for the five wind speeds (Nickling *et al.*, 1997). During experimental runs the sampler intake was positioned 0.4 m upwind of the tunnel exit, to avoid the aerodynamic effects as air is exhausted from the tunnel, and equidistant from the sidewalls to minimise edge effects.

3.2.4 Selection of cultivation techniques

The goal when selecting cultivation techniques to use in the trial was to mirror practices currently used in the region. This had to be balanced against the need to adopt methods practical for a split-block trial, and to fulfil the objective of determining the role of aggregate size distribution. Another factor was a requirement to work within the cultivation management on the Pakipaki site, which was ploughed and tine-cultivated prior to research taking place. The following criteria were used for selection of treatments;

- **Simplicity of implementation** – The treatments needed to be simple yet effective. Their implementation must be efficient in terms of time and effort.
- **Manageability within the trial design** – the treatments needed to fit with the split-block design, therefore multiple passes with wide and/or difficult-to-manoeuvre equipment were somewhat impractical.
- **Based on landuser practices in Hawke's Bay** – the treatments selected must be relevant to the region, and therefore should mirror practices used there.

- **Achievement of research objectives** – the treatments needed to produce a range of aggregate size distributions.

Prominent landusers representing the arable industry in the LandWise group were canvassed for their opinion, as were HBRC land management staff. The following four treatments were decided upon:

- Plough and roll. Fallow for one month then complete one pass with a spring-tine cultivator with rear crumbler followed by:
    1. One-pass with cultivator (denoted as T1 or P1, according to the Takapau or Pakipaki site);
    2. Two-passes with cultivator (denoted as T2 or P2);
    3. Three-passes with cultivator (denoted as T3 or P3).

- Minimum-tillage simulation (denoted as TM or PM) with a modified corn planter with a series of discs and spreaders in front of the coulter, designed to create a rough, thin seedbed and chop up vegetative matter (Figure 3.2.1).

The cultivation treatments were primarily designed to produce a range of soil aggregate sizes, in accordance with Objective 2 of this project, while also satisfying Objective 1. The minimum tillage treatment was undertaken to provide a very different cultivation practice to be used to support the fulfilment of Objective 1, as well as providing data to support possible recommendations made in accordance with Objective 3.

Figure 3.2.1: The modified Great Plains corn planter used for the minimum tillage treatment: **left** – preparing trial plot; **right** – the front set of discs on the planter.

3.2.5 Loss of sediment source

a) Identification of the issue

The wind erosion simulation process used for this experiment, involving running five velocities on each plot, creates a potential for limited sediment supply as the most erodible particles are preferentially transported in the first few runs. Lopez (1998) identified a drop in sediment flux with an increase in windspeed at the end of the experimental period in a natural erosion study. The observed reduction in soil erodibility with time might have been due to variations in the aggregate size distribution and the limited supply of erodible particles on the soil surface (*ibid.*) and there is the potential for this to also occur in wind tunnel-based studies (Leys & Raupach, 1991). This issue was discussed with several scientists and statistical advisors and several options were debated, these included:

- Moving the tunnel to a different plot for each speed. Such an approach would require 40 plots to complete the eight replications of each treatment, and moving between plots may introduce significant variability through changes in aggregate size distribution and other influencing factors.
- Running all five speeds on one plot, but in a random order. This approach was discounted because it would also require many replicates and stripping might occur if the highest speed was run first.

- Running all five speeds on one plot, in order of increasing flow velocity. This minimises the potential for a limited source, as each run applies more energy to the soil surface, and was considered the best available methodology.

b) Addressing the issue

Sediment supply limitation was therefore identified as a possible issue, and the next step was to develop a methodology to test if it was a significant problem. The following hypothesis was proposed:

> H_o: *That the supply of erodible soil particles is not limited at any of the five wind velocities simulated on each plot.*

To test the hypothesis, five additional plots on the Takapau site were cultivated with the T2 treatment. The plots were positioned side by side to minimise variability in soil physical factors. Three runs using the wind machine were completed on each plot, at a standard above-threshold wind speed. The wind speed used was 35 kmh^{-1}, chosen because it was above the threshold velocity and it was equal with the speed used for use in sediment flux/soil aggregation comparisons, potentially adding more data points. Sediment flux, aggregate size, and moisture content were estimated using the same methods as outlined in section 3.3.2.

3.2.6 Experimental sites

Through consultation with Hawke's Bay arable landusers and HBRC land management staff, two soil types were identified as being vulnerable to erosion and of greatest regional significance. While there are several other soil types also vulnerable to wind erosion in the region, time constraints meant that the research was focussed on the Pakipaki silt loam and Takapau silt loam soil types.

a) Pakipaki site

i) Soil characteristics

The Pakipaki soils are formed in alluvium from Taupo pumice deposited by the Ngaruroro River and lie at the southern end of the Heretaunga Plains extending from a few kilometres north of Bridge Pa to Pakipaki and near to Havelock North. They are susceptible to wind erosion if cultivated partly because the clay percentage is so low that it provides little binding matter for the sand particles (DSIR, 1939) and the rhyolite pumice has low particle density. The soils have very low fertility, are low in phosphate and exhibit a cobalt deficiency. It is suitable for pasture, and with good shelter, asparagus, berry fruit, and stonefruit (Griffiths, 1997). Pohlen (1971) mapped approximately 4160 ha of Pakipaki and Esk soil types collectively in Hawke's Bay.

Observations by Palmer (pers. comm., 1998) identified that some soils mapped as Turamoe peat, another extremely vulnerable soil type on the Heretaunga Plains, now resemble the physical characteristics of Pakipaki soil types. It is possible that the Turamoe, which is only distinguished from the Pakipaki by peat in the topsoil, has experienced oxidisation of the peat layer through drainage and cultivation or removal via wind erosion. The progression of the Turamoe soil to a Pakipaki variant further justifies the importance of research on the Pakipaki soil type.

ii) History of site

The Pakipaki site is located on Moray and Sandy Grants property, five minutes south of Hastings. The paddock is currently utilised as a minimum tillage trial in conjunction with the LandWise initiative set up in 1999. The Grants purchased the property three years ago, and have grown two seasons of squash prior to this trial with conventional cultivation methods.

b) Takapau site

i) Soil characteristics

The Takapau soil series is formed in alluvium from greywacke and volcanic ashes and is the soil most at risk from wind erosion in the Hawke's Bay. It is a well drained, fine textured soil which, with its tendency to dry out severely in summer, makes its topsoil susceptible to wind erosion when cultivated. This is more so for the silt loam than the sandy loam. The soils are situated on flat or gently sloping terraces, and are located chiefly on the Ruataniwha Plains but also occur adjacent to the middle reaches of the Ngaruroro, Tutaekuri and Esk rivers and to minor streams in the western foothills (Pohlen *et al*., 1947). Allophane contributes to low particle density of the Takapau soil, making it even more vulnerable to erosion but the presence of allophanic clays can assist in the maintenance of good soil structure and are also a factor in the high phosphate retention of the soil. The natural fertility is medium to low and a good response to phosphate fertiliser suggests low plant available phosphate (Pohlen, 1971). Griffiths (1997) lists potential uses of these soils on the Heretaunga Plains as asparagus, berry fruit, grapes, pasture, pipfruit, and stonefruit. Over 31,800 ha of Takapau soil is mapped in Hawke's Bay (Pohlen, 1971).

ii) History of site

The area used for this research used to be utilised for arable cropping on a rotational basis, however it has not been cultivated since the property was purchased by Jonathan and Kate Wiltshire in 1989. Since then perennial pasture has been the only crop grown.

3.3 EXPERIMENTAL DESIGN

3.3.1 Randomised split-block design

The experiment was designed as a split-plot, randomised block trial, which encompassed T1-T3 and P1-P3. The site was broken into four blocks, and in each block two replications of each tillage treatment were randomly allocated. The minimum tillage experiment was conducted in its own block due to the impracticality of including randomised minimum tilled strips in between ploughed plots.

Randomised split-plots were used in several studies with similar objectives. In a trial investigating tillage effects Cresswell *et al.* (1991) used a randomised split-plot design, as did Larney *et al.* (1994) in a comparable experiment. Leys *et al.* (1996) used the same approach and suggested that eight replicates were required to characterise a 400 m2 area, which is approximately the size of the trial sites adopted in this project. Therefore, eight replicates were used to characterise each treatment in this experiment.

The block design was adopted due to possible changes in soil physical characteristics across each of the sites. Visual assessment showed there to be indications of a difference in particle size distribution at the Pakipaki site, where some areas had a higher amount of pumice on the surface after ploughing. At the Takapau site the topsoil depth changed across the experimental area, becoming shallower towards one corner with a noticeable increase in gravels mixed in the surface soil. Particle size analysis of the sites may have shown if there was a significant difference but time and budget constraints prevented this. A split-block design was used to minimise the impact of any variation might have on results.

3.3.2 Data collection procedure

a) Fieldwork procedure

A summary of the fieldwork procedure is presented in Figure 3.3.1.

The pre-tillage treatment at both sites was carried out over one month prior to the tine-cultivation treatments being applied. At each site four blocks, all containing six plots, were measured out taking into account the width of the cultivation equipment.

Treatments were applied to plots the day prior to measurements being carried out in order to allow evaporation of moisture. The inherent risk involved with cultivating the day before is that an erosive event or rainfall might occur prior to experiments taking place, affecting the soil surface properties and erosion characteristics. This risk was balanced against the need to reduce soil moisture levels and knowledge of the medium-term weather forecast.

b) Wind erosion simulations

The wind machine was set up on each plot, taking care not to disturb the soil surface in the working section. Five wind speeds were simulated on each trial plot, from under the erosion threshold at approximately 15 kmh^{-1} (0.25 m height), up to 50 kmh^{-1} (0.25 m height). This number of speeds was used to provide several data points with which to graph erosion rates on each plot. Eight different wind speeds were simulated on each plot in research by Scott (1994) and Leys *et al.* (1996), and Leys & Raupach (1991) ran six speeds on each plot. A lower number of simulated wind velocities was chosen for this project to minimise the potential for error through sediment supply limitations.

Prior calibration established approximate tractor revs per minute (rpm) that corresponded with the desired fan rpm, which in turn were calibrated to wind velocities at a specified point in the tunnel (section 3.2.1). Therefore tractor rpm was manipulated to produce the desired speeds, and during each run the fan speed was measured with a digital tachometer.

The LUWT was run at each speed for one minute, based on similar work with wind tunnels by Leys & Raupach (1991), Scott (1994), Leys *et al.* (1996), Horning *et al.*, (1998), Leys & Eldridge (1998). Both time constraints and the possibility of removal of sediment source (section 3.2.4) determined the length of the runs.

The sediment sampler was placed in position prior to each run, and after the minute it was removed and the plastic bag removed, labelled and sealed. Any sediment left in the sampler after a run was tipped into the bag also.

c) Soil sample collection

Soil samples were collected on each plot, in an undisturbed strip beside the tunnel that was representative of the soil surface in the working section. Samples were collected for aggregate size distribution/stability and stored in an ice cream container prior to air drying (section 3.4.1). Soil moisture samples were collected, placed in a sealed plastic bag and stored in at 4^0C prior to oven drying (section 3.4.3).

d) Surface roughness

Surface roughness was measured by the chain method outlined by Saleh (1994). A 1.42 m long chain (L1 = 1.42 m), comprised of 25 mm links, was laid out on the surface after experiments had been conducted on each plot. A sliding rod was used to read the linear distance covered by the chain (L2) and this value was used to calculate the surface roughness (R) via the following equation:

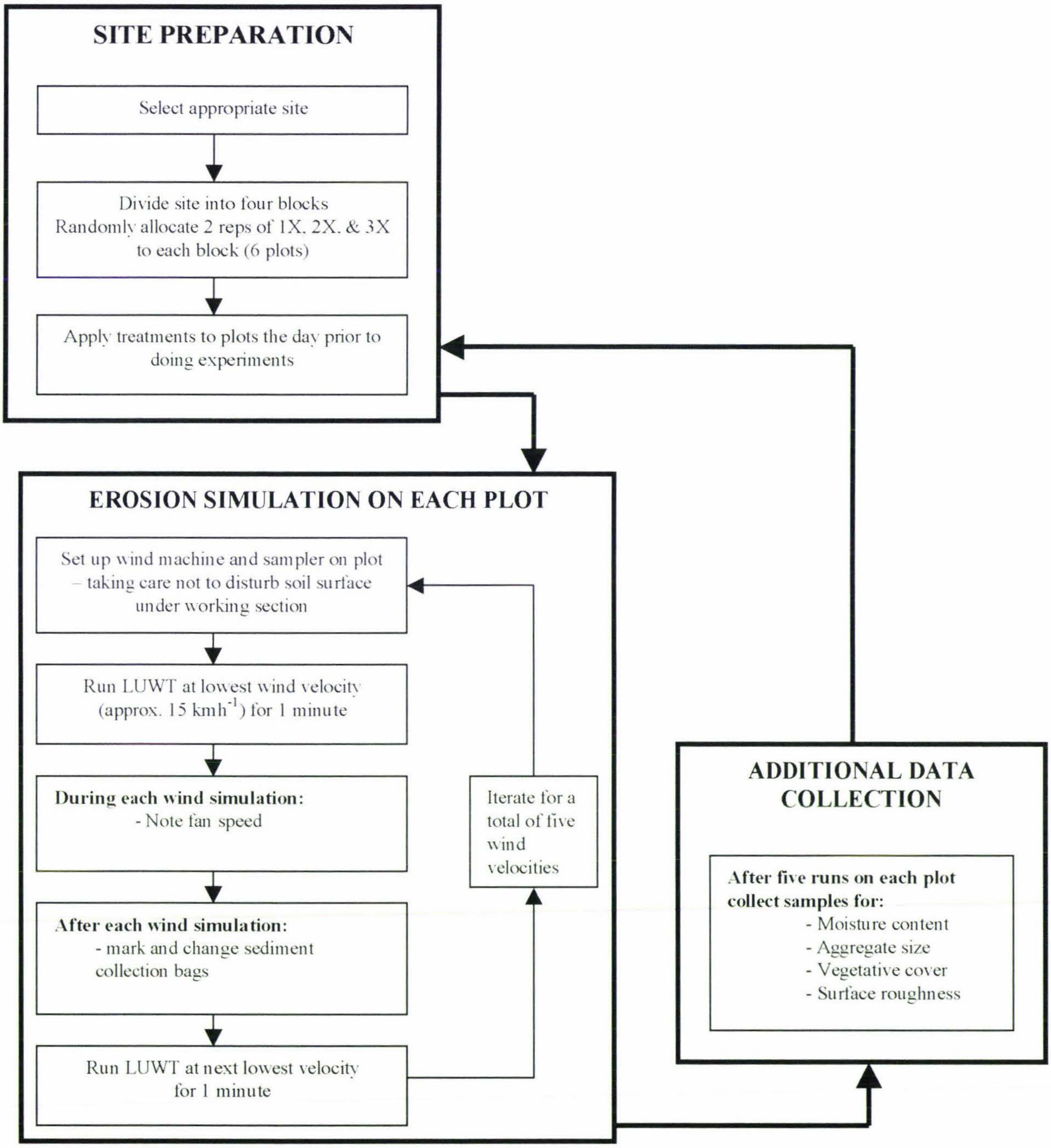
(Eqn. 3.2) $$R = (1 - L2/L1)\ 100$$

The limitations of this method are discussed in section 5.1.2.

e) Surface vegetation cover

Vegetative cover was measured by counting the number of 'hits' at each plot. A pole, marked with 20 points between 0 and 0.6 m, was laid across the working section of the tunnel after each run. A hit was counted if vegetation (including roots larger than 1mm diameter) was touching a mark on the pole. The horizontal measurements were completed six times at standard distances down the working section. Vegetative cover is presented as a percentage of actual hits per 120 possible.

Figure 3.3.1: Flow diagram of fieldwork procedure



3.4 LABORATORY ANALYSIS

3.4.1 Aggregate size analysis

At each research plot an ice-cream container full sample was collected of the soil surface. According to the aggregate sampling method used in similar international studies (section 2.3.5), the top 10 to 15 mm of soil was sampled with a small flat-bottomed shovel. Care was taken not to disturb the aggregate sample site while setting up the wind machine. The sample taken was collected from alongside the tunnel, considered to be best representative of the aggregate size distribution in the working section. Samples of the soil surface were not taken were not taken prior to cultivation due logistical difficulties.

Surface soil samples were air dried and then mechanically sieved at 1 mm amplitude for three minutes each. Sieve sizes of 2, 1, 0.85, 0.5, 0.25, and 0.09 mm were used, with the 1 and 0.25 mm sieves acting as separators to prevent the other sieves being clogged with soil (Dando pers. comm., 2000). The remaining sieves represent the size classes for suspended, saltating and creep transport modes (section 2.3.2) and the internationally recognised dry aggregation particle size, 0.85mm (Chepil, 1951; Leys *et al.*, 1996). Percentage mass dry aggregation >0.85 was found by Leys *et al.* (1996) to be a good predictor of sediment flux rates, and accounted for other factors such as past management.

The sieving procedure used was specifically designed drawing on experience from previous work with similar soil types (Eastwood, 1999). It was found that standard mechanical sieving processes to be too vigorous for the fragile volcanic soils tested, producing skewness to smaller particle sizes.

3.4.2 Wet aggregate stability

The influence of aggregate stability on wind erosion was outlined in the literature review, and due to its important role, measurement of stability was included in the fieldwork. Dry aggregate stability shows the resistance of soil aggregates to breakdown from abrasion during the erosion process. Wet-aggregate sieving provides an indication of the aggregate stability of different soils, and their resistance to breakdown under stress while wet, such as raindrop impact. Wet sieving is a common test of soil aggregate stability (McLaren & Cameron, 1990) and gives a longer term indication of structural stability, able to take into account the effects of past management practices (Cresswell, 1990). Wet aggregate stability was assessed for this project due to availability of equipment. Soil aggregates from two to four mm in diameter were collected in the aggregate-size sieving process and used for wet aggregate stability. Analysis was carried out in the Landcare Research building at Massey University's Turitea campus. The analysis followed the 'NZ Soil Bureau' procedure outlined by Gradwell (1972).

3.4.3 Soil surface moisture content

Nickling (1978) found that standard ceramic soil moisture blocks and Soil Test soil moisture modules were of little use for soil moisture measurement because the instruments could not be placed close enough to the soil surface to give representative measurements. Instead, soil surface samples of the upper millimetre were collected with a sharpened spatula and soil moisture content measured gravimetrically. Nickling used this approach on a virtually flat and smooth sediment surface, which made collection of samples to one millimetre depth possible. Use of this exact technique is not appropriate for this study due to the higher aggregation levels and surface roughness. Samples were therefore collected from the top 10 mm soil surface.

Painter (1976) stated that there are few alternatives to thermo-gravimetric sampling for near-surface soil moisture measurement and Scotter (pers. comm., 1998) confirmed that this is still the case currently. Therefore, 0.6 to 1 kg soil surface samples were collected at each plot, pre-weighed then oven dried at 105°C for 48 hours and reweighed. Soil moisture content is given as a percentage of the dry weight, using the measured weight loss.

3.4.4 Mass of sediment flux sampled

The eroded soil collected during each run was weighed in grams to four decimal places. The weight was converted to a sediment flux rate of grams per metre per second by using the equation listed in section 3.5.1 below.

3.4.5 Sieving of eroded sediment

The eroded soil collected and weighed for each run on a plot was bulked to give one sample per plot. This sample was hand-sieved for one minute though a stack of sieves 2mm, 0.5 mm and 0.09 mm in size. These sizes represent the transport modes of creep (0.5 to 2mm), saltation (0.09 to 0.5 mm), and suspension (<0.09 mm) identified in section 2.3.2. The mass of soil remaining on each sieve, including the mass in the bottom collection pan, was weighed and recorded.

3.4.6 Nutrient analysis

Eroded soil <0.09 mm size collected from each plot was bulked across the whole site and analysed to represent the suspended fraction carried off-site, as discussed in section 2.4.1. Soil surface samples representative of each site were also analysed to provide a base against which the suspended samples could be compared. The Fertiliser and Lime Research Centre conducted nutrient analyses, providing data on pH, Olsen P, SO_4, K, Ca, Mg, Na, and CEC, and conversion to MAF quick test values.

3.5 ANALYSIS OF RESULTS

3.5.1 Calculation of sediment flux (Q)

The eroded soil collected in the sampler has temporal and spatial dimensions as it represents a one-minute sampling period, over a 3.5 m working section. In previous studies with similar methods (Leys & Raupach, 1991; Leys *et al.*, 1996; Horning *et al.*, 1998; Leys & Eldridge, 1998), sediment flux (Q) is calculated as mass moved (m) per second (T), over a 1 m wide area perpendicular to the wind flow (Y), with a infinite height. Soil flux Q is therefore presented in g m/s. The assumptions inherent with this calculation unit are discussed in section 5.

(Eqn. 3.3) $Q = m/YT$

The international studies listed above also corrected the sediment flux rate for saltation overshoot, where the saltation component of erosion in the working section of the tunnel is actually higher than the equilibrium level for the same site under natural erosion conditions. However, a 'scaling flux' value is required to carry out the correction and this was not available for the specific soils tested.

3.5.2 Calculation of sediment flux at 35 kmh^{-1}

In their investigation into dry aggregation and erosion rates, Leys *et al.* (1996) compared between nine soils by determining the sediment flux at 65 kmh^{-1}. This specific velocity was chosen by Leys *et al.* because it followed similar international studies, it was above the wind erosion threshold, and it was typical of <1% of wind velocities in the region. The velocity represents a conversion from the velocity at 0.2 m height in the tunnel to the equivalent wind velocity at 10 m height, well above the atmospheric boundary layer and free from frictional effects of the soil surface. To complete this calculation, the friction velocity and surface roughness length is required to be measured in the tunnel with Pitot static tubes, which were unobtainable for the Hawke's Bay research.

Sediment flux in this project was determined at 35 kmh^{-1}. It is above the threshold velocity of all plots, but below where some plots exhibited decreasing erosion rates. Due to the lack of appropriate equipment discussed in section 3.2.1, the value represents velocity at 0.2 m above the soil surface but is approximately equivalent to 50 kmh^{-1} at 10 m height. It is acknowledged that this introduces potential error because it is below the atmospheric boundary layer, however it still allows for inter-plot comparison, if not comparison with international findings. The sediment flux at 35 kmh^{-1} was manually determined by reading the appropriate point off a graph, as done by Leys *et al.* (1996).

3.5.3 Calculation of nutrient losses

An attempt to value the nutrient losses was undertaken by estimating the cost of replacing the nutrients using common fertilisers as done by Raupach *et al.* (1994). Particles less than 90 μm in size were identified as representing the portion of soil lost to the paddock and the nutrient values for this fraction was used for the calculation (Leys *et al.*, 1994). The values derived were very small, and this is discussed in the chapter 5.

4. RESULTS

4.1 INTRODUCTION

This section presents the results of the Hawke's Bay wind erosion research conducted in 1999.

4.1.1 Experimental sites

A randomised block design was fully implemented at the Takapau site, with a 20 m by 40 m area split into quadrants. The Pakipaki site was structured slightly different due to less control over original cultivation and concerns with perceived soil textural changes across the paddock. The four blocks were not positioned in one area, and were spread between 10 m to 20 m apart according to soil texture and surface roughness.

The plots have been labelled according to the applicable block and treatment. Treatments 1, 2 and 3 on the Takapau site (T) and the Pakipaki site (P) have been termed T1, T2, T3 and P1, P2, P3 respectively. Blocks were labelled 1, 2, 3 and 4, with the first replicate of each treatment run in a block labelled as 'A' and the second labelled 'B'. For example the first replicate of Treatment 2 run in block three on the Takapau site is denoted as '3A-T2'.

The experiments run on the Takapau silt loam and Pakipaki sandy loam soils are referred to as the Takapau 'site' and Pakipaki 'site' respectively throughout the result section. This is to prevent the findings from being interpreted by readers as being indicative of each soil type. Results uncovered during the experimental portion of this thesis are only indicative of specific physical, spatial and temporal characteristics. For example they indicate erosion rates on a tunnel scale, in paddocks with specific management histories, on soils with specific physical characteristics. Any extrapolation of the data to similar soils in the region, or in other regions, must recognise its site-specific nature.

4.2 WIND MACHINE USE

4.2.1 Calibration

A visual assessment of the fan speed versus wind velocity (0.25m height) showed a near linear relationship and therefore a linear regression analysis was conducted in SPSS in order to fit an equation to the relationship. The resulting equation, with an R^2 of 0.957 was:

(Eqn. 4.1) Wind speed = (0.04129 x fan revolutions per minute) – 5.386

Figure 4.2.1 presents the calibration data and shows the linear regression trendline. The regression equation and R^2 value are also included on the graph.

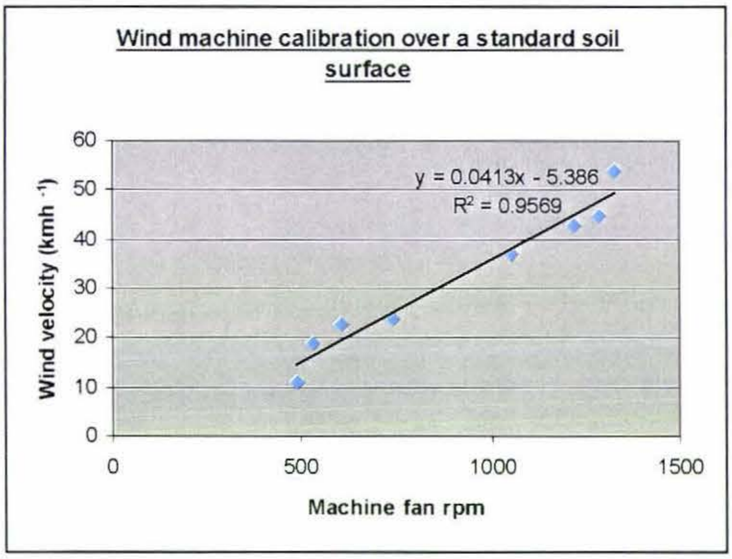


Figure 4.2.1: Wind machine calibration over a bare, cultivated soil surface.

4.3 EXPERIMENTAL RESULTS

4.3.1 Limited sediment supply investigation

a) Sediment flux

The results of the investigation into possible sediment supply limitation are presented in Table 4.3.1. Five plots were used, each cultivated via the method described for Treatment 2, and wind velocities of approximately 37 kmh^{-1} were simulated in three consecutive runs on each plot. Results were averaged across the five plots. There was a significant difference ($P < 0.05$) in sediment flux between the first run on each plot and the second and third runs. There was no significant difference ($P < 0.05$) between the second and third wind simulations.

Table 4.3.1: Sediment flux ($\text{gm}^{-1}\text{s}^{-1}$) at 37 kmh^{-1} for three sequential runs

	Run 1	Run 2	Run 3
Mean	8.19[a]	2.19[b]	1.17[b]
Min	2.88	0.53	0.29
Max	14.84	4.23	1.92
StDev	5.54	1.62	0.79
S.E. Mean	2.48	0.72	0.35

[a]Means with the same letter are not significantly different at $P < 0.05$.

The additional variables measured did not show major differences between the five plots. Gravimetric moisture contents ranged from 6.2 percent to 9.2 percent and percentage of aggregates >0.85 mm ranged from 23.8 percent to 27.8 percent. There was no significant difference between plots for roughness and vegetation.

There was a significant difference ($P = 0.032$) in surface roughness between plots 1 and 5 at the 95 percent confidence level, and plots 5 and 4 were also quite different ($P=0.080$), but not statistically significant at the 95 percent level.

Due to the variable nature of the tractor rpm, and its influence on wind speed in the tunnel, simulated velocities in the tunnel varied slightly around 37 kmh^{-1}. A standard speed of 35 kmh^{-1} was originally targeted, arbitrarily chosen because it was above the threshold velocity and equated to the speed used for sediment flux determination. A one-sample t-test showed that 37 kmh^{-1} was the most representative value of the 15 runs. This analysis showed no statistically significant difference ($P<0.05$) between the measured velocities and a test value of 37 kmh^{-1}.

4.3.2 Soil aggregate size

The soil aggregate sieving process separated the aggregates into three main categories, corresponding to the approximate size ranges of soil transported via suspension, saltation or creep, as shown in Figures

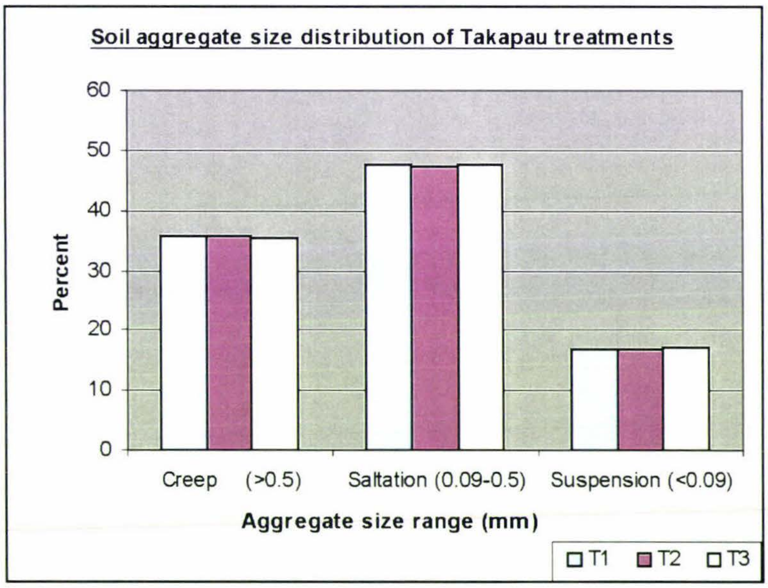
4.3.2 and 4.3.3. During the same sieving process aggregates were also categorised into greater or less than 0.85 mm, the results of which are included in Table 4.3.1.

a) Aggregate size distribution

i) Takapau site

Figure 4.3.1 presents the size distribution of soil aggregates in the top 10-20 mm of Takapau plots. The primary aggregate size (approximately 47 percent) lies between 0.09 mm and 0.5 mm. Creep-sized aggregates make up the next largest category (35 percent) in the erodible layer of soil on the Takapau site. Aggregates < 0.09 mm accounted for 15 percent of the total soil sampled for plots in each treatment. One-way ANOVA tests highlighted no significant differences between aggregate sizes produced any of the three cultivation treatments within each of the three sediment transport categories.

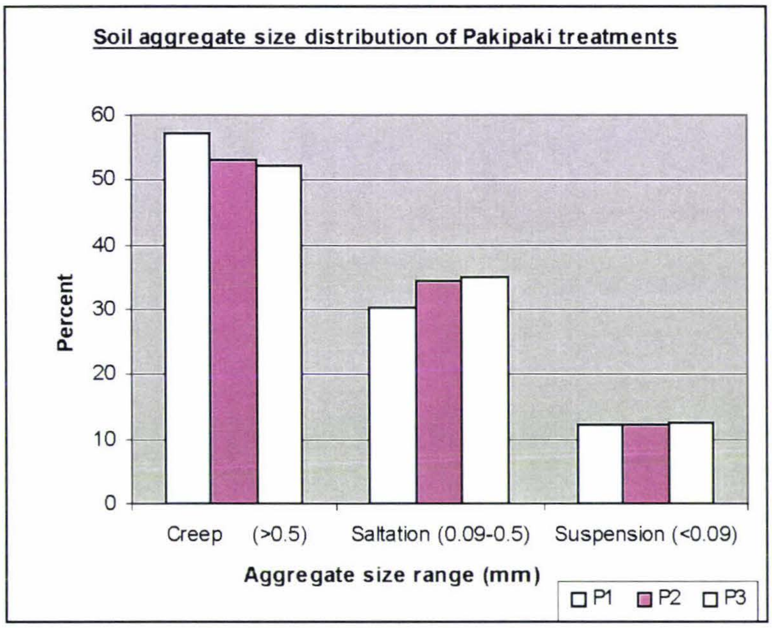
Figure 4.3.1: Soil aggregate size distribution of Takapau treatments



ii) Pakipaki site

There was a visible decrease in the percentage of large aggregates (>0.5) with an increase in tillage intensity on the Pakipaki soil (Figure 4.3.2). The percentage of suspension-sized aggregates remains constant across the three treatments, and the drop in large aggregates is negatively related to an increase in the middle size range, 0.09 mm to 0.05 mm.

Figure 4.3.2: Soil aggregate size distribution of Pakipaki treatments



b) Dry aggregation > 0.85 mm

The trend shown in the aggregate size distribution graphs for the Takapau site also holds true for the percentage of aggregates that exceeded 0.85 mm in size (Table 4.3.2). Different cultivation treatments had no significant impact on the proportion of aggregates above the threshold size. At the Pakipaki site treatment P3 produced significantly less ($P \leq 0.05$) aggregates over 0.85 mm in size, when compared to P1 and P2. Between sites, aggregates > 0.85 mm under P1 and P2 were significantly greater than those under any of the Takapau treatments were. P3 was not found to be different than the three Takapau treatments, at the 95 percent confidence level.

Table 4.3.2: Percentage of soil aggregates > 0.85 mm

	T1	T2	T3	P1	P2	P3
Mean (%)	26.5^a	26.9^a	26.2^a	50.1^b	45.1^b	43.3^a
Min (%)	23.9	22.9	23.3	27.3	27.4	16.4
Max (%)	33.5	33.1	28.9	68.8	62	62.5
StDev	2.9	3.3	1.8	13.8	11.6	14.4
S.E. Means	1.0	1.2	0.6	4.87	4.12	5.1

[a] Means with the same letter are not significantly different at $P \leq 0.05$.

[1] Means with the same superscript number are not significantly different at $P \leq 0.05$.

4.3.3 Soil surface moisture content

Gravimetric moisture content of the surface soil in the Takapau and Pakipaki plots is presented in Table 4.3.3. Treatment means all occur in a close range of 4.6 to 8.5 percent moisture, and on each site there is no difference ($P \leq 0.05$) between the treatments. Between sites there is a significant difference in moisture content, and this may have a bearing on the relative erosion rates between the sites. The possible causes of the higher moisture content on Takapau plots is discussed in the next chapter.

Table 4.3.3: Gravimetric moisture content of soil to 10 mm depth

	T1	T2	T3	P1	P2	P3	T-Site	P-Site
Mean	7.9	8.3	8.5	5.0	4.6	5.1	8.2^1	4.9^2
Min	5.7	6.7	6.9	3.4	2.3	3.9	5.7	2.3
Max	12.2	11.6	10.7	6.9	7.0	6.3	12.2	7.0
StDev	2.0	1.9	1.4	1.0	1.4	0.7	1.7	1.1
S.E. Means	0.7	0.7	0.5	0.3	0.5	0.3	0.3	0.2

^{1}Means with the same superscript number are not significantly different at $P \leq 0.05$.

4.3.4 Wet aggregate stability

The wet aggregate stability of aggregates under each of the treatments on both sites is shown in Figure 4.3.3. Stability is indicated by the percentage of aggregates that remain on the 2 mm, 1 mm, and 0.5 mm sieves. In Figure 4.3.3 the difference between the cumulative percentage of the mass remaining on the three sieves and the 100 percent mark indicates the proportion of particles smaller than 0.5 mm that were washed through the bottom sieve in the wet sieving procedure. Aggregates initially placed on the sieve are between 2 and 4 mm in diameter. The higher the percentage of aggregates remaining on the 2mm sieve after the procedure, the higher the stability of the soil tested.

The results indicate that aggregates on the Takapau plots were more stable in comparison to Pakipaki plots. Takapau plots averaged over 73 percent aggregates > 2 mm, while the highest percentage of aggregates remaining on the 2mm sieve in the Pakipaki treatments was 66 percent under P1. There was a significant difference ($P \leq 0.05$) between the combined results at each site. There was no statistical difference ($P \leq 0.05$) between treatments within each site.

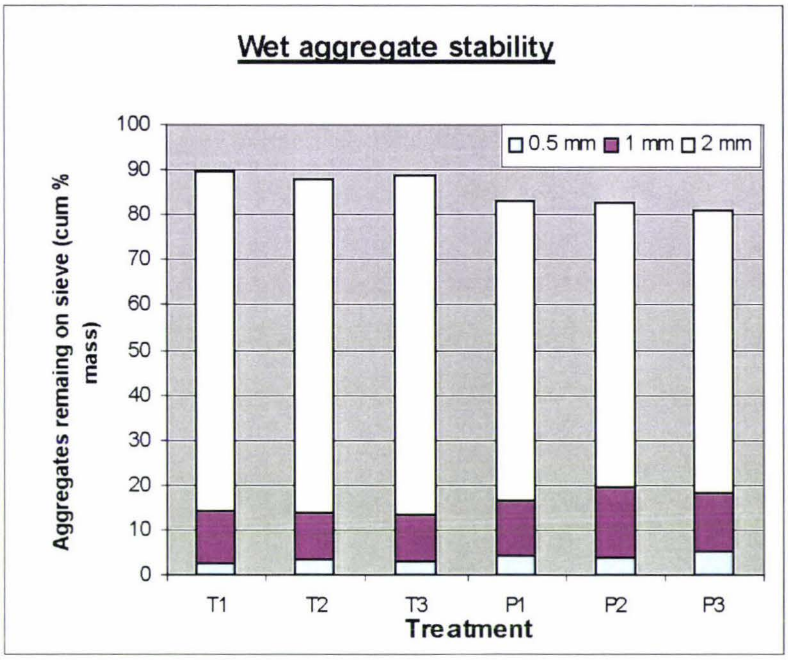


Figure 4.3.3: Aggregate stability of Takapau and Pakipaki soils.

4.3.5 Surface roughness

Surface roughness data are presented in Table 4.3.4, and constitute a percentage as determined by the equation outlined in section 3.3.2. The lower the surface roughness coefficient the greater the surface roughness. Surface roughness was only measured on Takapau plots, due to concern over the irregularity of the initial plough and roll on the site. Subsequent cultivation with the tine-cultivator failed to completely remove undulations and surface roughness measurements were used to investigate the significance of the surface roughness. No such concerns were held for the surface roughness of the Pakipaki site and no measurements were carried out there.

The mean surface roughness of each treatment at the Takapau site lies in a close range between 98.5 percent and 98.91 percent. The greatest range of values measured on plots in one treatment group is from 92.6 percent to 99.6 percent for T1. The larger range of roughness is reflected in a higher S.E. mean value. One-way ANOVA statistics illustrated no significant difference ($P \leq 0.05$) between plots. The results from surface roughness measurements suggest that roughness was not a contributing variable for rates of erosion. This is discussed further in the next chapter.

Table 4.3.4: Descriptive statistics for mean surface roughness on Takapau treatments (%)

	T1	T2	T3
Mean (%)	98.5	98.86	98.91
Max (%)	99.65	99.65	99.93
Min (%)	92.61	97.89	96.83
St Dev	1.46	0.56	0.80
S.E. Mean	0.30	0.11	0.16

4.3.6 Vegetation cover

The extent of vegetation on the Takapau site is presented as mean percentages for each treatment in Table 4.3.5. The data presented represents the percentage of 'hits' measured via the method described in section 3.3.2. There is a large range in values in each of the three plots, with one standard deviation close to the size of the mean in each case. No significant difference was found when the means were compared via a one-way ANOVA at the 95 percent level of significance.

Vegetation measurements were taken on the Takapau site for the same reasons used to justify measurement of surface roughness at the site. Ploughing produced a surface that still included many tufts of non-buried grass. After the tine-cultivator treatments were applied vegetation was still apparent. This method was adopted to examine the significance of the residual vegetative matter on erosion rates. The Pakipaki site was predominately clear of vegetation and no measurement was conducted on this site.

Table 4.3.5: Descriptive statistics for mean vegetation cover on Takapau treatments

	T1	T2	T3
Mean (%)	2.65	2.81	2.88
Max (%)	10.0	11.0	13.0
Min (%)	0	0	0
St Dev	2.27	2.62	2.71
S.E. Mean	0.33	0.40	0.39

4.3.7 Sediment flux

a) Takapau

The results of sediment flux measurements on Takapau plots are presented in treatment groups. T1 and T2 are included in Appendix A-3, and the results from treatment T3 are shown in Figure 4.3.4 below. Combination all 24 plots on one graph was undertaken to exhibit any increase in erosion rates between treatments, but the resulting graph only acted to highlight the variable erosion rates and did not show any strong differences and it has not been included. Sediment flux data are very variable in all three treatments, for example in T3 plots 1a and 1b exhibit the more 'classical' increase in erosion rates as wind speed increases, with sediment flux rates of 27 to 28 g/ms^{-1} at approximately 50 kmh^{-1} (0.25 m height). The threshold velocity of these plots appears to be between 35 and 40 kmh^{-1}. In comparison, plots 3a and 3b show much lower erosion rates and threshold velocity does not appear to be reached before the last wind speed simulated (45 kmh^{-1}). The remaining plots to which treatment 3 was applied show a highly variable relationship between sediment flux and wind velocity. In plots 2a, 2b, 4a, and 4b there is a sediment flux decrease exhibited between the forth and fifth wind speed simulated. This drop-off in erosion rates is mirrored in many of the T1 and T2 treatments (Appendix A-3.1, A-3.2) and the implications of this are discussed in the next chapter.

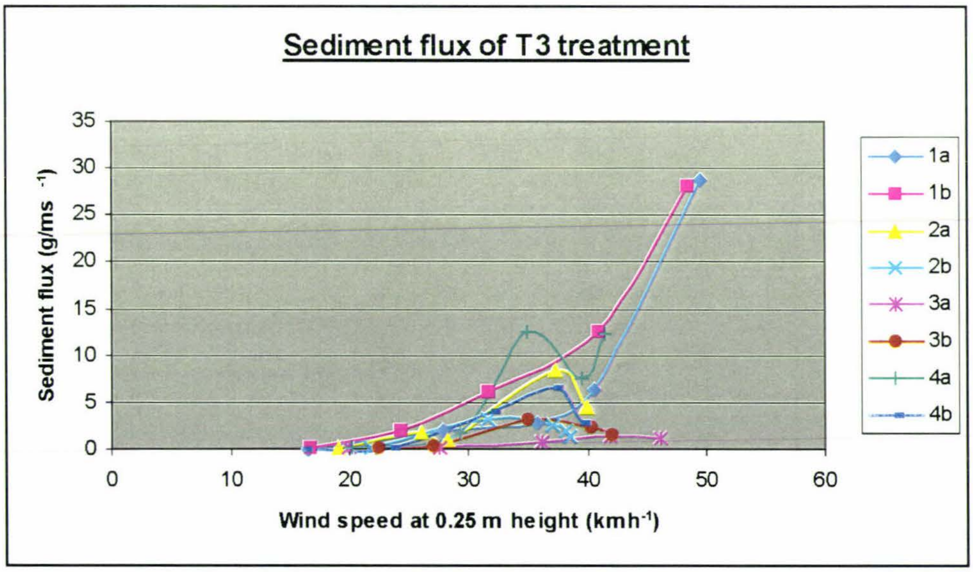


Figure 4.3.4: Sediment flux at a range of wind speeds under treatment T3

In general peak rates of erosion increased as cultivation intensity increased, with 17.5 $gm^{-1}s^{-1}$ for T1, 26 $gm^{-1}s^{-1}$ for T2, and 28 $gm^{-1}s^{-1}$ for T3. It is difficult to determine if there is a definite increase in average sediment flux with increase in cultivation intensity. The best way to undertake a more quantified assessment would be to find an average trendline for each treatment and then to compare between T1, T2, and T3. This would be achievable if each of the five wind speeds simulated were the same between all 24 plots, or within a tight range. The methodology adopted where velocity in the tunnel was primarily determined through adjustment of the tractor rpm lead to a wide range of actual velocities simulated at each of the five graduations. Statistical advice was sought on the possibility of combining individual plots with such variable velocities, and no satisfactory solution could be found. Therefore, no aggregation of plots or statistical comparison of possible relationships was undertaken for this form of data. The difference between sediment flux rates at 35 kmh^{-1} was investigated statistically, as outlined in section 4.3.8.

b) Pakipaki

The relationship between sediment flux rate on the Pakipaki site and wind velocity at 0.25 m height is presented in Figure 4.3.5 (P3) and in Appendix A-3.3, A-3.4 (P1 and P2). Sediment flux on P3 plots exhibited the most consistent increase with wind velocity increased out of all the treatments on both sites. Plot 2a stands out in Figure 4.3.5, with a dramatic increase in erosion between 42 and 48 kmh^{-1} to a peak of 57 $gm^{-1}s^{-1}$. This is not indicative of the remainder of P3 plots, which are closely grouped in comparison with plots under other treatments, and have a much lower sediment flux peak (2 – 19 $gm^{-1}s^{-1}$). The decrease in sediment flux at the fourth and fifth wind velocity, exhibited in plots under other treatments, is not apparent in P3 plots. There is a high degree of variability in sediment flux within P1 and P2 plots. Decreases in erosion rates at the higher wind velocities is also exhibited in several of the plots in each of these treatments (P1 – 1a, 2b, 4a, 4b; P2 – 3a).

A visual comparison between sediment flux graphs of P1, P2, and P3 shows no consistent trend between increasing cultivation intensity and relative erosion rates. Sediment fluxes in P1 plots are predominantly below 3 $gm^{-1}s^{-1}$ at the highest velocity simulated. P2 plots predominately group around a similar sediment flux rate, but with plots 2b, 4a, and 4b exhibiting higher rates (7 to 35 $gm^{-1}s^{-1}$) above 35 kmh^{-1}.

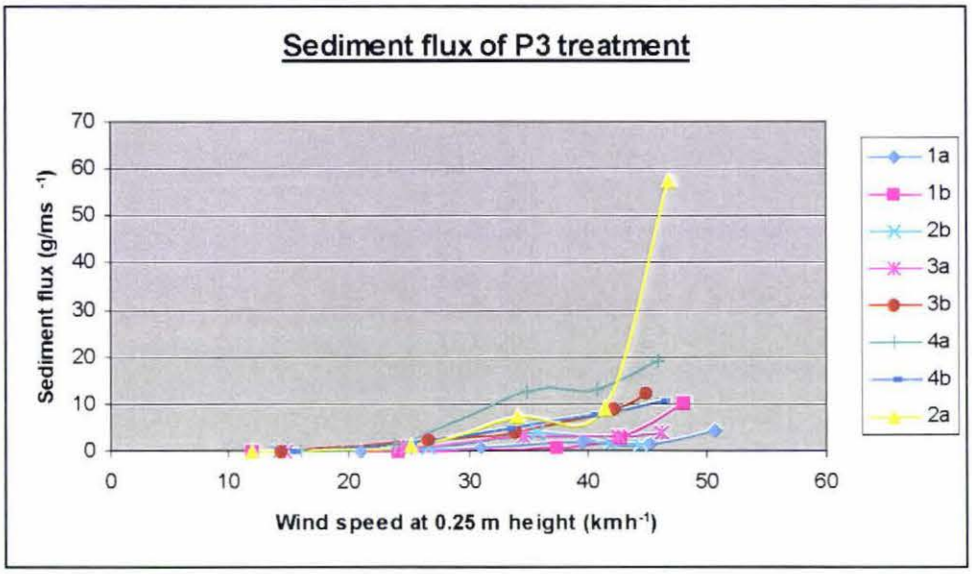


Figure 4.3.5: Sediment flux at a range of wind speeds under treatment P3

c) Threshold velocity

There is no clear indication of the threshold velocity of either of the soil types, or the effect that increasing cultivation may have had on the threshold. Visual assessment of Figures 4.3.4, 4.3.5, and Appendix A-3 suggest that the point at which wind erosion occurs lies between 25 to 35 kmh^{-1}, but this is highly variable within and between treatments.

4.3.8 Sediment flux at 35 kmh^{-1}

A single point sediment flux rate was determined by manually reading the flux ($gm^{-1}s^{-1}$) corresponding to a wind velocity of 35 kmh^{-1}, as shown in Figure 4.3.6. In each plot any decrease in erosion rates between the fourth and fifth wind velocity occurred over 35 kmh^{-1}, and therefore any sediment supply in the tunnel working section should not have greatly effected the single-point flux rate. This wind velocity also constituted a point above the erosion threshold in all plots.

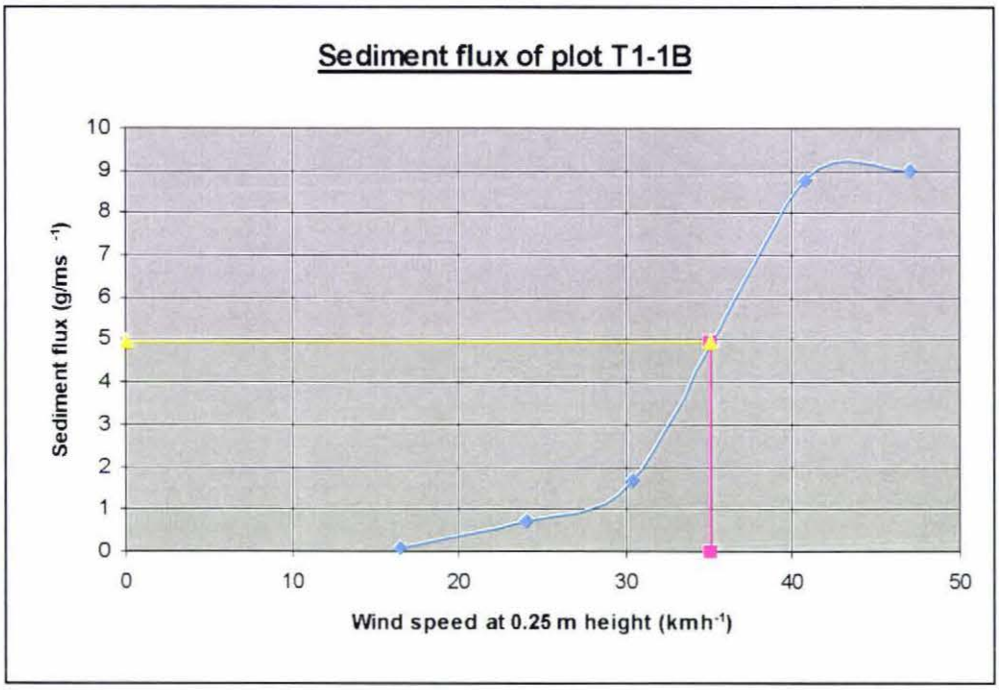


Figure 4.3.6: Method used to manually determine sediment flux at 35 kmh^{-1}.

The treatment means and descriptive statistics for each site are presented in Table 4.3.6. Mean sediment flux rates for Takapau plots were 3.4 gm^{-1}s^{-1} (T1), 5.7 gm^{-1}s^{-1} (T2), and 4.5 gm^{-1}s^{-1} (T3). Pakipaki plots had slightly lower flux rates, with 1.8 gm^{-1}s^{-1} (P1), 4.0 gm^{-1}s^{-1} (P2), and 4.1 gm^{-1}s^{-1} (P3). One-way ANOVA tests for significant difference ($P \leq 0.05$) between treatments and between sites found no statistical differences. Visual assessment of the information listed in Table 4.3.6 suggests that there is a difference between the means of P1 and P2, and an independent-samples T-test showed that although not significant at the 95 percent confidence level, the means had a $P=0.08$. All plots showed high variance in sediment flux, with standard deviations almost as large (or larger in the case of T1 and P2) as the mean. This may account for the lack of significant differences.

Table 4.3.6: Descriptive statistics for treatment means of sediment flux (gm^{-1}s^{-1}) at 35 kmh^{-1}

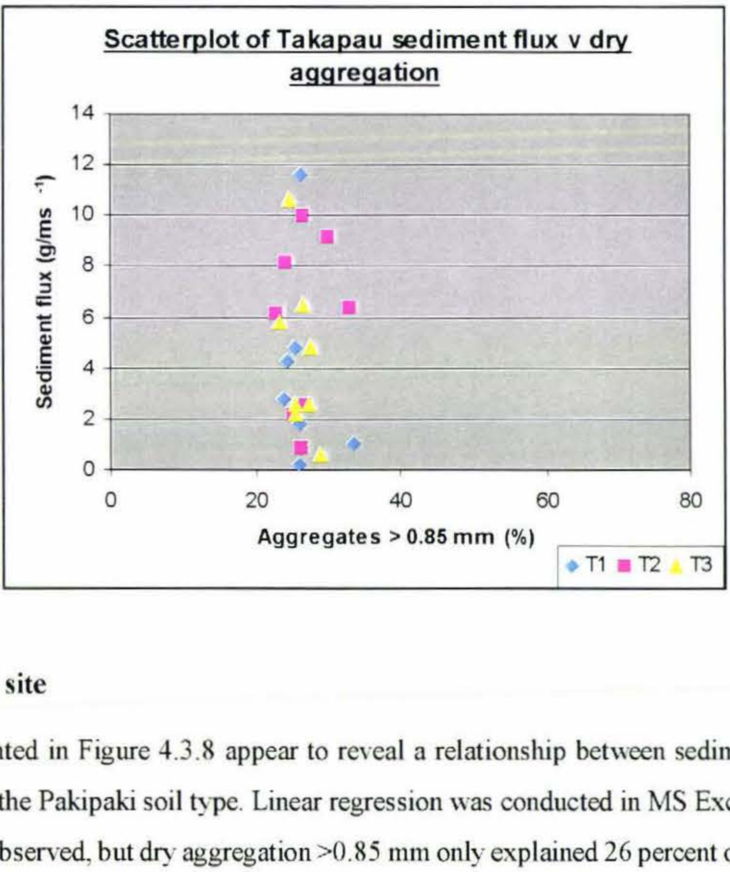
	T1	T2	T3	P1	P2	P3
Mean (gm^{-1}s^{-1})	3.4	5.7	4.5	1.8	4.0	4.1
Min (gm^{-1}s^{-1})	0.2	0.9	0.6	0.2	0.4	0.4
Max (gm^{-1}s^{-1})	11.6	10.0	10.6	5.0	12.0	13.0
StDev	3.7	3.4	3.2	1.4	4.3	4.1
S.E. Means	1.3	1.2	1.1	0.5	1.5	1.4

4.3.9 Percentage of soil aggregates >0.85mm v sediment flux ($gm^{-1}s^{-1}$) at 35 kmh^{-1}

a) Takapau site

The relationship between sediment flux at 35 kmh^{-1} (0.25 m height) and the percentage of soil aggregates greater than 0.85 mm in diameter for Takapau plots is presented in Figure 4.3.7. The three treatments are grouped in individual series. The data collected indicates no relationship between aggregation and sediment flux on the Takapau soil type. Results from treatments T1, T2, and T3 do not show any separate groupings, with the data points spread quite evenly. Possible implications of these results are discussed in the next chapter.

Figure 4.3.7: Sediment flux ($gm^{-1}s^{-1}$) at 35 kmh^{-1} v percentage of Takapau soil aggregates >0.85mm

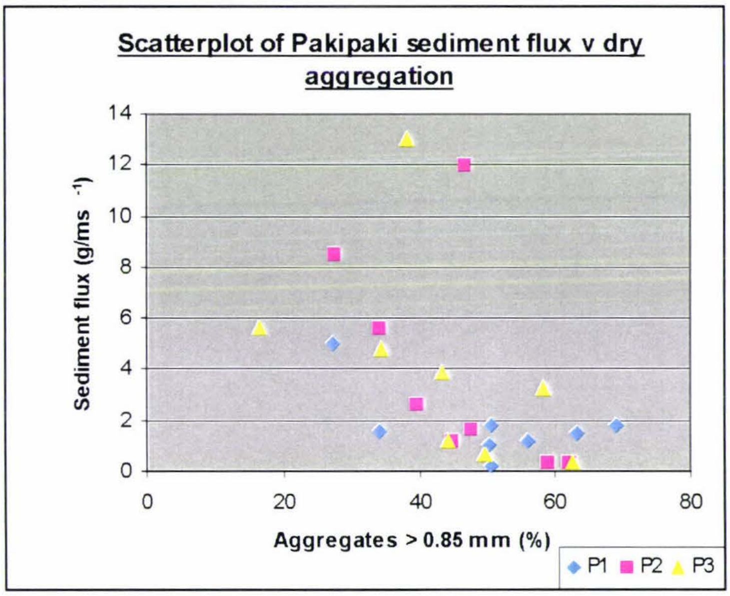


b) Pakipaki site

The results presented in Figure 4.3.8 appear to reveal a relationship between sediment flux and soil aggregate size on the Pakipaki soil type. Linear regression was conducted in MS Excel and a negative relationship was observed, but dry aggregation >0.85 mm only explained 26 percent of the variance the (R^2=0.2618) and therefore no confidence was placed in the regression equation produced. The two outliers seen at the top of the Figure 4.3.8 were examined in terms of additional variables possibly contributing to the high sediment flux. No reason was found for exclusion of these variables from the regression equation.

In comparison with the Takapau data (Figure 4.3.7 above) the Pakipaki site shows greater percentage aggregation, in addition to a wider spread of data points. It might be expected that the three treatments would be loosely grouped, with different aggregation levels arising from increases in cultivation. This is not exhibited in Figure 4.3.8, and in similarity to the Takapau site treatments P1, P2, and P3 are distributed evenly as one macro-group.

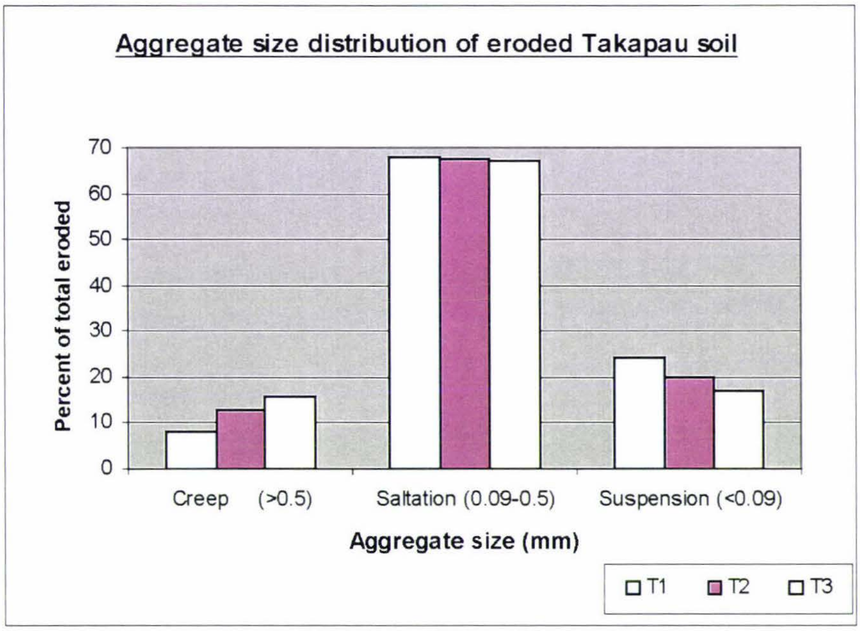
Figure 4.3.8: Sediment flux ($gm^{-1}s^{-1}$) at 35 kmh^{-1} v percentage of Pakipaki soil aggregates >0.85mm



4.3.10 Aggregate size distribution of eroded soil

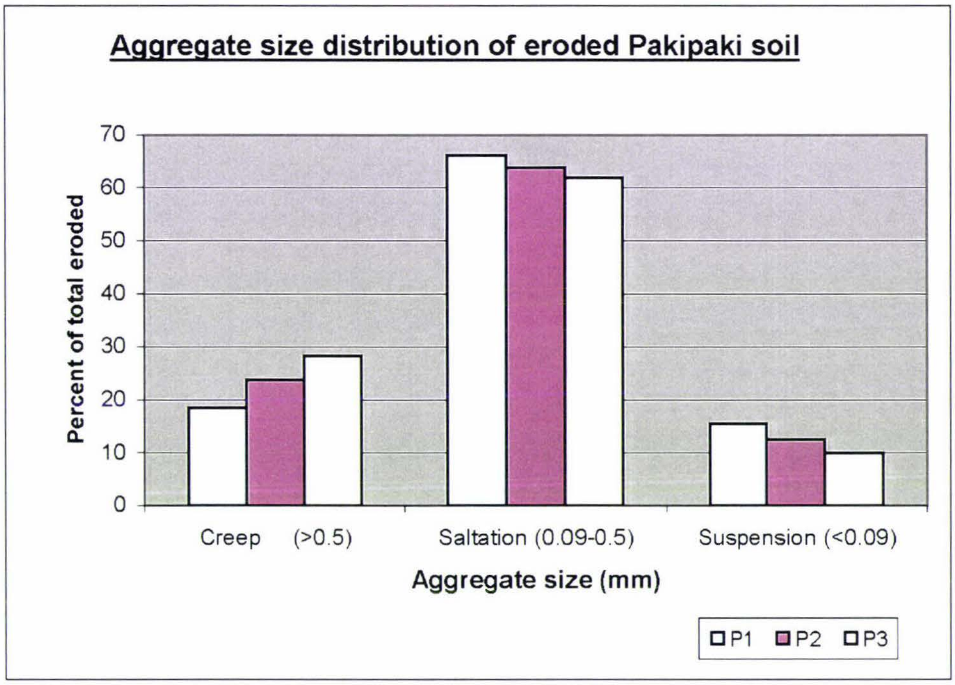
The eroded sediment collected from each plot was bulked and sieved into the fractions outlined in section. Results of this sieving are presented in Figures 4.3.9 and 4.3.10. Both sites exhibit very similar trends, with saltation-sized aggregates contributing the predominant mass of sampled soil (approximately 65 percent). Aggregates less than 0.09 mm moved in suspension were the next most significant transport mode in the Takapau plots, accounting for over 15 percent of total flux. In the Pakipaki plots sampled aggregates larger than 0.5 mm is the second highest grouping in terms of total eroding soil, with greater than 19 percent on total mass occurring inn this fraction. At both sites creep (>0.5 mm) and suspension (<0.09 mm) constitute similar percentages of the total soil caught in the erosion sampler.

Figure 4.3.9: Mean aggregate size distribution of Takapau sediment flux



Increasing tillage intensity induced similar trends in mode of transport at both sites. Creep-sized aggregates made up a greater percentage of the total sediment sampled as tillage intensity increased, while there was a decrease in saltation, although very slight in Takapau plots, and suspension-sized material. The differences in transport mode between treatments were not significant when analysed at the 95 percent level of confidence, but the difference in suspended sediment captured in treatment P1 and P3 has the highest significance level (P=0.093).

Figure 4.3.10: Mean aggregate size distribution of Pakipaki sediment flux



4.3.10 Nutrient loss in sediment flux

The nutrient status of the surface soil and suspended sediment at the Takapau and Pakipaki sites are listed in Table 4.3.7. The suspension-sized material (<0.09 µm) from Takapau plots had higher proportions of Potassium (K), Sulphur (SO_4), Calcium (Ca) and Magnesium (Mg) than the soil surface sampled. The suspended fraction of eroded soil collected from Pakipaki plots was higher in Olsen P, SO4, and K than the soil surface from which it was blown.

Table 4.3.7: Nutrient analysis of surface and eroded soil from Takapau and Pakipaki sites.

Soil	Sample	Olsen P µg/g	SO4 µgS/g	K me/100g	Ca me/100g	Mg me/100g	Na me/100g	CEC Me/100g
Takapau	Soil surface	13.0	23.5	0.24	9.3	0.90	0.85	21
	Suspended flux	8.8	33.5	0.44	13.9	1.18	0.52	27
Pakipaki	Soil surface	18.5	19.0	0.15	12.6	1.43	0.79	21
	Suspended flux	22.7	22.3	0.20	10.7	1.25	0.62	17

The results from the nutrient analyses are compared to other soil surface analyses completed on Hawke's Bay soils by Lorentz (1996). The values listed above were converted to nutrient (kg) per 100 tonnes of soil eroded (approximately 1cm of topsoil per ha), using conversion factors supplied by the Soil Science Department of Massey University. The conversion factors are listed in Appendix A-5.

4.3.11 Minimum tillage

There was low sediment flux rates under the minimum tillage treatment (Appendix A.4). On the Pakipaki site the peak flux was 0.24 $gm^{-1}s^{-1}$ at 48 kmh^{-1}, and rates were primarily below 0.1 $gm^{-1}s^{-1}$ at velocities of up to 50 kmh^{-1}. Slight increases in erosion occurred at approximately 35 kmh^{-1} but then reduce again between the fourth and fifth wind speeds. The gravimetric moisture content of disturbed topsoil at this site was 4.4 percent, comparable to the mean moisture contents of the cultivated treatments at the same site.

The implement used for the minimum tillage trial at the Pakipaki site was not available for use at the Takapau site. The tine-cultivator used for cultivation experiments was adapted to produce a soil surface with similar roughness and vegetative matter as the previously used direct drill. Adaptation involved removal of some of the tines, leaving enough tines to disturb a similar soil width as the Pakipaki treatment. Additionally, only four replicates were completed over the strips, due to time constraints on the day of experimentation. This low number of replicates should not influence the validity of results as the site showed similar erosion rates to the comparable Pakipaki trial.

The results from the Takapau site are presented in Appendix A-4.2. The maximum sediment flux rate is 0.35 $gm^{-1}s^{-1}$ with most of the sediment flux less than 0.2 $gm^{-1}s^{-1}$. Surface soil moisture content was 6.3 percent.

4.3.12 Regression analysis of all variables by site

a) Takapau

A stepwise linear regression was carried out using the sediment flux on Takapau plots at 35 kmh^{-1} as a dependant variable, with independent variables of dry aggregation (>0.85 mm), soil moisture, vegetation cover, surface roughness, and aggregate stability. Pearson correlation's showed that soil moisture and surface roughness were most important in explaining the variance in sediment flux. The regression was carried out using these two variables, and together they explained 41.2 percent of the variation in sediment flux at 35 kmh^{-1}. Moisture as a single independent variable explained 26.1 percent of the variance in erosion rates at the standard velocity.

b) Pakipaki

Sediment flux was entered into a stepwise linear regression as the dependant variable, with dry aggregation (>0.85 mm), moisture content, and aggregate stability as dependant variables (Appendix A-6.1). Using all three independent variables explained 26.6 percent of the variation, and leaving only dry aggregation as an independent variable explained 26.2 percent of the variation in sediment flux at 35 kmh^{-1}.

5. DISCUSSION

The results gathered in the fieldwork component of this thesis raise some interesting questions and discussion points that will be covered in this chapter. Quantitative wind erosion data is initially discussed, followed by the implications of the results for wind erosion management in Hawke's Bay and possible regional policy initiatives. Where possible, results and discussion are compared with applicable national and international work.

5.1 QUANTITATIVE WIND EROSION DATA

5.1.1 Introduction

The fieldwork component of this research produced a significant volume of data. The wind tunnel was used to simulate wind velocities on over 50 cultivated plots and 16 minimum tillage plots. At each plot five velocities were simulated and sediment samples collected, weighed and sieved. Several additional site-specific measurements were also taken. As the result section indicated, many interesting issues were uncovered through analysis of the data, and those issues are discussed further in this section.

5.1.2 Research methodology

The research methodology used for this project took into account the lessons learnt from last year, from additional literature reviewing, and from the trip to Australia. The main improvement surrounded the implementation of a trial design with a higher rigour than last year, achieved by maintaining greater control over cultivation techniques and timing at both sites. Some changes were also made to the wind tunnel in an attempt to improve its flow characteristics. Measurements of other variables that might have influenced sediment flux were also taken at the Takapau site due to concerns over the poor quality of pre-trial tillage.

The modifications made to the wind tunnel included strengthening of the tunnel sections to prevent joints breaking during fieldwork. This was very successful and made moving the tunnel around much easier and efficient. After the trip to Australia concern was expressed over the effectiveness of the PVC pipe straightening sections. To address this, the pipes in one of the sections were replaced with drinking straws, as used by Leys & Raupach (1991) in the NSW tunnel. This did not prove to be successful because inserting this modified section in the tunnel create a large pressure drop for the airflow to attempt to move across. The impact of this was that the air moved out of the base of the tunnel prior to new section, entraining dust and lowering tunnel velocities. This section was not used during the experimental treatments for the project.

The Australian tunnel, observed during the 1999 fieldtrip, has the straightening section sealed inside the tunnel. The wind was forced to move through the straws by the air continuously forced down the tunnel by the fan. The LUWT has an open base, out of which air will preferentially flow if faced with a impedance to flow. Improved straightening of the flow is required if the tunnel is to be used for similar work in the future, and the best way to achieve this might be to permanently seal the conditioning sections into the first tunnel section. The practical problem faced with doing this is that with all conditioning elements included, the section will be very heavy, in fact almost too much to lift. This could be overcome by use of a manual winch or hydraulic boom attached to the fan section, which can be used to move the conditioning section on and off a trailer and around a research site.

Using a tripping board in the tunnel proved beneficial in two ways. It aided the development of boundary layer flow in the tunnel, although the full impact was not tested, but it also helped to prevent scouring occurring after the straightening sections. The board might have worked better if it were longer (up to 2 m), but this would have severely diminished the working section length. In future research using the LUWT it is suggested that the additional Perspex section that arrived too late to be used for this project be used to add length to the working section and allow a longer tripping board.

Experience gained through using the tunnel for this project and the 1998 Honours project suggests that the LUWT is best suited to comparing erosion rates between soils and the relative influence of soil environmental factors on erosion rates. The most appropriate method adopted with the tunnel in New Zealand's arable soils is use of a single run per plot, due to the effects of sediment supply limitations. The LUWT is not appropriate for definitive measurements of erosion rates, although most portable tunnels have similar aerodynamic constraints as experienced in the LUWT.

The Nickling vertically-integrating sediment sampler used for this research was a large improvement on the triple-sampler technique used by Eastwood (1999). Using one sampler, instead of three, saved time in the field and in the lab, and the Nickling sampler is stated as having significantly higher sampling efficiency than the Leatherman style traps used last year (Nickling *et al.*, 1997). The actual collection efficiency of the sampler is not known, but the trap design closely followed that described by Nickling *et al.* (1997) and similar efficiencies are expected (over 90 percent).

A problem encountered with the sampler was the difficulty in getting the base of the intake flush with the soil surface when the ground was uneven. This may have induced an under-sampling of particles moving via the creep transport mode. Nickling *et al.* (1997) suggest overcoming this through addition of a lip onto the base of the intake, which is pressed into the soil surface, allowing creeping aggregates to enter the trap. In design of the trap used for this research the additional time involved in using a lip-device was weighed against the expected low significance of the issue and the lip was not added. After observing the trap performance over relatively rough cultivated surfaces it is recommended that a lip be added to the trap if similar research is carried out again.

The sediment transport rate used in this thesis uses the assumption that the trap is catching everything moving past the intake slot and that the height of the erosion cloud in the tunnel is less than 0.5m. Erosion is expressed as the total eroding material passing through a one-metre wide window of dimensionless height (Leys & Raupach, 1990). It is ambitious to assume that the passive sampler used for this project is completely isokinetic. Also, there might be some soil moving in suspension or saltation above the height of the sampler, but this is expected to be minimal. It is therefore expected that the trap slightly under-samples the true rate of erosion in the tunnel.

5.1.3 Discussion of results

a) Soil aggregate size

The partitioning of soil aggregate size into size ranges representative of creep, saltation, and suspension modes produced some of the most interesting and potentially useful results in this project. The two sites showed quite different trends. Pakipaki plots showed a decreasing proportion of large (>0.5 mm) aggregates with increasing intensity of tillage and there was a corresponding increase in the saltation sized aggregates (0.09 to 0.5 mm). These results indicate that on a soil with physical characteristics similar to the Pakipaki sandy loam, there is a link between cultivation intensity and aggregation levels. In terms of wind erosion, increasing cultivation intensity produces a higher fraction of easily erodible soil, in addition to a lower threshold velocity and raising potential sediment flux rates. Interestingly there was no difference in the finer aggregate fraction (<0.09 mm) of Pakipaki plots. The possible reason for this is unclear, but an influencing factor could be the type of implement used. Some tine-cultivators are designed to bring clods to the surface and bury the finer particles. It is not certain if the cultivator used for this experiment was designed to act in this manner.

The link between cultivation treatment and aggregate size on the Pakipaki plots follows a fairly logical pattern, the more a soil is worked with an implement the greater the breakdown of aggregates. This logical trend was not observed in Takapau plots under the same treatments. There is no evident change in the three measured fractions with increasing cultivation intensity. This is also supported by the data for percentage of aggregates greater than 0.85 mm in size. Landuser feedback during the 1998 research (Eastwood, 1999) indicated that Takapau silt loam soils are very structurally fragile. This is not supported by the wet aggregate stability results, which showed Takapau silt loam soil to have significantly higher wet aggregate stability than the Pakipaki sandy loam. This anomaly is discussed further below. The aggregate size distribution of Takapau plots, presented in Figure 4.3.1, suggests that the soil aggregates are very sensitive to cultivation and one pass with the tine-cultivator acts to break down most of the fragile aggregates. The 'damage' is done with the first pass, and subsequent tillage does not cause further breakdown.

Comparison of aggregate size distribution between the two sites suggests the more fragile nature of the Takapau silt loam soil. After Treatment 3 over 50 percent of surface soil on the Pakipaki plots is still comprised of aggregates over 0.5 mm in size. With similar tillage intensity Takapau plots are made up of approximately 35 percent of aggregates in the same size range. Further, after one pass (Treatment 1) over 45 percent of Takapau aggregates are between 0.09 and 0.5 mm in size, compared to 30 percent in the same size range in P1 plots.

The information suggests that landusers are able to manipulate aggregate size to some extent on soils such as the Pakipaki sandy loam. Cultivation management can be used as a wind erosion control technique avoids large-scale tillage or land management changes, for example undertaking minimum tillage or stopping cultivation altogether. On fragile soils like the Takapau silt loam, any form of tillage that places pressure on the soil aggregates will result in significant aggregate breakdown in the plough layer. Landusers therefore have little opportunity to manipulate aggregate size to minimise erosion risk.

b) Soil aggregate stability

The wet aggregate stability results are surprising and difficult to explain. Anecdotal evidence from land managers in Hawke's Bay, and from work by Eastwood (1999) indicates that the Takapau silt loam soil is more fragile than the Pakipaki sandy loam. Visual assessment of the two sites supports this view. Wet aggregate stability tests showed that the Takapau plots were statistically more stable under wet sieving than the Pakipaki plots. This surprising result mirrors findings in last year's work by Eastwood where a seemingly more fragile soil exhibited higher aggregate stability under the wet sieving technique.

A potential reason for the disparity between visual observations and measured stability is that the weak aggregates broke down during transportation. This is unlikely due to the care taken to protect the aggregates prior to dry sieving for size distribution. Significant abrasion and aggregate breakdown would be most likely to occur during the dry sieving procedure. The same treatment was applied to all samples and therefore if the weakest aggregates broke down in Takapau samples then the same should apply to Pakipaki plots.

Given the results of wet aggregate stability tests it is concluded they are not useful for explaining the influence of aggregate strength on wind erosion rates.

c) Soil moisture content

Gravimetric soil moisture contents were significantly different between sites but not between treatments within each site. The moisture content on Takapau plots appears to have had an effect on the supply of erodible particles as discussed below. It is not certain what the threshold is before surface soil moisture will begin to have a large bearing on erosion rates. Visual assessment during the fieldwork suggests that the Pakipaki plots were very dry and that moisture was not a factor. Significant concerns were held over the moisture content of Takapau plots, to the point where cultivated strips were left longer than usual before experiments were conducted in an attempt to lower moisture levels. The mean moisture contents of both sites were 7.7 percent and 4.7 percent for Takapau and Pakipaki respectively. The question is apparent: is 3 percentage points more in moisture content enough to have a significant difference on erosion rates? It is hard to tell, because we are discussing two very different soils with different characteristics that confound the influence of moisture. It does appear that surface moisture contents (10 mm depth) of 7 to 8 percent begin to influence erosion rates. This is an important finding in terms of land management on Takapau soils, because it highlights the need to maintain high moisture for as long as possible.

d) Surface roughness and vegetation measurements

It is uncertain how useful the surface roughness measurement was in describing the variation in sediment flux. Concern has been expressed by some authors that the chain method would give the same measurement for a surface with many small roughness elements as for one with a smaller number of larger roughness elements (Merrill *et al.*, 1998). An additional point is measurements were collected on plots after the five wind tunnel runs so as not to disturb the soil surface prior to erosion simulations and some smoothing of the surface had already occurred. The temporal characteristics of wind erosion mean that flattening of the soil surface occurs during the erosion process, and to be fully representative of the roughness during each speed simulation, roughness measurements would be required after each one minute run. This is impractical because it would require the tunnel to be lifted of the plot after each run, measurements taken, and then re-installed without disturbing the soil surface.

There was no significant difference found between the mean surface roughness measured for the three Takapau treatments, suggesting that roughness was not different across the plots on that site. The regression using surface roughness as one of the variables to explain the variance in sediment flux identified it as the second most important explanatory factor. When modelled with moisture content, surface roughness explained 41.2 percent of the variance in sediment flux on Takapau plots.

e) Sediment flux

The observed decrease in sediment flux after the fourth wind speed was particularly pronounced on the Takapau plots. There could be many reasons for this, but a major influencing factor is likely to be the higher moisture content of the surface soil measured at the Takapau site in comparison to the Pakipaki site. This is supported by the regression performed on all measured variables on Takapau plots, where moisture content was found to explain 26.1 percent of the variance in sediment flux, the highest R^2 of all the variables entered. At the time of wind tunnel testing on the plots, it was noted that the dry layer of topsoil was removed between the threshold velocity and approximately 40 kmh^{-1} (0.25 m height). This also is linked to the sediment supply limitations found in section 4.3.1. All possible actions were taken to dry the topsoil out to a state where moisture would not be a determining factor in erosion rates, including cultivating plots over a day in advance – in turn running the risk of losing the erodible fraction if a strong wind event occurred. Rain, and lack of warm temperatures to dry out the soil surface, disrupted the trials on the Takapau site. The 24 Pakipaki plots were sampled over a 10 day period, but completion of all the Takapau took over a month and a half due to high soil moisture levels. The frequent rain and higher moisture contents might were probably a major influence on the limited supply effects on Takapau plots.

There are some implications of the limited supply on Takapau plots for landusers. The results suggest that the erodible fraction of a soil with moist subsoil (below 10 mm depth) will be stripped in winds less than 40-45 kmh-1 (57 - 64 kmh^{-1} at 10 m height). In medium strength winds of easterly or southerly direction, the sub surface moisture may prevent continued wind erosion. In northerly or north-westerly winds, which have relatively higher evaporative energy potential, the moisture may be drawn out of the surface soil layer very quickly and the protection it offers will not be long-lasting.

There are also implications for the extrapolation of the data collected in this project. The tail-off in erosion rates occurred after a cumulative erosion period of four minutes, at speeds not exceeding 45 kmh^{-1} at 0.25 m height (approximately 64 kmh^{-1} at 10 m height). If considered on a whole paddock scale this information suggests that erosion rates may be limited during a high wind event after a little as four or five minutes. This would be true if the limiting factor were moisture content, although wind with high evaporative potential can rapidly remove moisture from the soil surface as discussed above. If the limiting factor in tunnel-related erosion is due a soil physical characteristic such as crusting, the supply may actually become less limited over time in a natural event as saltation bombardment breaks down the crust. This emphasises the limitations of extrapolating wind tunnel-based data temporally or spatially, and highlights the care required when quoting such data.

f) Soil aggregate distribution v sediment flux at 35 kmh^{-1}

The relationship between the percentage of soil aggregates over 0.85 mm and sediment flux at 35 kmh^{-1} forms a large part of this project. It is specifically designed to address Objective 2, identified earlier in this thesis. Following on from the trends discussed above, the Takapau site showed markedly different results compared to the Pakipaki site. Increasing tillage intensity did not produce significantly different levels of aggregates >0.85 mm (dry aggregation), and all of the plots had dry aggregation levels between 22.9 and 33.5 percent, a very narrow range. Consequently, no relationship was exhibited between erosion rate and dry aggregation. This is not to say that the proportion of large aggregates would not play a role in the Takapau silt loam soil type, more that the cultivation methods used failed to achieve a wide enough range of aggregate sizes to allow a relationship to be found. The possible reasons for the narrow range of aggregate sizes are discussed above.

The Pakipaki plots produced a larger range of dry aggregation values, from 16.4 to 68.8 percent. Increasing cultivation intensity did not correlate with decreasing number of large soil aggregates, but nevertheless a wide range of values was produced. This range enabled a trend to develop between aggregate size and sediment flux, as shown in Figure 4.3.8. The relationship between dry aggregation and sediment flux did not prove to be statistically significant, due to the high variance in results. The variability highlights the difficulty in isolating one variable in wind erosion research because there is a myriad of factors involved and to quantify each one accurately is very difficult. In addition, the equipment used may introduce variance through the wind flow characteristics of the tunnel and sampling errors.

Dry aggregation versus sediment flux in the Pakipaki plots shows some similarities with international findings. Leys *et al.* (1996) found that on soil with greater than 40 percent dry aggregation erosion reduces to negligible levels. Although by no means conclusive, the Pakipaki plots exhibit a tail off in erosion rates above 40 percent aggregation. Wind erosion still occurred at greater than 60 percent dry aggregation (under 2 $gm^{-1}s^{-1}$), however this may be due to the lower particle density of the pumice-based soil in comparison to clay soils in the Australian study.

g) Size of aggregates in eroded material

The results of sieving collected sediment samples into creep, saltation, and suspension categories highlights the importance of saltating material in erosion. The approximate proportions of 10-15 percent creep, 65-70 percent saltation, and 10-20 percent suspension mirrors international studies on the size distribution of eroded soil (Sterk & Raats, 1996; McTainsh & Leys, 1993). These results provide some indication of the collection performance of the sediment sampler used, and suggest that it is sampling all forms of erosion movement. The proportion of material moving in suspension is also important for the estimation of nutrient losses from Takapau silt loam and Pakipaki sandy loam soils.

The increase in proportion of creep-size aggregates from both sites with an increase in tillage intensity is an interesting finding, especially on the Pakipaki site where soil surface aggregate size analysis showed a decrease in the same sized material. It is possible that increased cultivation acts to 'fluff up' the soil surface and decrease bonding between aggregates, therefore freeing larger particles to roll along the surface.

h) Nutrient analysis

The nutrient analysis of the suspended fraction of the Pakipaki and Takapau sites aimed to provide an insight into an economic cost of losing topsoil during a wind erosion event. Shearer (1982: cited in Cresswell, 1990) indicated 100 tonnes of topsoil eroded from the Hakataramea Valley would contain approximately 85 kg of Total P, 55 kg of Total S, and 1015 kg of total P. Cresswell (1990) placed a cost on such a loss, quoting \$1100 ha^{-1} in 1990 terms. Nutrient analyses carried out for this project provided plant available nutrient losses, rather than total N, P and K. This is more realistic if the aim of the exercise is to show immediate losses of nutrients because the suspended soil lost from the paddock will carry a higher proportion of plant available nutrients than surface soils (Zobeck & Fryrear, 1986; Leys & McTainsh, 1994; Sterk *et al.*, 1996).

Lorentz, 1996 indicated losses of available nutrients in 100 tonnes of a typical Hawke's Bay topsoil, as shown in Table 5.1.1. Also shown in Table 5.1.1 are the comparable losses that would occur from 100 tonnes of suspended soil measured in this project.

Table 5.1.1: Losses of available nutrients in 100 tonnes of soil

Nutrient	Lorentz, 1996	Takapau suspension	Pakipaki suspension
Phosphorus	3	0.88	2.27
Nitrogen	2.5	n/a	n/a
Calcium	200	5.57	4.29
Potassium	30	0.34	0.16
Magnesium	1.5	0.29	0.30
Sulphur	1	3.35	2.23

Nitrogen is one of the principal losses from wind erosion, but plant available forms are very volatile and were not measured for this project.

Comparing the results of this project to those of Lorentz (1996) raises some issues. The measured losses of Potassium and Calcium are orders of magnitude lower than those quoted by Lorentz, suggesting a possible calculation error. Recalculation of the figures did not give a different answer.

Using plant available nutrients to calculate the monetary value of nutrient losses produced figures that only came to several dollars lost nutrient per 100 tonnes of suspended sediment lost. These figures have therefore not been quoted in this report. The difference between the losses found in this thesis and those quoted by Cresswell centre around the use of Total nutrients for calculations. Also, it is likely that the 100 tonnes of soil used related to total soil flux, not just the suspended fraction. To move 100 tonnes of suspended soil, at 15 percent of total flux, would mean a total soil movement in the order of 667 tonnes. This is a large mass of soil to be moved, and would only apply to regional losses during an erosive event, or paddock-scale losses over a decade. Calculations of nutrient losses require many assumptions concerning loss rates and actual nutrient losses in the soil moved.

i) Investigation of limited supply

The investigation into the possibility that the methodology adopted for this project, namely five sequential runs on each plot, proved the stated H_0 to be false. The alternative hypothesis, which states:

> H_a: *That the supply of erodible soil particles* **is** *limited at any of the five wind velocities simulated on each plot.*

is therefore accepted. This finding could have obvious implications for this research and the use of the LUWT in general. The results revealed that, with a standard above-threshold wind speed and soil surface characteristics, the first run of the wind machine has the potential to erode a much higher proportion of soil than subsequent runs.

It was noted in the methodology section that the approach adopted had possible limitations in this area, and that it constituted the 'lesser of two evils'. The recognition of the issue was why this sub-experiment was designed and carried out.

Limited supply of erodible material should not affect the crux of the research, to investigate any relationship between soil aggregate size and erosion rates. The problem should be constant over the whole experiment, so the results will still be relevant proportionally. The results that do require qualifications are the erosion threshold point and actual sediment flux rates. International wind tunnel studies presented in the literature review of this thesis often quote the danger involved with extrapolating field tunnel-scale data, to a per hectare scale, or relating it to natural rates of erosion. The limited sediment supply issue illustrating in this report reinforces that assertion.

It is possible that the wind velocity used (35 kmh^{-1}) may have a more pronounced effect on the level of stripping than when velocities are started at below threshold level and incrementally increased. An interesting approach to assess the significance of limited supply in this project is to compare the sediment flux at 35 kmh^{-1} on T2 plots with the limited supply plots, which were treated in the same fashion. Mean flux for T2 plots was 5.7 $gm^{-1}s^{-1}$, and for limited supply plots it amounted to 8.19 $gm^{-1}s^{-1}$. This illustrates that at 35 kmh^{-1} there may be a significant impact due to lack of sediment source. Therefore the erosion rates stated in the results section are probably underestimates of actual erosion rates on a freshly cultivated surface. This probable underestimation is compounded by tunnel airflow mechanics because erosion rates in tunnel simulations may also be underestimated due to the short working length preventing full expression of abrasion and effects (Leys *et al.*, 1990).

It would have been interesting to analyse the eroded soil captured after each run in the limited supply trial for the proportion of particles transported in the suspension, saltation, or creep fraction. For example, it is possible that the first run on each plot predominantly removed suspended particles. This information might have given a clearer indication of the processes behind the limited supply of erodible particles. During weighing of eroded samples, soil from the three runs completed at each plot were bulked into one bag, preventing individual sieving of aggregates being undertaken.

j) Minimum tillage

The results found in the minimum tillage simulations were striking. Erosion rates under minimum tillage were almost non-existent and appeared to be limited after the fourth wind speed was simulated. Compared to mean sediment flux at 35 kmh^{-1} from the lowest tillage intensity in the other treatments, 3.4 $gm^{-1}s^{-1}$ and 1.8 $gm^{-1}s^{-1}$ for T1 and P1 respectively, the minimum tillage plots exhibited dramatically lower erosion, not surpassing 0.25 $gm^{-1}s^{-1}$ even at the highest velocity of 50 kmh^{-1}.

It should be noted that the wind tunnel was placed perpendicular to the slot direction, and therefore any saltating aggregates would probably have been trapped in the vegetation between strips or by the clods in downwind slots. Erosion rates might be higher if the wind runs parallel to slot direction. The tunnel was placed over the minimum tilled strips in this fashion for two reasons, the first being that running the tunnel parallel would cause bias depending on where the sampler was placed, for example if it were placed on top of the disturbed strip erosion rates may be significantly higher than if it were placed on the undisturbed surface. The second reason was that the HBRC advises land managers to plant crops parallel to the prevailing wind, (usually north-westerly) and running the trial in this fashion gives some firm data to reinforce such advice.

5.1.4 Qualifications to use of results from this thesis

The results outlined in this thesis indicate erosion rates within the limits of a portable wind tunnel. Extrapolation of the results temporally or spatially, for example to a per-hectare scale, is inadvisable due to differences between tunnel erosion processes and those in a whole field context. The differences arise from the short working section (3.5 m) where erosion has not yet reached an equilibrium rate because saltation avalanching, armouring, and abrasion have had little time to develop (Leys *et al.*, 1996). Additionally, there are possible flow constraints in the tunnel, for example axial flow may still be present and full turbulent structure is not simulated. Cumulative wind simulations on each plot also introduce bias due to limited supply of erodible aggregates for each separate speed. The results should also be viewed as only representative of the two soil types investigated with specific soil physical characteristics, and caution used when attempting to estimate erosion rates on other soils in the region using these data.

It should also be noted that, unless otherwise stated, the wind velocities quoted in this thesis relate to speeds at a certain point in the tunnel, equating to where the erosion sampler was placed. Wind speed quoted by meteorological services is commonly measured at 10 m above the ground. In relation to the speed at 0.25 m height in the tunnel, the 'equivalent' 10 m wind speed will be greater, due to lower frictional forces. Therefore any erosion thresholds discussed in this thesis will actually be slightly higher if they are related to meteorological data.

5.2 WIND EROSION MANAGEMENT IN HAWKE'S BAY

The true usefulness of data and scientific information lies in its practical application. In the case of this project, it is the implications for the management of wind erosion in Hawke's Bay. This research is extremely useful for land managers and the HBRC, because it forms the first quantified assessment of wind erosion rates in the region, and investigates the possible influences on these rates. The main outcomes discussed above surround the fact that there are soil types in Hawke's Bay that are very vulnerable to wind erosion. This vulnerability is influenced by soil aggregate size, which in turn is influenced by cultivation intensity. The main implications of this project in respect to wind erosion management therefore relate to these factors.

There are many possible approaches to wind erosion management on arable land, including:

1. *Reducing the wind velocity at the soil surface.*
2. *Trapping soil particles.*
3. *Increasing size of soil aggregates.*

Nicholas *et al.*, (1995) produced a literature review on the possible methods of wind erosion control for Hawke's Bay landusers, therefore in this section the three approaches will be discussed with respect to the information gathered through the literature review and fieldwork components of this project.

5.2.1 Reducing wind velocity at the soil surface

The use of windbreaks, maintenance of crop residues, surface roughness, and strip cropping are all possible methods of using friction to slow wind velocities near the soil surface. They are also all very pertinent for use within the environmental and farm management parameters specific to Hawke's Bay.

A major result from this project was the quantification of just how little erosion can occur under a minimum-tillage system. Such a system integrates almost total maintenance of crop residues with development of surface roughness through planting perpendicular to the prevailing erosive winds. Anecdotal evidence collected through discussions through landusers in the region suggests that uptake of such a system is still hindered by the mindset that minimum-tillage is a higher risk system than conventional cultivation, and likely to result in lower yields. The LandWise initiative discussed in section 2.2.3 includes a field trial designed to illustrate that growing sweetcorn with minimal tillage can be financially equivalent to conventional cultivation. Seeing the results in person will be the best way to convince landusers of the benefits of converting to such a system.

The reduction of wind velocity over the soil surface is relevant to the results of this project. The fragile nature of the Takapau silt loam soil illustrated a high susceptibility to aggregate breakdown with even minimal tillage. Therefore if a seedbed is required that needs the soil to be worked, for example the crop cannot be planted by direct drilling or minimum tillage techniques, the aggregates on soils such as the Takapau are very likely to be broken down to an erodible state. Consequently, the threshold velocity will be lowered and the land manager must look for methods of slowing the surface wind velocity.

Surface roughness is applicable in soils that have a high enough aggregate stability that they can be cultivated and retain large aggregates, and resist abrasion of these aggregates under bombardment by rainfall or other soil particles. Of the two soils investigated in this study, the Takapau does not suit wind erosion management through surface roughness alone, while the more stable Pakipaki soils may suit this method.

The most applicable techniques for both soil types are those that involve vegetation. Windbreaks, maintenance of crop residue, and the use of strip crops are all used in Hawke's Bay, but to varying degrees. It is important that landusers are aware of these techniques as options within their current cultivation management systems, and are able to apply the most appropriate technique to their individual situation.

There are often gaps between knowledge of wind erosion management techniques and uptake of these practices. The reasons for this can be many and varied, but often they are based on economics. International research has found that although many landusers know about shelterbelt benefits, most do not carry through with planting or maintaining shelterbelts. The main barrier to uptake is economic as many landusers consider the costs of shelterbelt establishment and maintenance to exceed the benefits received by them (Cable & Cook, 1997). This is also applicable to Hawke's Bay, as indicated in a small survey of arable farmers by Eastwood (1999). The HBRC has recognised the problem and is attempting to address it with grants for erosion-related plantings, but the major uptake gains will come though convincing landusers that the benefits from shelterbelts are more than just the timber they provide. There needs to be a wider consciousness of the non-market and diffuse costs of wind erosion. This issue is discussed further in the next section.

5.2.2 Trapping soil particles

Ridging or roughening the soil surface are common methods used in the United States to trap moving soil particles. Ridging the soil through cultivation has minimal application to Hawke's Bay due to the crops grown there and their seedbed and harvesting requirements. Maintaining surface roughness was discussed in section 5.3.2, and is a viable option only on soils with stable aggregates and where a crop can germinate in a relatively rough seedbed. It probably is less applicable to Hawke's Bay than other methods of erosion control using vegetation and minimum tillage techniques.

Strip crops and surface vegetation can also act to trap soil particles, in addition to their ability to reduce surface wind velocity. These methods are discussed in section 5.3.2 and in Nicholas & Kemp (1995).

5.2.3 Increasing the size of soil aggregates

Soil aggregate size is an important aspect in wind erosion management, and the emphasis on aggregate size in this thesis is an acknowledgement of that fact. It is this area of wind erosion management that the results from this thesis can be applied. A strong relationship between soil aggregate size and rates of erosion may not have been discovered through the fieldwork in Hawke's Bay, but the weight of international literature quantifying the relationship, discussed in the literature review section, has proven the link.

Maintaining or increasing the size of soil aggregates can be achieved through organic matter retention and minimising physical impacts that might cause aggregate breakdown, for example stock trampling. Organic matter levels are increased through crop rotations that include grasses and legumes and returning crop residues to the soil. The most effective method of increasing organic matter levels can be through not cultivating the soil at all and using direct drilling or minimum tillage techniques instead.

In terms of cultivation techniques to maintain erosion-resistant aggregates, the focus needs to be placed on minimising tillage wherever possible. The choice of cultivation method must take into account the sensitivity of the specific soil to aggregate breakdown. The Takapau soil, for example, is very sensitive to aggregate degradation and this should be a primary factor influencing cultivation management.

Soil moisture retention is another important erosion control option identified by this project. It is more spatially and temporally variable than many of the other methods discussed above, but it can be applicable in some situations. Chemical fallowing instead of ploughing and rolling can help retain moisture, and such a system can be appropriate on fine-textured soils such as the Takapau silt loam where little cultivation is required to produce the required seedbed. In some system irrigation can also be used as a temporary wind erosion control technique, but in most cases it is impractical due to the time and volume of water required to cover whole paddocks, and the rapid removal of moisture by wind with high evaporative energy.

5.2.4 Summary

Each of the wind erosion management techniques listed above might have some level of effectiveness if applied individually, but the real control of erosion is achieved through integration of several methods. Adoption of an erosion control paradigm in respect to whole farm management is essential, for example including possible erosion control methods in the next seasons crop rotation planning, and budgeting for investment in shelterbelts.

5.3 POSSIBLE POLICY INITIATIVES FOR WIND EROSION MINIMISATION

5.3.1 Factors influencing uptake of management advice

In order to discuss possible policy initiatives uncovered from this research, it is first useful to distinguish that there will be barriers to policy implementation and uptake, and outline what some of these barriers may be in regard to wind erosion. There are many possible factors influencing uptake of wind erosion management techniques and these will affect any the design and implementation of any policy initiatives. As discussed previously economic barriers, real or perceived, are often significant impediments to adoption of new techniques (Cable & Cook, 1997). A study in Sahel also found that although protection against wind erosion by wind breaks was a promising measure, farmers were reluctant to implement them due to uncertainty about their benefits (Michels, 1994: cited in Sterk, 1997).

The identification of economic benefits surrounding a management option does not lead to instant uptake by landusers. A survey of landusers in Canterbury found that practical experience, soil conditions, and types of crop to be grown, rather than cost efficiencies influenced the choice of cultivation method (McGuigan, 1989). Erosion control was considered the least important factor. The survey identified a shift from conventional to reduced cultivation in Canterbury but the decision to change was driven more by cost effectiveness, maintenance of soil structure and moving to an easier system than erosion control (*ibid.*). Changes in cultivation practices are also influenced by the type and age of equipment owned by the landuser. The landuser will obviously be reluctant to buy new equipment required to undertake minimum tillage if they have a plough, discs, and cultivator that will return them little if sold.

There is also an overall need for awareness of wind erosion as a serious issue in Hawke's Bay before any initiatives will be successful.

5.3.2 Policy approaches at regional council level

The Regional Council is very focussed on reducing the incidence of accelerated wind erosion through non-regulatory methods. Land management officers are very proactive on the issue, facilitating research, organising field days and demonstrations, collecting information for dissemination to arable landusers, and providing one-on-one advice were required. The Council has a well-rounded repertoire of policy approaches as just mentioned, but the impetus for increased erosion control needs to be transferred to landusers themselves, and the current LandWise initiative is aimed at doing this (section 2.2.3).

The dissemination of information is a very important facet of the non-regulatory approach adopted by the HBRC. Uptake of the information requires wind erosion being accepted as an issue by landusers. The issue therefore needs to be highlighted, and emphasised to the wider community. Frequent articles in local papers on the subject currently aim to achieve this goal, but there are other possible approaches.

McTainsh & Leys (1993) discussed a climatic index of potential erosion. The index utilises wind erosivity and soil moisture information to predict wind erosion risk. A similar index might be of use to the HBRC to increase awareness of wind erosion risk in the region on a weekly basis. Using basic information supplied by this project on wind erosion thresholds and rates for two erosion-vulnerable soils in the region, and using meteorological data, the Council could turn a long-range weather forecast into a wind erosion risk scale. A scale could be devised which states the potential erosion risk for certain areas of the region as either 'extreme', 'high', or 'moderate', when vulnerable soils are cultivated.

The scale would be very general in application, and would operate in much the same fashion as the 'Fire Risk' scales that are used throughout New Zealand. Adjustable signs could be erected in the most erosion-prone areas, and a erosion-risk scale could be included in the local newspaper during periods of high erosivity, for example in a weekly farming supplement.

The limitations of such a scale would occur due to the varied nature of weather and soils across the region, and trying to produce a standard 'erodible' condition against which the climatic conditions could be compared. Having a low risk day or week may lead to problems if it does blow because a false sense of security may be created. Any such initiative would have to be carefully constructed as a guide only, and so as not to open the HBRC to criticism or even litigation.

An alternative approach is to undertake site specific wind erosion risk assessment, using the information uncovered by this thesis. Individual properties could be assessed for their erosion risk, in line with the farm management plans produced by the council. The relative risk would be based on the soil types present, current management techniques, presence of shelterbelts, and potential wind run. Some general management techniques to reduce this risk could also be suggested. This approach may not be feasible as a stand-alone assessment due to the cost of staff input, but could be included in an overall erosion assessment – or as a prerequisite to grants for shelterbelt establishment.

Whatever approach adopted by the HBRC to address the issue of wind erosion in the future, it needs to take into account the physical processes of wind erosion, the social and economic constraints faced by landusers, and the capabilities of the council itself.

5.4 ACHIEVEMENT OF PROJECT OBJECTIVES

The focus of a research project is to fulfil the original study objectives. It is useful to look back at the objectives stated in the introduction and briefly discuss how they were achieved, or if they weren't achieved, what the major reasons were.

Objective 1:

Investigate the effect of different cultivation practices on wind erodibility of selected Hawke's Bay soils.

Several different cultivation practices were simulated for this project, all indicative of practices used in Hawke's Bay. The results discussed above proved very interesting and not completely in line with what may have been expected. The actual effects of increasing cultivation intensity were not statistically significant, but the low erosion rates under minimum tillage is a graphic example of the potential for wind erosion control through cultivation management.

Objective 2:

Investigate the influence of soil aggregate size on sediment flux of cultivated soils.

A significant relationship between soil aggregate size and sediment flux was not determined in this project. This is not a result of poor selection of cultivation methods, rather a result of the intricate factors involved in wind erosion. A range of soil aggregate sizes was not produced on the Takapau site, probably due to the extremely fragile nature of aggregates in that soil. Cultivation on the Pakipaki plots produced a wide range of aggregate sizes but although there is an indication of a relationship, it was not statistically significant. The objective of investigating the influence of soil aggregate size on erosion rates was achieved through the methodology adopted, but no firm conclusions can be made on the nature of the relationship.

Objective 3:

Discuss implications for management of cultivation to reduce wind erosion in Hawke's Bay.

The results uncovered in this project highlight some interesting wind erosion-related issues. As discussed above, the aggregate structure results on the Takapau trial plots show that cultivation should be avoided on soils with similar characteristics due to the high risk of aggregate breakdown a subsequent wind erosion risk. On such soils the use of minimum tillage, and preferably no-tillage, techniques are the most appropriate for continued arable farming. While results indicated that soil aggregate size can be manipulated on Pakipaki sandy loam soils, the wind erosion risk is still high and this means a whole-farm approach to wind erosion control is required. Such an approach would involve techniques such as stubble retention, minimum tillage, careful tillage timing and establishment of shelterbelts.

6. CONCLUSIONS

Two soils types were used for the investigation, a Takapau silt loam and Pakipaki sandy loam. The local Regional Council identified these soils as vulnerable to wind erosion. A portable wind tunnel was used to simulate erosion on these soils.

Increasing in cultivation intensity did not produce a significant impact on the erodibility of the Takapau silt loam and Pakipaki sandy loam soils investigated. Results indicated that there was an increase in relative erosion rates on the Pakipaki soil, but this was not statistically significant at the 95 percent confidence level.

Erosion rates under a minimum tillage system were almost negligible, and over a magnitude lower than erosion rates on an equivalent soil disturbed by cultivation.

Increasing tillage intensity did not produce statistically significant differences in soil aggregate size on the Takapau soil. Statistical differences ($P \leq 0.05$) identified that increasing tillage intensity produces a seedbed with decreasing levels of soil aggregation.

A narrow range of soil aggregate size > 0.85 mm in the cultivated Takapau soil prevented any relationship being identified between soil aggregate size and sediment flux rates. Visual assessment of the results suggested a negative relationship between percentage of aggregates over 0.85 mm and sediment flux rates on the Pakipaki soil. Regression analysis did not support the relationship at the 95 percent confidence level.

Surface soil moisture was a significant limiting factor on erosion rates at the Takapau site. Moisture levels in the top 10-15 mm of soil averaged over 7 percent and some exceeded 10 percent, causing a limited sediment supply for the wind tunnel research.

Wind erosion management on soils such as those investigated requires an integrated approach. The results of this project indicate that reliance upon erosion control through maintenance of large soil aggregates will not prevent significant erosion from occurring, due weak aggregate stability, especially on Takapau silt loam soils. Management techniques that act to slow the wind surface wind velocity will be most effective on these soils. Such techniques include shelterbelt planting, maintenance of surface residues, and strip cropping. The most effective method of reducing wind erosion on arable land is use of minimum tillage techniques.

The methodology used for this project encountered several limitations. Use of cumulative wind erosion simulations on individual plots introduced supply limitations of erodible material. This was exacerbated by high surface moisture contents in Takapau plots. It is recommended that if the portable wind tunnel used for this project is used for similar scientific assessment of wind erosion in the future, its use be concentrated on examining relative differences in erosion rates between soil types, and between cultivation management options. Information derived from experiments with this wind tunnel is not appropriate for estimation of actual erosion rates.

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7.1 PERSONAL COMMUNICATIONS

Griffiths, Elwyn. 1998: Soil Scientist, Hawke's Bay. February 1998.

Bloomer, Daniel. 2000: HBRC land management officer.

Brennan, Kyle. 1998: HBRC land management officer.

Dando, John. Soil physicist Landcare Research Palmerston North. December 1999.

Leys, John: Australian wind erosion researcher, 1999/2000.

McGowan, Hamish. 1999: Post doctoral student at Victoria University. October, 1999

Palmer, Alan: Soil scientist Massey University, 1998.

Scotter, David: Soil physicist. Massey University, March 1998

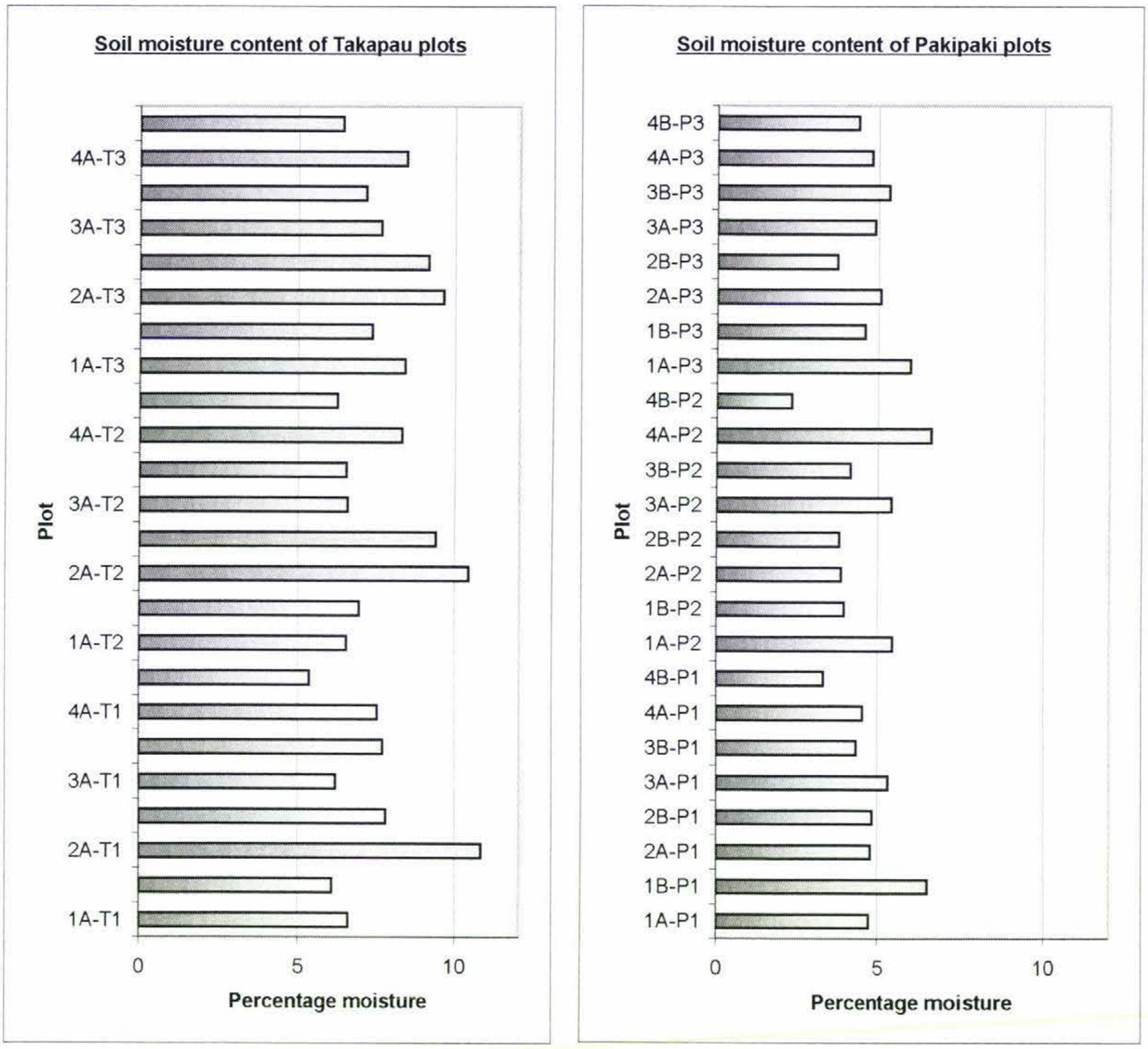
APPENDICES

A-1 GLOSSARY

Aeolian processes:	another name for wind erosion processes.
Wind erosivity:	the capacity of the wind to erode.
Threshold friction velocity (u_*):	the friction velocity value at which entrainment starts.
Boundary layer:	depth of the air flow above a surface where the flow is affected by the friction effects of the boundary or surface.
Surface roughness (z)	roughness of the soil surface.
Erodibility	the susceptibility of soil particles to detachment and transport by an erosive agent.
Site	One of the two soil types investigated.
Block	A collection of six plots. Four blocks at each site.
Plot	Individual replicate of a treatment.

A-2 SOIL SURFACE MOISTURE CONTENT

Figure A-2.1: Soil surface moisture content of Takapau and Pakipaki plots



A-3: SEDIMENT FLUX FOR T1, T2, P1, AND P2

Figure A.3.1: Sediment flux at a range of wind speeds under treatment T1

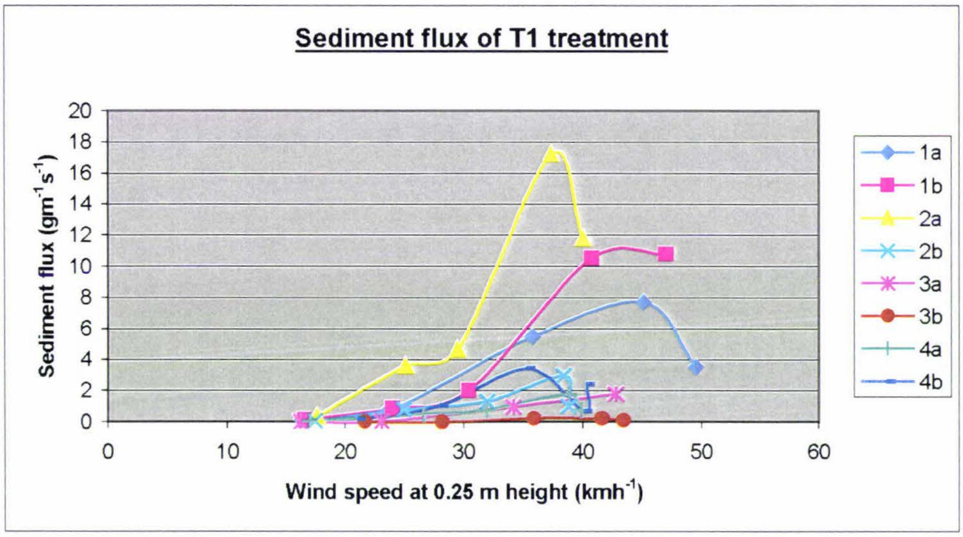


Figure A-3.2: Sediment flux at a range of wind speeds under treatment T2

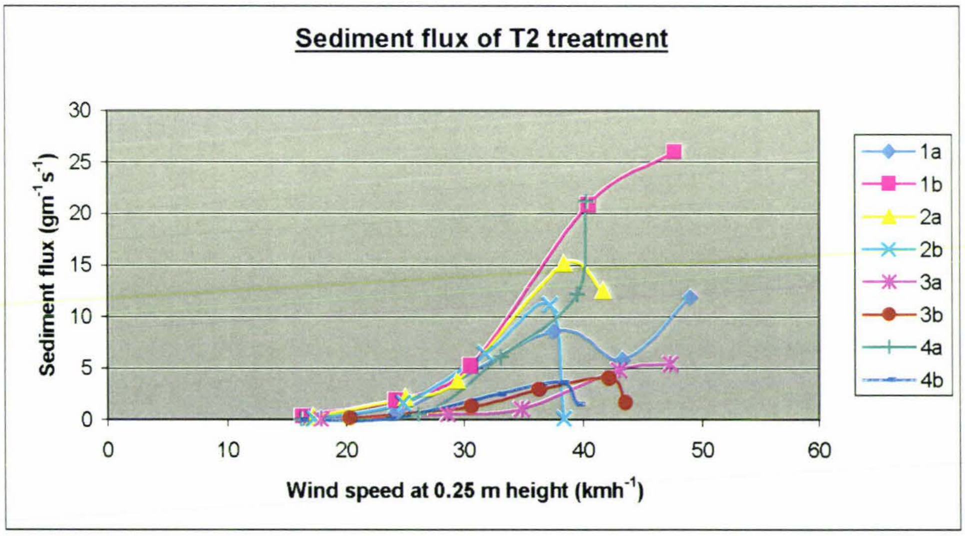


Figure A-3.3: Sediment flux at a range of wind speeds under treatment P1

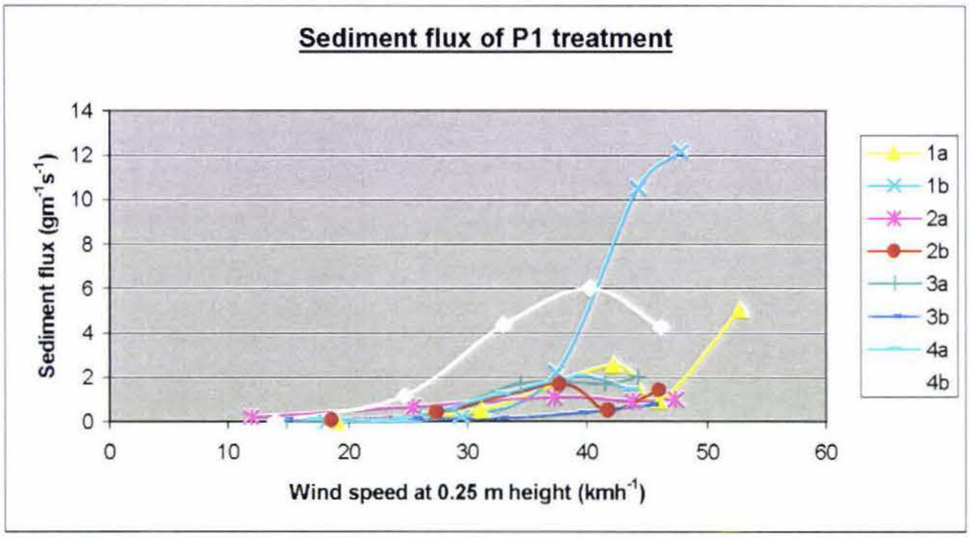
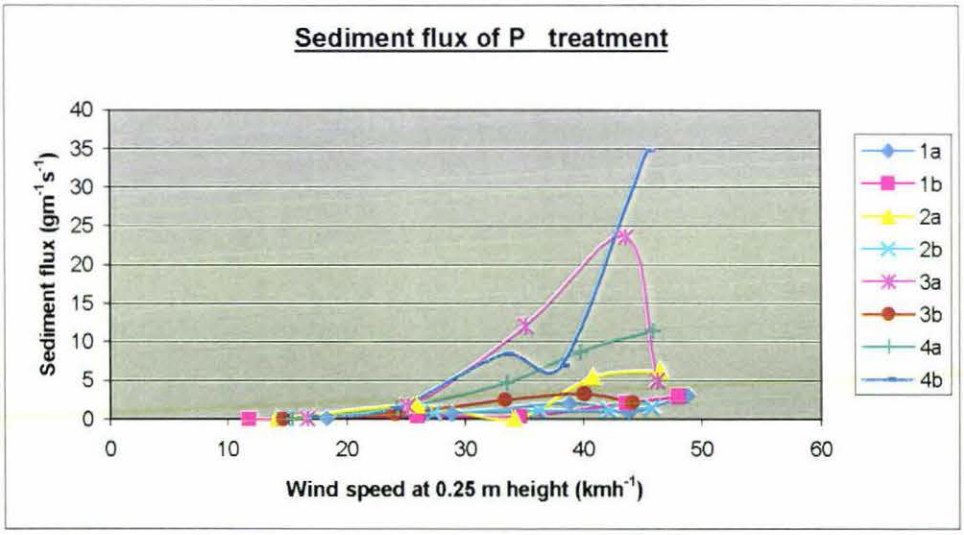


Figure A-3.4: Sediment flux at a range of wind speeds under treatment P2



A-4 MINIMUM TILLAGE SEDIMENT FLUX

Figure A-4.1: Sediment flux at a range of wind speeds under minimum tillage on Pakipaki site

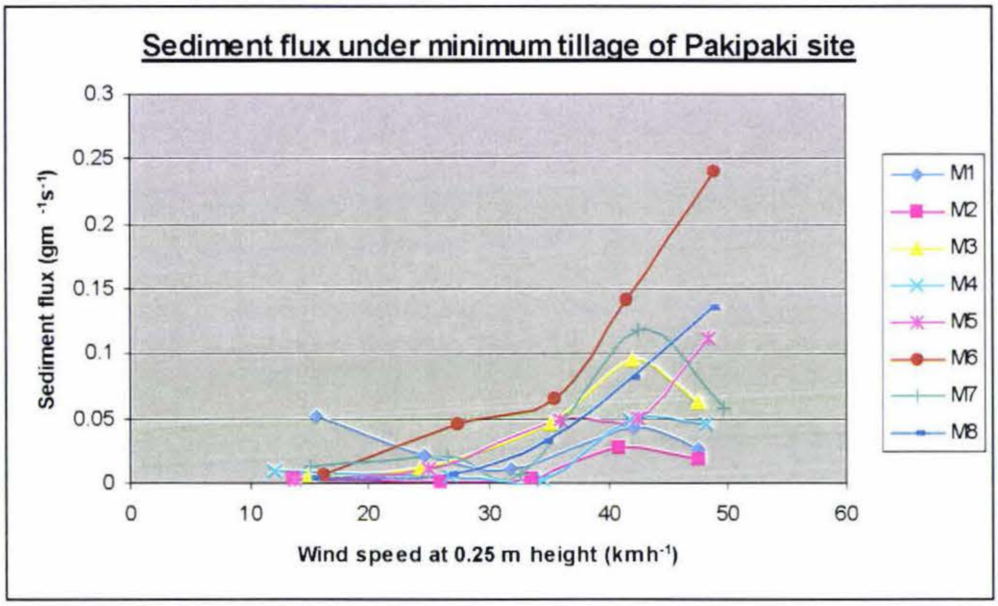
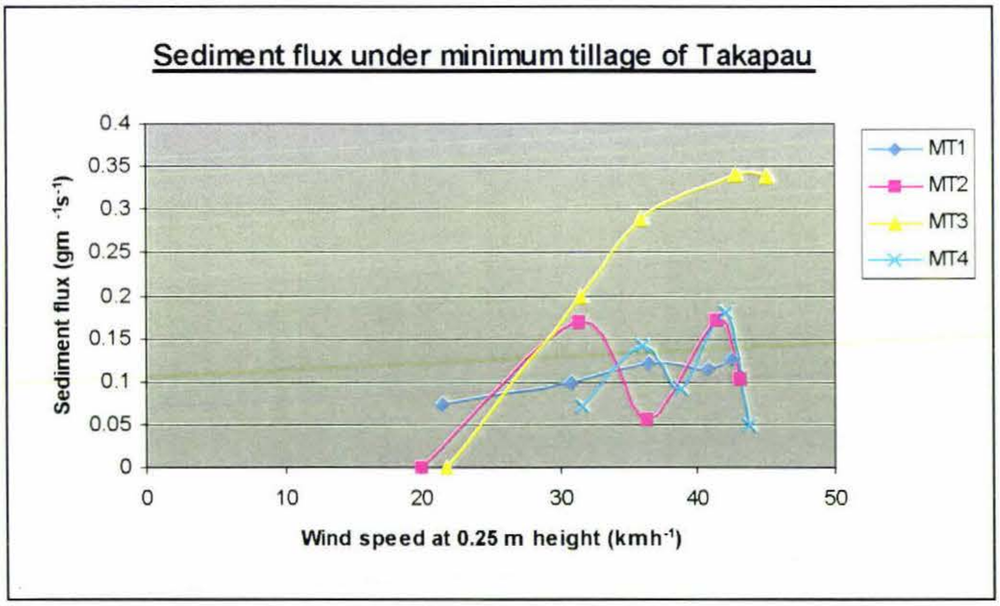


Figure A-4.2: Sediment flux at a range of wind speeds under minimum tillage on Takapau site



A-5 NUTRIENT CONVERSION FACTORS

To convert me/100g to ppm:

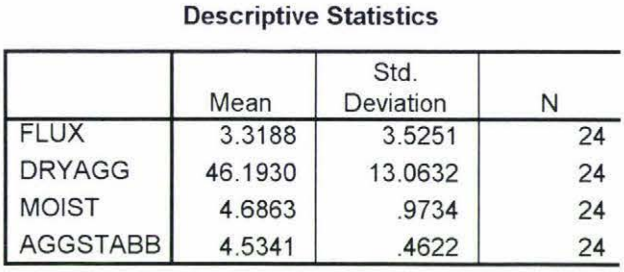
- (K / 1.278) x 10
- (Ca / 2.495) x 10
- (Na / 2.175) x 10
- (Mg / 4.113) x 10

To convert ppm (μg/g) to kg/100t soil

- ppm / 10

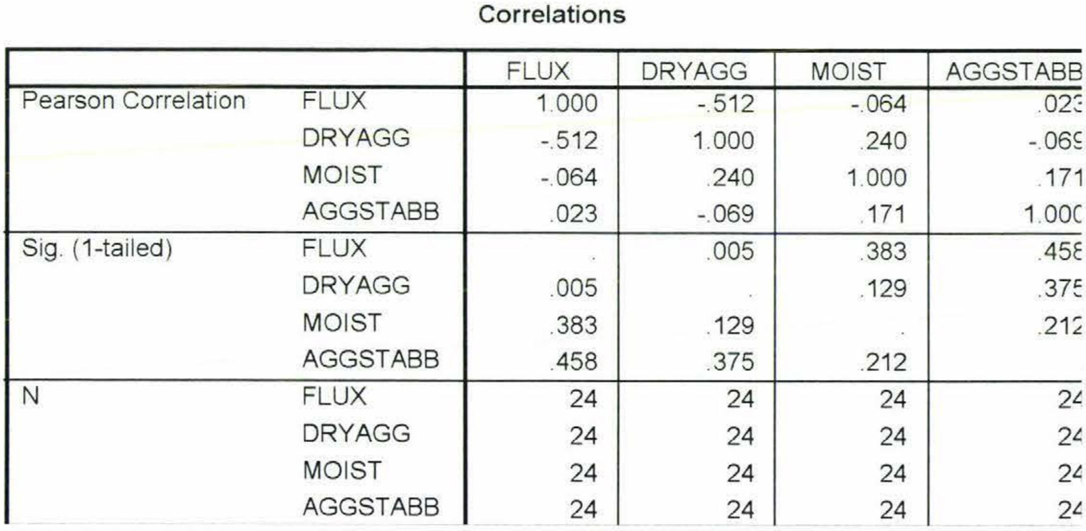
A-6 EXAMPLES OF SPSS ANALYSIS

A-6.1: Regression analysis on influence of aggregation, moisture and aggregate stability on sediment flux.



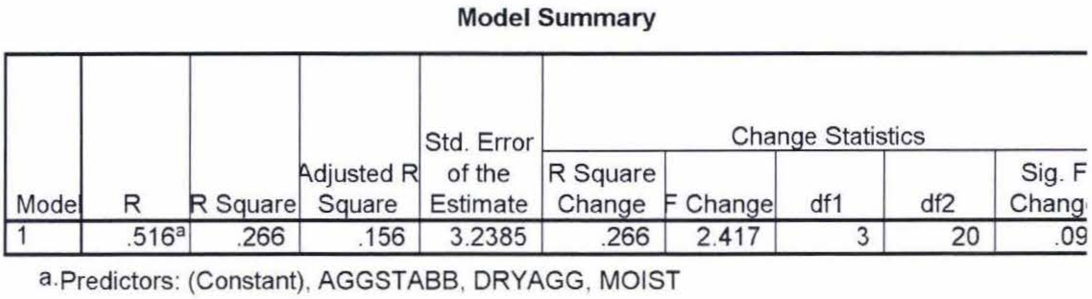
Descriptive Statistics

	Mean	Std. Deviation	N
FLUX	3.3188	3.5251	24
DRYAGG	46.1930	13.0632	24
MOIST	4.6863	.9734	24
AGGSTABB	4.5341	.4622	24



Correlations

		FLUX	DRYAGG	MOIST	AGGSTABB
Pearson Correlation	FLUX	1.000	-.512	-.064	.023
	DRYAGG	-.512	1.000	.240	-.069
	MOIST	-.064	.240	1.000	.171
	AGGSTABB	.023	-.069	.171	1.000
Sig. (1-tailed)	FLUX	.	.005	.383	.458
	DRYAGG	.005	.	.129	.375
	MOIST	.383	.129	.	.212
	AGGSTABB	.458	.375	.212	
N	FLUX	24	24	24	24
	DRYAGG	24	24	24	24
	MOIST	24	24	24	24
	AGGSTABB	24	24	24	24



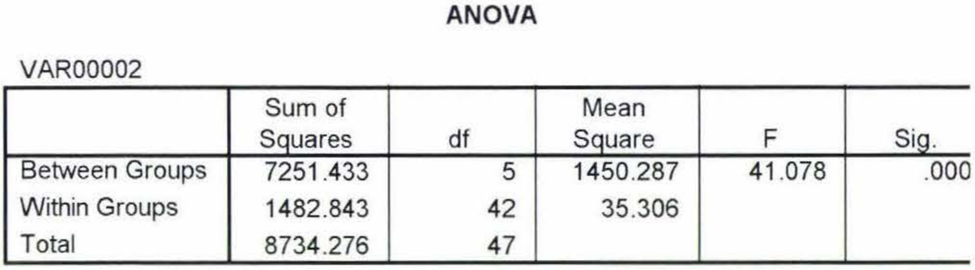
Model Summary

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Chang
1	.516^{a}	.266	.156	3.2385	.266	2.417	3	20	.09

a. Predictors: (Constant), AGGSTABB, DRYAGG, MOIST

Figure A-6.2: One-way ANOVA testing for significance between aggregates size on plots.

1 = T1
2 = T2
3= T3
4=P1
5=P2
6=P3



ANOVA

VAR00002

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	7251.433	5	1450.287	41.078	.000
Within Groups	1482.843	42	35.306		
Total	8734.276	47			

Multiple Comparisons

Dependent Variable: VAR00002
Bonferroni

(I) VAR00001	(J) VAR00001	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1.00	2.00	-.3750	2.971	1.000	-9.6218	8.871
	3.00	.2938	2.971	1.000	-8.9531	9.540
	4.00	-27.4788*	2.971	.000	-36.7256	-18.231
	5.00	-26.6488*	2.971	.000	-35.8956	-17.401
	6.00	-4.9750	2.971	1.000	-14.2218	4.271
2.00	1.00	.3750	2.971	1.000	-8.8718	9.621
	3.00	.6688	2.971	1.000	-8.5781	9.915
	4.00	-27.1037*	2.971	.000	-36.3506	-17.856
	5.00	-26.2737*	2.971	.000	-35.5206	-17.026
	6.00	-4.6000	2.971	1.000	-13.8468	4.646
3.00	1.00	-.2938	2.971	1.000	-9.5406	8.953
	2.00	-.6688	2.971	1.000	-9.9156	8.578
	4.00	-27.7725*	2.971	.000	-37.0193	-18.525
	5.00	-26.9425*	2.971	.000	-36.1893	-17.695
	6.00	-5.2688	2.971	1.000	-14.5156	3.978
4.00	1.00	27.4788*	2.971	.000	18.2319	36.725
	2.00	27.1037*	2.971	.000	17.8569	36.350
	3.00	27.7725*	2.971	.000	18.5257	37.019
	5.00	.8300	2.971	1.000	-8.4168	10.076
	6.00	22.5037*	2.971	.000	13.2569	31.750
5.00	1.00	26.6488*	2.971	.000	17.4019	35.895
	2.00	26.2737*	2.971	.000	17.0269	35.520
	3.00	26.9425*	2.971	.000	17.6957	36.189
	4.00	-.8300	2.971	1.000	-10.0768	8.416
	6.00	21.6737*	2.971	.000	12.4269	30.920
6.00	1.00	4.9750	2.971	1.000	-4.2718	14.221
	2.00	4.6000	2.971	1.000	-4.6468	13.846
	3.00	5.2688	2.971	1.000	-3.9781	14.515
	4.00	-22.5037*	2.971	.000	-31.7506	-13.256
	5.00	-21.6737*	2.971	.000	-30.9206	-12.426