PASTURE CONDITION AND SOIL DESICCATION AS INFLUENCES ON TUNNEL-RELATED EROSION

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Tunnel gully erosion at Wither Hills, Blenheim in the 1950's.

ABSTRACT

Soil conservation control measures have been developed to ameliorate the effects of tunnel-related erosion on agriculture in areas of New Zealand, usually areas with seasonally dry loessial soils. These control measures have included: mechanical destruction of both tunnels and related gullies, establishment of improved pasture, and maintenance of that pasture by lenient grazing. They were designed with the assumption that tunnels had formed as a result of concentrated water penetration into the subsoil via desiccation-induced shrinkage cracks.

Criticism of previous research into the various aspects of tunnel-related erosion was undertaken and enabled the identification of some limitations, contradictions, and wrongly placed emphasis, in the accepted model of tunnel formation in loessial soils in New Zealand.

An experiment was designed to measure the effects of grazing intensity upon soil moisture levels. This experiment resulted in the rejection of the accepted mechanism by which leniently grazed pasture was thought to reduce soil drying and subsequent cracking, as soil drying actually increased with longer pasture. It could not be disproved that the supposed effects of lenient grazing were actually due to the accompanying mechanical treatment or possible climatic changes. However it was shown to be highly likely that the effects of lenient grazing were due to the promotion of the pasture's root growth. Enhanced root growth could restrict both crack development and tunnel initiation, and encourage intact tunnel roof subsidence rather than complete roof destruction - a precursor to gullying. Development of strong root systems is particularly encouraged by lenient grazing in late autumn and early spring. It is recommended that grazing by cattle instead of sheep continue in the areas with seasonally dry loessial soils subject to tunnel-related

erosion. Particular care should be taken in late autumn and early spring to ensure that pasture is not overgrazed. This recommendation is qualified by economic considerations which may dictate that cattle grazing is untenable.

Further research into the effects of grazing on the development of root systems of pasture species is also recommended. This research would have implications for the control of a number of erosion types throughout New Zealand but has unfortunately been largely ignored in the past.

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CHAPTER 1 INTRODUCTION

1i General background

Subsurface erosion (piping, tunnel-gully etc) has been recognised as a significant erosion problem in New Zealand since at least the late 1930's particularly in areas with loessial soils. Early descriptions by Taylor (1938), Cumberland (1944) and Gibbs (1945) were among work which stimulated state intervention via the then Public Works Department in the field of soil conservation. The most spectacular subsurface erosion in New Zealand occurred on the Wither Hills near Blenheim, where it was referred to as tunnel-gully erosion (Gibbs 1945). Historical records and the pedological surveys of Laffan (1973) both indicated that this erosion was at most minimal before the clearance of scrub and tussock in the period 1860-1900. This indicates that it was man-induced or "accelerated" erosion. Accelerated erosion is that which occurs at rates above the natural or geological erosion rates.

Prior to European settlement the climate, soils, vegetation and topography had developed into a state of dynamic equilibrium. The Polynesian inhabitation of Marlborough was accompanied by widespread burning of the indigenous vegetation and possibly resulted in an increase in erosion though not of the same magnitude as that which followed European settlement (Laffan, 1973). The major difference between Polynesian and European settlement was the influx of grazing animals and the development of agriculture associated with the latter. The effect of the animals, principally sheep and rabbits, when accompanied by burning, was a widespread and continued reduction in the original vegetative cover. Subsurface erosion can be seen as an attempt by the pedological, hydrological and topographical elements to regain balance with the changed vegetative and faunal influences. On the Wither Hills, control of these biological influences before 1940 resulted in the situation whereby the soil could not cope with the rainfall. The soil was being lost downslope in tunnel-gullies and as surface wash. Hence the related problems of flooding and soil erosion.

This was the situation when the Public Works Department established the Wither Hills Soil Conservation Reserve in 1944. The Reserve was used as an example of the productive benefit that could be obtained when appropriate management was applied to susceptible areas. Principal soil conservation measures applied were:

- smoothing affected slopes (by bulldozing);
- establishment of improved pasture (deeper rooting and more resistant to drought than former pasture);
- a change to grazing by cattle instead of sheep.

It was thought that analysis of the effects associated with these control techniques may not only provide insights into improving erosion control but also into those processes which operate to initiate subsurface erosion.

Previous research has concentrated on those properties which have been believed to make a soil susceptible to tunnelling. Examples are high levels of potential shrinkage, dispersibility and slaking (Miller 1971, Laffan 1973, Wilms 1979, and others). This line of work ignored the fact that these soils probably had these same properties before severe erosion commenced following European settlement. It is apparent that factors other than the soil properties previously investigated, were responsible for the widespread initiation of tunnel-gully erosion in the period 1860-1940. It is probable that those same factors need to be controlled today if tunnel-gullying is not to redevelop.

It is suggested that the alteration and destruction of the original vegetation was the single event primarily responsible for the initiation of tunnel-gully erosion following European settlement. Conservation works have generally comprised attempts to reverse these effects by re-establishing a 'good' vegetative cover. This does not preclude the possibility that some tunnelling occurred before European settlement. Some large tunnels may well have existed prior to 1860. The reduction in vegetative cover - reduction in root mass/root strength - may well have been sufficient to cause these tunnels to collapse and form gullies. The effects on soil stability associated with the reduction in vegetative cover will be described in a later chapter.

Section ii of this chapter describes the development of soil conservation in New Zealand. This provides a background against which the current aims and ideals of soil conservation (research) can be placed and the value of such clearly seen. In later chapters the processes of subsurface erosion will be examined in some detail, important soil and climatological factors described and soil conservation measures (and their effects) discussed.

There seems little doubt that the conservation works used to control tunnel-gully erosion have been beneficial. (Marlborough Catchment Board, 1981). However it is still unclear as to whether these are the best of the possible options, whether they will continue to be successful, or why they have been successful.

It has been thought that the main effect of removal of vegetation is an increased development of soil shrinkage cracks. However after reviewing and interpreting the literature this effect is seen to be but one of several, and possibly not the most significant.

It was initially expected that the extensive fieldwork planned would elucidate the relationships between levels of grazing, soil moisture levels (desiccation) and the development of shrinkage cracking. The degree to which this could happen was restricted by the wetter than normal summer of 1985-86 but considerable useful information relevant to such (postulated) relationships was gained nevertheless.

Other work involved measuring the relationships between pasture condition and root development. The question of whether the erosion could have been the result of special climatic conditions was also investigated. In an effort to achieve a more cohesive study, additional information was obtained by an extensive search of the literature. This revealed a number of contradictions and omissions in previous research into subsurface erosion. It is hoped that these have been elucidated and our understanding of the topic improved by the preparation of this thesis.

1ii An appraisal of soil conservation

Rose (1985) characterised the operation of soil conservation into three (not necessarily sequential) phases. These were:

i) identification and quantification of processes;
ii) development of soil conservation practices;
iii) evaluation of options into overall policies of land use.

In New Zealand these three phases are apparent, though not complete, and have been subject to continual re-evaluation since the first state intervention into soil conservation in the late 1930s. This intervention was stimulated by the two disastrous East Coast floods of 1938, particularly the 'Anzac storm' which afflicted the Tangoio area north of Napier. This storm clearly brought to public attention the problems - such as soil loss, flooding, lowered water quality, lowered soil fertility and increased slope instability - caused by unsuitable land use practices (McCaskill, 1973). The next few years saw increasing awareness of the types and magnitude of the soil erosion problem facing New Zealand with publications by Taylor (1938), a Committee of Inquiry headed by Taylor (1939), Cumberland (1944), Gibbs and Raeside (1945), Gibbs (1945), Campbell (1945 a, b), and Grange and Gibbs (1946).

Hudson (1981) observed that major soil conservation programmes have only occurred where they have been heavily subsidised by the state. He viewed soil conservation as an issue extending over the next 50 or 100 years given the probable development of cheaper synthetic food sources. This time scale was contrasted with that of those used by political leaders, acting as resource managers, whose outlook was thought to seldom extend beyond the next election, and of farmers who do not expect to pay now for preserving the land for posterity unless immediate economic benefits are also gained. Hudson concluded that soil conservation is in the greater long term interest of the state or community rather than the government of the day or any individual. The New Zealand experience reflects this description.

The Soil Conservation and Rivers Control Act was passed by Parliament in 1941. This Act created the Soil Conservation and Rivers Control Council (SCRCC) whose tasks included:

- the carrying out of surveys and investigations to ascertain the nature and extent of soil erosion in New Zealand;
- the carrying-out of experiments and demonstrations in soil conservation and reclamation;
- the investigation and design of preventative and remedial measures in respect of soil erosion (McCaskill, 1973).

The SCRCC administered the formation of Catchment Boards in those areas where soil erosion and flooding were serious problems. It was through these local bodies and the Public Works Department that the policies of the SCRCC were implemented. The functions of the SCRCC (and the Water

Resources Council) are now discharged by the National Water and Soil Conservation Authority (NWASCA), while the Public Works Department has evolved into the Ministry of Works and Development.

Since 1941 the available soil conservation technologies have changed resulting in better definition of erosion processes and costs and the development of more effective control techniques. Over these years the ethics and philosophies of land use have altered in several respects resulting in changing policies and practices which in turn affect the direction of erosion processes research.

NWASCA has statutory functions which include control of erosion and the wise management of (water and) soil resources (WASCO 41, 1984). NWASCA is serviced by the Water and Soil Directorate of the Ministry of Works and Development, including the three water and soil science centres. The work described in this thesis was carried out as part of the research programme of the Erosion Processes Group of the Soil Conservation Centre at Aokautere. According to Rose's classification (processes, practices and policies - see above) this study would form part of the link up between processes and practices from which appropriate land use policies can be formulated. NWASCA, MWD (Head Office Water and Soil Directorate), and Catchment Authorities are concerned dominantly with establishing policies and encouraging (by subsidy) practices. A principal function of the science centres, and a goal of this study is to strengthen the link between processes and practices.

Soil conservation studies have tended toward the pragmatic. That such an "if it works, do it" approach has been successful can be seen by the amelioration of many soil conservation problems over the last forty years. This approach came from the need to get results quickly if the serious erosion problems recognised were not to get worse.

This pragmatic approach also encouraged the non-specialist. The 1939 Report of the Committee of Inquiry recommended the development of a soil conservation programme involving the "active collaboration and co-operation of foresters, agrostologists[1], botanists, agriculturalists, engineers and soil technologists." Looking back it is possible to say that all of these fields of study plus many more have been involved in the development of soil conservation practices. Nevertheless for the formulation of practices and policies, from individual to national problems, decisions have been made that cut across such academic boundaries, hence the development of a generalist school of thought.

Soil conservation studies are not simply erosion studies in which a process oriented positivist approach would suffice. They are also land management studies which require adherence to a particular set of values or ethics regarding land use. Rose (1985) recognised this philosophical issue. Processes can be identified and quantified via scientific investigation, whereas selecting and designing practices requires "recognition of the priority order of social goals of the landholder" and the overall policy evaluation "depends upon consent to some philosophy or ethic or series of ethics".

For example the economic benefit consequent upon the implementation of conservation works is frequently used as justification although this depends on the land use: social benefits such as security, the ability to maintain a lifestyle, environmental conservation (flora and fauna as well as soils) and aesthetic enhancement, cannot be quantified but still need to be acknowledged.

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1 *Agrostology - the study of grasses*

The recognition of reasons why actions are taken may well be as important as what is done or how it is done. Soil conservation is neither science nor social science but the two combined into an integrated geographic discipline.

In this study an objective quantitative approach has been adopted for the investigation of those processes involved in the initiation and control of tunnel erosion. In considering the relationship of these findings to practices the assumption has been made that continued pastoral use of the land is desired. Consideration of changing this land use 'prejudice' is beyond the scope of this study.

CHAPTER 2 A REVIEW OF TUNNELLING

2i Terminology

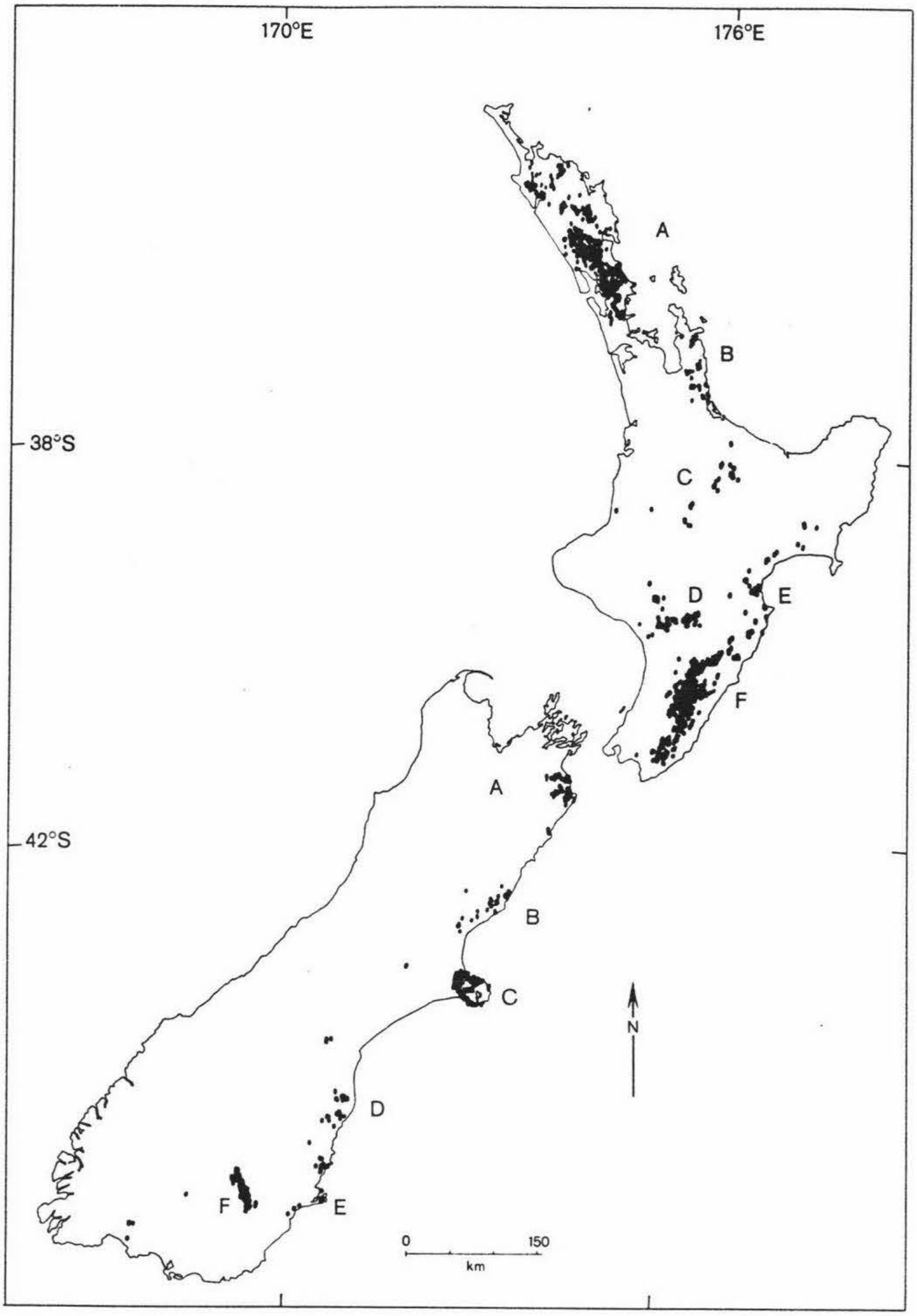
A simple descriptive definition of the tunnelling (or piping) process is that used by Masannat (1980) of "a subsurface, form of erosion which involves the removal of subsurface soils in pipe-like erosional channels to a free or escape exit". Distinctions between tunnelling and piping have on occasion been made - for example by Rosewell (1970) and Sherard *et al.* (1972). However this dichotomy of meaning is now largely ignored and the two words used interchangeably.

In New Zealand the term tunnel-gully is also in common usage. It is regarded as "a compound erosion form initiated by subsurface tunnelling, which often causes surface collapse, leading to open gullying" (Lynn and Eyles, 1984).

The term tunnel-related erosion will be used in this thesis to cover both tunnelling and tunnel-gullying when both are being referred to. It does not refer to any other erosion forms such as soil-slip, which may sometimes have origins in tunnelling (see 2ii).

2ii Occurrence of Tunnel-related Erosion in New Zealand

Analysis of the New Zealand Land Resource Inventory (NZLRI) by Lynn and Eyles (1984) indicated an extensive distribution of tunnel-gully erosion throughout New Zealand (see fig 2.1). From the NZLRI, an estimate of the total area of the type of land in which tunnel-gully erosion occurs can be made. In the South Island NZLRI map units in which tunnel-gulling occurs cover some 99,000 hectares (0.7% of the Island) compared with some 328,000 hectares of the North Island (3% of the Island).



North Island: A, Northland; B, Coromandel; C, Waikato Basin/Volcanic Plateau; D, Manawatu-Wanganui hill country; E, Hawke's Bay; F, Wairarapa.
South Island: A, NE Marlborough; B, Coastal North Canterbury; C, Banks Peninsula; D, South Canterbury/North Otago downlands; E, Otago Peninsula; F, Mid-Clutha valley.

Fig. 2.1 The distribution of tunnel gully erosion in New Zealand (after Lynn and Eyles 1984).

In the North Island, tunnel-gully erosion was recorded mostly on sandstone and mudstone lithologies overlain by yellow-brown earth soils. In the South Island it was mostly recorded on loess covered hillslopes with yellow-grey earth soils. Tunnel-gullies occur in two broadly defined climatic zones - sub-humid to arid, and humid, and in four distinct environments. These are:

a) loess and mixed loess colluvium in sub-humid to semi-arid climates (31,700 ha);
b) soils derived from strongly weathered sedimentary rocks in humid climates (75,900 ha);
c) tephra deposits under a cool humid climate (16,300 ha);
d) colluvial footslope deposits on North Island Tertiary sedimentary hill country with a humid climate (141,200 ha) (Lynn and Eyles, 1984)

Some other associations were noted by Lynn and Eyles (1984). They found that tunnel-gullying was most common and severe on slopes between 16° and 25°, and that it was essentially a hill country and downlands phenomenon except for tunnel-gullying on tephra deposits which usually occurs on flat terrain. They also noted that tunnel-gullying usually occurs in association with other erosion types. In the South Island it was most frequently associated with sheet and soil slip erosion, the occurrence with sheet erosion indicating a possible relationship between areas of bare ground and tunnel-gullies. In the North Island they found soil slip to be the most commonly associated erosion type.

The relationship between tunnel-gullying and soil slip may be significant. Pierson (1983) postulated blocked tunnels as a cause of higher localised soil moisture levels prior to slipping. However Baillie (1975) points out that tunnelflow and mass movement are both likely to occur when throughflow is large, so that the relationship may not be causative.

Throughout both islands approximately 95% of tunnel-gullying was recorded in areas presently under grassland, with only minor amounts recorded under scrub or forest. However identification of tunnel-gullies is hampered under scrub or forest: there may be much more than has been recorded.

In Table 2.1 publications which refer to tunnel-related erosion in New Zealand are set out according to regions mentioned by their respective authors.

2iii The Soil Conservation Problem

Recognition of tunnel-related erosion began as part of the more widespread awareness of soil erosion in the late 1930's. The initial studies concentrated on tunnel-related erosion as a soil conservation problem, for example Gibbs (1945) in New Zealand, Downes (1946) in Australia, and Fletcher and Carroll (1948) in the United States. In all of these studies the problem was recognised after tunnel collapse had occurred and gullies had been initiated. Removal of subsoil by tunnels is of some importance as is the changed hydrological regime associated with this development. However it is after the gullies have developed that serious soil loss, sediment deposition, disruption of production and flooding result. Mason (1981) reviewed the problems relating to the area of dryland loessial soils in New Zealand subject to tunnel-gully erosion. He summarised these as:

"a) low productivity;
b) favoured habitat for rabbits;
c) because of the broken nature of the land, nasella tussock which is an important noxious weed problem on many tunnel-gullied areas is difficult to find and expensive to control;
d) some stock losses, particularly at lambing, occur in the gullies;

Table 2.1 Publications which refer to tunnel-related erosion in New Zealand, listed according to region.

Northland
- Ward (1966 a,b)
- Visser (1969)
- Riley (1977)
- Sutherland *et al* (1981)

Auckland
- Ward (1966 b)
- Goldsmith and Smith (1985)

Waikato/Volcanic Plateau
- Cussens (1888)
- Taylor (1938)
- Campbell (1950)
- Blong (1965 a,b)
- Ward (1966 b)
- Selby (1967, 1970)
- Nairn (1976)

Taranaki
- Cumberland (1944)

Manawatu/Rangitikei
- McCaskill (1973)
- McLoughlin (1983)

Hawkes Bay
- Guthrie-Smith (1926)
- Cumberland (1944)
- McCaskill (1973)

Wairarapa
- Gibbs (1945)
- Jackson (1966)
- Kerrison (1981)
- Owens (1981)

Wellington
- Riley (1977)

Blenheim
- Taylor (1938)
- Cumberland (1944)
- Gibbs (1945)
- Laffan (1973, 1974)
- Laffan and Cutler (1977a,b)

Christchurch
- Cumberland (1944)
- Gibbs (1945)
- Hosking (1962, 1967)
- Hughes (1970, 1972)
- Miller (1971)
- Evans (1977)
- Bell (1978, 1981)
- Trangmar (1978)
- Bates (1979)
- Wilms (1979)
- Evans and Bell (1981)
- Schafer and Trangmar (1981)
- Sheppard and Lambrechtsen (1983)

South Canterbury
- Cumberland (1944)

Otago
- Crozier (1969)
- McCaskill (1973)

Mid-Clutha Valley
- Cumberland (1944)

e) the gullies impede access and stock movement;
f) bulldozed tracks need frequent attention;
g) sediment washed off the tunnel-gullied land is deposited over the top of high producing pasture or may find its way into watercourses or farm storage dams;
h) these areas are often unattractive and serve as a constant reminder of poor land management practices."

As outlined in 2iv the causes, the processes, and the relationships between causes and processes of tunnel initiation and development are imperfectly understood. The degree to which causes and processes can be controlled is also imperfectly understood. In spite of this lack of understanding some control measures have been effective.

The soil conservation measures that were designed to control tunnel-gullying, and so ameliorate the problems listed above, are outlined in chapter 6.

In New Zealand recognition of tunnel-related erosion problems has spread from dryland loessial environments where it was first described 40-50 years ago to encompass a much wider range of environmental conditions (Lynn and Eyles, 1984) Nevertheless tunnel-gully erosion is still most severe in those dryland loessial areas and the most intensive conservation efforts have been applied there.

Some more recent studies have placed emphasis on different aspects of tunnel-related erosion, such as:

a) the engineering aspects, particularly the failure of earth dams - for example, Ritchie (1963), Evans (1977), Sherard and Decker (1977), Schafer and Trangmar (1981), and Goldsmith and Smith (1985);
b) the hydrological aspects - for example, Jones (1971), Bates (1979), McCaig (1979), and Gilman and Newson (1980);

c) the geomorphological aspects - for example, Parker (1963), Hughes (1972), Barendregt and Ongley (1977), and Bryan and Harvey (1985);

d) the pedological aspects - for example, Charman (1969) Miller (1971), Laffan (1973), Rooyani (1985), and Crouch *et al.* (1986).

This research is all of direct relevance to soil conservation: soil conservators have to attempt to integrate these aspects - the engineering, the hydrological, the geomorphological and the pedological. This reinforces the premise advanced in chapter 1 that soil conservation is an essentially generalist subject area especially when additional studies of relevance such as those into plant materials or production management are considered.

2iv Tunnel Initiation

Jones (1981, p. 31) reviewed the literature concerned with tunnel-related erosion and concluded that, "no single factor or group of factors is universally responsible for piping". This was in recognition of the wide environmental variation in the occurrence of tunnelling and the different mechanisms thought to operate in those areas.

a) Mode of initiation

Tunnelling could conceivably begin at the upper end, the lower end or at some point along the length of a future tunnel. A pre-existing surface crack might well fill with water and thereby give rise to pore water pressure (PWP) gradients greater than would otherwise occur. Increases in PWP gradients must always be matched by increases in intergranular stresses within the soil. Where increased intergranular stresses lead to (even micro) movements of soil particles, zones of increased permeability will occur. Where these approach downstream 'exit' faces PWP gradients will be increased substantially. Instances have been observed where these increased gradients at exit faces have been sufficient to cause soil particles to leave the exit face. This further steepens the PWP gradients and the tunnel progresses back upslope as material is removed, - carrying the zero (atmospheric) PWP and the associated increased PWP gradient, with it.

b) Processes of Particle Release

The processes of soil particle release from the soil matrix are thought to be similar in all three cases. They are:

1) *Dispersion* - where individual colloidal clay particles repel each other and remain in suspension in the soil water;

2) *Slaking* - the macroscopic breakdown of unsaturated aggregate;

(Emerson 1954).

The first of these two processes can be thought of as dominantly chemical and the second dominantly physical. They will be discussed further in Chapter 3.

Jones (1981, p. 234) describes the factor most universally present in tunnelled soils as being "the presence of horizons or surfaces of restricted permeability". When the rate of infiltration from above is greater than that of percolation downward, water is concentrated at this level. If an hydraulic gradient occurs this water will move in response to this. This situation may arise because of excessive infiltration rates (e.g. as a result of water penetration down shrinkage cracks) or alternatively because of a change in soil properties leading to a layer of naturally low hydraulic conductivity. It is possible that such an impermeable layer is composed of soil that is not as susceptible to slaking or dispersion as the overlying more permeable layer. This would also concentrate tunnel development at the contact between layers.

c) Modes of Water Flow Concentration

The above mode of tunnel development involves the concentrating of water flow towards those zones of the soil where tunnels subsequently form. The most commonly cited method of flow concentration is for rainfall to penetrate to the subsoil via desiccation-induced soil shrinkage cracks (Gibbs 1945, and many others). In many areas where tunnels have developed desiccation-induced cracks are apparent. However most tunnelled soils are dispersive and by that property will also be soils that exhibit volume change as dispersion and swelling are similar processes. This will be shown in chapter 3. Tension-related cracks have also been mentioned as a factor in water penetration (Carroll 1949, Jones 1968).

In New Zealand and Australia tunnelling has often occurred in areas that have been infested by rabbits. The burrows of these animals have been mentioned as a factor contributing to water penetration and tunnel development (Gibbs 1945, Downes 1946). However Jones (1981) noted many instances where burrowing was not a factor and concluded that although it was probably important where it did occur it was neither a necessary or sufficient condition to initiate tunnelling.

In some areas tunnels seem to have been initiated in saturated soils. In this "wet tunnel" situation flow concentration will occur towards any zones of greater hydraulic conductivity (see 2iva above). Such flow concentration will be enhanced by factors inducing saturation, such as large infiltration, poor drainage, or low water use. Colclough (1973) working in Tasmania suggested that clearance of the original dense vegetation of trees and shrubs and replacement by relatively shallow rooting pasture species resulted in less water loss by transpiration and a consequent increase in the amount of moisture in the subsoil. This increase in moisture was thought to have initiated tunnelling.

2v Origins of tunnel-related erosion in New Zealand

The currently accepted mode of formation of tunnel-related erosion on loessial soils in New Zealand is that outlined by Laffan and Cutler (1977b) working on the Wither Hills, Marlborough. This description is similar to that of tunnelling initiated from cracks (see 2iva above) with the addition of steps relating to the formation of gullying. In these yellow-grey earth soils there is a hard, compact, and relatively impermeable layer termed the fragipan at about 0.5 m depth below the surface. This is overlain by a clay-rich (argillic) horizon which has a high shrink-swell potential and is susceptible to dispersion. This in turn is overlain by a hard and crusty A horizon. The fragipan is underlain by conglomerates.

"1) Depletion of the vegetation after European settlement led to the exposure of bare soil and deterioration of soil structure. Hard crusts formed in these bare patches had low infiltration rates, and consequently soil below the crusts dried out and cracks developed.
2) Shrinkage cracks develop downwards into the argillic horizon where shrink-swell potential is greatest. Secondary cracks develop in the argillic horizon and later small cavities develop.
3) Cracks and cavities in the subsoils are enlarged by dispersion of clay from the walls of cavities and cracks in times of heavy rainfall.
4) Tunnels begin to form and link up to form a continuous piping system downslope. The floor of the tunnel is the top of the compact fragipan.
5) Outlets from the tunnels form on the soil surface at lower backslope/footslope inflections and at free faces on exposed footslopes due to hydrostatic pressure exerted by water and sediment in tunnels.
6) Further tunnel enlargement causes collapse of sections of tunnel roof; and this shows as a line of holes in the ground surface.

7) Lateral erosion of subsoil adjacent to collapsed roof causes cave-in of tunnel side walls.
8) New tunnels may form at contact of collapsed soil material and fragipan.
9) Complete collapse of entire tunnel roof down slope, and enlargement of new secondary tunnels by erosion.
10) Vertical walls of gully (usually on one side of gully only) collapse as a consequence of lateral erosion undermining the wall. Many gullies are asymmetric in cross-section, one side being vertical and the opposite side sloping upwards to the soil surface.
11) Further erosion of tunnels and gullies eventually leads to deepening of the gully below the fragipan and to further collapse the columns of side walls.
12) Continued lateral and vertical erosion deepens gullies eventually to the underlying conglomerates."

This description is similar to those previously outlined by Gibbs (1945) and Hosking (1967) also for New Zealand loessial soils as there is emphasis on concentrated infiltration via shrinkage cracks. The conservation works that were devised and successfully applied on loessial soils were based on the assumption that this is how tunnel-gullies form. The other two modes of tunnel initiation outlined above do not seem to have been considered in New Zealand for loessial soils. However Laffan does mention "wet tunnel" systems investigated by Ward (1966) and Selby (1967, 1970) in the humid areas of Northland and Waikato and not in loessial soils, which appeared to have formed because of continuous or near continuous subsurface flow.

The widespread acceptance of Laffan and Cutler's description, see for example Trangmar (1976), Evans (1977), and Bell (1981) is surprising as it has an important omission of detail in one regard concerning point 4 above. The sentence reading, "Tunnels begin to form and link up to form a continuous piping system downslope", is an inadequate explanation of how tunnels actually form and link up.

As water is the eroding agent, water movement is necessary for tunnel formation. Water flow in large macrovoids, such as cracks, will only occur where either:

a) the surrounding soil is saturated, or
b) the rate at which water enters voids exceeds the rate at which the surrounding unsaturated soil can in effect 'suck' it away, and also where either:
c) a gravitational potential gradient sufficient to induce downslope movement occurs and/or
d) a moisture potential gradient sufficient to induce lateral movement occurs.

This is because water has the tendency to be attracted by sites of the lowest potential in a soil, usually the smallest pores and voids in preference to larger pores or voids, such as cracks, and will only move from these sites if pulled by gravity or the attraction of a site of lower moisture potential. As Laffan and Cutler's description is apparently concerned with dry soils on hillslopes the two necessary alternatives would be b) and c). It has been assumed that these occur and not actually shown. It has also been assumed that a) and d) are insignificant factors. This has also not been shown. It is shown in Chapter 7 that Wither Hills soils can become saturated in winter conditions - an effect which may be an influence on tunnel development.

The "wet tunnel" systems described by Ward (1966) and Selby (1967, 1970) would depend upon the often saturated condition of the surrounding soil i.e., alternative a above. It is interesting that Bates (1979) working on loessial soils on the Port Hills, Christchurch found that tunnel flow only occurred when the soil in the vicinity of the tunnels was saturated. This required heavy (approx 50 mm) summer rain onto previously dry soils (alternative b), or light (approx 10 mm) winter rain onto near saturated soils (alternative a). The latter is far more common than the former. Bates concluded that tunnel flow and enlargement was considerably more likely in winter than summer. However he offered no conclusions about any seasonal influence on tunnel initiation.

Summary

The current state of knowledge concerning the initiation of tunnelling is still vague and worthy of further investigation. The currently accepted description of tunnel-gully development in loessial soils outlined by Laffan and Cutler (1977b) has at least one unexplained drawback concerning tunnel initiation. Conservation works have been designed with this description in mind hence the emphasis on reducing soil cracking in dry weather. The success of the conservation works may be due to effects other than those intended. It is suggested that investigation of the full range of effects associated with conservation works may throw light on the processes actually operating at tunnel initiation. A discussion of these effects occurs in Chapters 4, 5, and 6.

2vi Tunnel-related Geomorphology

Descriptive geomorphology is not an end in itself, being only a tool for interpretation of landform origins and development processes. Very little detailed information concerning the forms present in the early stages of tunnel development is available. Rather more, but still limited, information has been gathered about the later phases when relatively large tunnels are present and also on the processes leading to tunnel roof collapse and gully initiation. This lack of information presumeably relates to the difficulties of identifying the location of tunnels in their formative stages and of monitoring the subsequent development of that tunnel as such discovery usually results in the destruction of the tunnel system concerned.

In addition to this genetic approach to ascertaining tunnel development and origin, geomorphological studies have been useful in attempts to model the hydrological response of tunnelled areas (Gilman and Newson 1980). The most detailed research has been that sponsored by the Institute of Hydrology in upland Wales summarised by Gilman and Newson (1980) and Jones (1981). However these tunnels have formed in a humid climate area in peat soils and may be quite unrepresentative of those dryland loessial soils in New Zealand where tunnel-related erosion has been a serious problem and which are the direct concern of this thesis. Some observations can be made from these studies and also from the limited information available from studies in more representative areas.

a) Tunnel Size

Jones (1981) summarised the reported relationships between size, material, geomorphic location and climate (see Table 2.2). Because of the variation of other factors the differences in tunnel size are not surprising. The most interesting point is that globally the largest tunnels apparently occur in the more arid climates. Jones (1981) used this relationship as an explanation for the longheld opinion that tunnelling was an erosion process typical of dryland areas. The small size of tunnels in humid areas explaining why they were not recognised until recently.

In New Zealand the reported information on tunnel size (see table 2.3) does not show this relationship. However for a given material it is probable that larger tunnels occur in a drier climate, because as moisture content of soil increases, shear strength decreases, and tunnel roof destruction is more likely to occur. Roof destruction obviously restricting the continued enlargement of tunnels. The maximum reported size in New Zealand of about 1 m diameter would reflect the lowest strength of the material concerned which occurs at its highest (usually winter) water content. Whether this maximum size is reached

Table 2.2 Summary of reported tunnel size in relation to soils, geomorphic location and climate (after Jones, 1981)

Size	Material	Geomorphic location	Climate	Source
max. 0.6-4.6 m	mainly alluvial soils	river terraces	semi-arid	Jones (1968)
'few metres'	shales and erosion glacis	canyon walls	semi-arid	Barendregt (1977)
.05 - 6.1 m .06 - 1.8 m 0.15 - 0.38 m	alluvial soils derived from shale with blocky B horizon	alluvial valleys	semi-arid	Barendregt and Ongley (1977)
max. 3 m	clay loam/silt clay loam	badlands on alluvial terraces	semi-arid	Brown (1961; 1962)
0.91 - 1.22 m	Pleistocene White Silts	river terraces	arid highland	Buckham and Cockfield (1950)
0.91 m	loess	flat upland, usually <45 m from plateau rim	semi-arid	Fuller (1922)
0.15 - 0.96 m	silt loam	hillslopes and gully walls	marine	Gibbs (1945)
25 mm - 0.91 m	loess soils, often hardpan	hillslopes and stream-banks	marine	Hosking (1967)
< 0.76 m	cracking A horizon, prismatic B, impermeable clay C on sedimentary rocks	valley heads, seepage, lines, landslides	marine	Ward (1966)
0.15 - 0.35 m	brown earths with clay loam and C horizon	10-20° slopes	humid continental	Czeppe (1960)
< 0.30 m	alluvial and volcano-alluvial sediments	terraces and plateau edges	savanna to wet tropical	Löffler (1974)
< 0.30 m	clay soils on shale and in colluvium	-	tropical rainforest	Baillie (1975)

(continued over)

Table 2.2 cont.

80-120 mm	solonetz and solodic soils	cultivated slopes, banks, dams	marine	Floyd (1974)
max. 400 mm mode 50-100 mm	peat gleys and podzols	highland mid-slopes	marine	Bell (1972)
max. c.0.30 m mode 12.50 mm	pumice soils	hillslopes in 'maturely dissected' relief	marine	Blong (1965)
< 100 m	shale badland surface	mid-slopes	arid	Yair *et al.* (1980)
mean 90 mm (ephemeral) 220-900 mm (perennial)	lessive brown earth on alluvium/colluvium	streambank	marine	Jones (1971; 1975)
14.41 mm (ephemeral) 130 mm (perennial)		mid-slopes	marine	Humphreys (1978)
60 mm	estuarine alluvium	salt marsh	marine	Lear (1976)
c. 50 mm	estuarine and coastal alluvium	salt marsh	marine	Jones (1975)
mean 46 mm	peaty podzol	highland mid-slope	marine	Morgan (1977), Newson and Harrison (1978) Gilman and Newson (1980)

Table 2.3 Summary of reported tunnel size in New Zealand in relation to soils, geographic location, geomorphic location and rainfall.

Size	Material	Geographic location	Geomorphic location	Rainfall (mm/yr)	Source
< 0.76 m		Northland	Valley heads, seepage lines, landslides	1500	Ward (1966b)
<0.15 - 1 m	Podzolic clay loam over weathered sandstone	Northland	Hillslopes	1500	Visser (1969)
0.5 - 1 m	Silts and clays over sandstone	Auckland	Gully walls and hillslopes	approx 2000	Goldsmith and Smith (1985)
<0.03-<0.5 m	Yellow-grey - Yellow-brown earth intergrade on mudstone	Wairarapa	Hillslopes and valley floor	900-1150	Kerrison (1981)
0.15 - 0.96 m	Silt loam	Wither Hills, Blenheim	Hillslopes and gully floor	650	Gibbs (1945)
< 0.71 m	Loessial yellow-grey earth soils	Wither Hills, Blenheim	Hillslopes	650	Laffan and Cutler (1977 a, b)
0.025 - 0.91 m	Loess soil	Port Hills, Christchurch	Hillslopes and streambank	700	Hosking (1967
< 0.5 m	Loess	Port Hills, Christchurch	Hillslopes	700	Evans (1977)

depends on the relationship of water supply to time since tunnel initiation. It is expected that until a tunnel outlet is formed and free water flow commences (similar to that in surface channels), tunnel enlargement would not be great. After an outlet is formed the rate of tunnel enlargement would depend upon the rate at which the moving water could erode the tunnel walls by corrasion, dispersion, and slaking, and then remove the sediment so released.

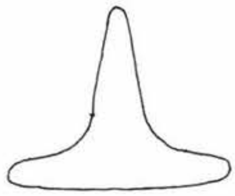
b) Tunnel Shape

Jones (1981) suggests tunnels may develop from small rounded pipes to larger flat-bottomed or rectangular pipes,

He related this to different flow regimes operating as tunnels develop. During initiation and the early stages of development the entire tunnel would be filled with water. Presuming homogeneity of material, which is likely with a small tunnel, dispersion and slaking are equally likely to occur from the entire internal surface of the tunnel and so a small circular tunnel is formed. As the tunnel is enlarged and an outlet formed, flow and erosion processes similar to surface channel flow occur. Slaking and dispersion continue, but corrasion of the tunnel sides and floor begin accompanied by collapse of material from the tunnel roof. The tunnel would now be bigger than its usual flow volume. The circular shape of the roof of these enlarged tunnels is due to the differential collapse of the soil, there being least support over the middle of the tunnel. The flat base that develops is due to the seemingly ubiquitous impermeable layer (also often less erodible than the overlying soil).

In New Zealand circular shapes are mentioned by Cumberland (1944) and Visser (1969), while sizes are quoted in diameters, implying at least a roughly circular shape, by

Evans (1977), Kerrison (1981) and Goldsmith and Smith (1985). Ward (1966) described tunnels with a circular shape except for an irregularly flat floor. Hosking (1962) described the tunnels he observed as being pear shaped. Gibbs (1945), Laffan and Cutler (1977b), Kerrison (1981) described tunnels with an inverted lemniscate shape;



It was proposed by Gibbs (1945) that this shape was due to enlargement of soil cracks by penetrating water. The rounded base was thought to form when the penetrating water strikes an impermeable layer and lateral erosion commences.

c) Tunnel Networks

No general model for the evolution of tunnel networks has yet been devised because of; ; the variety of materials and climatic areas, random tunnel blockage changing networks, tunnels developing at different levels, and the difficulties associated with identifying tunnels where roof destruction has not occurred (Jones, 1981). A variety of networks have been mapped ranging from dendritic to anastomosing to discontinuous (see Jones 1981, pp 139-144). Jones (1981) speculated that initially discontinuous networks may go through an anastomosing stage before developing into a more advanced dendritic stage. Tunnel collapse may then result in the tunnel channels assuming importance as part of the surface drainage network.

In New Zealand, Kerrison (1981) carried out limited mapping of a tunnel system in the Wairarapa. His maps show a very simple dendritic pattern. More detailed mapping was carried out by Bates (1979) on the Port Hills. This tunnel system he described had an elongate dendritic pattern. No downslope branching was observed to occur though remnant surface hollows were apparent, thought to be possibly indicative of branching occurring in the past. This provides some support for Jones' (1981) speculation on network development.

The size of tunnel networks is dependent upon a number of site related factors which influence where, when, and for how long tunnel flow could be sustained. These include:

- length of time since tunnel initiation;
- length of slope;
- homogeneity of soil and slope angle (as influences on whether surface or subsurface flow occurs);
- ability of material to resist roof destruction and tunnel blockage;
- relationship of tunnel-flow to rainfall and ground water influences.

2vii Hydrological Importance of Tunnels

The development of tunnels in a soil may substantially affect the hydrological regime compared with a previously non-tunnelled situation. A further large scale change may occur when tunnel roof destruction takes place and open gullying develops.

Most investigation of the hydrological properties of tunnels has taken place in Britain. Once again the applicability of this research, on peat soils in the humid climate of upland Wales, to tunnelling in dryland loessial soils in New Zealand, can be questioned. The only research of direct relevance is that of Bates (1979) working on the loessial soils of the Port Hills, Christchurch. He attempted to "quantify the hydrological input/output relationship and characteristics of a natural pipe system", by measuring the input of rainfall, the moisture storage capacity of the soil and the output of tunnel flow. The hydrological purpose of this work was to:

a) determine the climatic and catchment conditions under which tunnelflow is generated,

b) measure the rates of removal of sediment from the tunnels in the study area.

With regard to the first of these aims Bates found that whether water flowed in tunnels depended on the antecedent soil moisture condition (see 2iv above).

With regard to the second aim of Bates' study he found that the greatest sediment concentrations per unit discharge occurred in the first flow generation following long periods without flow. This 'flushing-out' effect was also noted as occurring in individual events when more sediment was discharged as tunnel flow was increasing than when flow was declining for the same flow volume (Bates, 1979). Unfortunately Bates could not fully describe the rates of sediment removal from tunnels because of data that was both insufficient and inconsistent. This is an obvious area for further research, as no quantitative information is available on the amount of soil lost due to the presence of either tunnels or tunnel-gullies.

Jones (1981) reports a typical interval for rainfall to tunnel flow of about one hour on Welsh peat soil with an A-horizon hydraulic conductivity of around 3.4 cm hr^{-1}, too slow to directly generate flow. This discrepancy was accounted for by inferring that water infiltrated directly to the water table through large structural voids and soil cracks. Jones (1981) suggested that tunnel-flow was largely due to a rise in the phreatic surface, similar to the idea of Colclough (see 2ivc above), which is assisted by high antecedent soil moisture conditions or current heavy rainfall. Dovey (1976) working in the same catchment was quoted by Jones (1981) as analysing flow data and concluding that a mean of 35% of streamflow could be attributed to tunnel flow. Jones (1981) considered this a low estimate because of the difficulty in identifying all the tunnels present.

The importance of tunnelflow to streamflow will depend on the type and density of individual tunnel networks in relation to those other pathways of water entry to streams such as overland flow and unsaturated and saturated throughflow. The importance of tunnelflow to streamflow is not known in New Zealand. As tunnelflow is related to intermittent rainfall the level of tunnelflow would increase with increasing rainfall intensity or duration. If this is so tunnels would have their greatest outflow in those situations where streamflow is also greatest i.e., floods. However this does not mean that the presence of tunnels increases flood peaks, as there is a delay period in rainfall reaching streams via tunnels. This period may be longer than if the water had been transferred via different pathways, so there is the possibility that tunnels reduce flood peaks. This is a point on which further investigation is definitely required. However it is almost certain that when tunnels have collapsed into open gullies the speed with which precipitation becomes streamflow is reduced and flood peaks increased. As water is concentrated in exposed areas of the highly erodible subsoil these floods are also accompanied by high sediment levels adding to the problem. This was one of the major problems on the Wither Hills, Blenheim, before 1945, as described by Wilkie (1965)

> "regular yellow floods poured out of the area with every heavy rain ... Good black soil on the flat land was covered by layers of stones, silt,and sand. Almost without fail, the Wither Road which crossed the land below the property was scoured out by these floods, and holes big enough to bury a truck made the road impassable".

When gullies were removed in later years by bulldozing, contour furrows established and pasture cover improved, the flood peaks and the problems were reduced (Wilkie, 1965). This was because the rate at which water gained access to streams was reduced while the velocity of that water was also lowered reducing its erosive effect.

The presence of tunnel-related erosion lowers the moisture storage capacity of a slope as there is less soil available to hold water. This would be most severe over tunnels where the soil would become more susceptible to desiccation. This is an alternative explanation for the often noted presence of cracks over tunnels.

Where tunnel-related erosion was accompanied by poor grazing management other components of the hydrological system are also affected. Infiltration is reduced and runoff increased due to deterioration in soil structure while evaporation increases and transpiration decreases due to destruction of vegetation. However these are not direct effects of tunnelling and will not be considered further in this section. However they are of direct relevance to the effects of conservation works and so will be considered in Chapter 4.

CHAPTER 3 A CRITICAL REVIEW OF THOSE SOIL PROPERTIES ASSOCIATED WITH TUNNEL-RELATED EROSION

There are three soil properties which have been regarded as prime influences on the initiation and enlargement of soil tunnels. These are:

1. Susceptibility to cracking - cracks are usually cited as pathways for concentrated water penetration;
2. Susceptibility to dispersion) - these are the two
3. Susceptibility to slaking) processes usually cited as causing the release of soil particles before removal by flowing water.

Although these soil factors make a soil susceptible to tunnelling, it is possible to have soils which crack, disperse and slake, that do not tunnel (Laffan, 1973). Laffan noted no evidence for widespread tunnel-gullying prior to human settlement in Marlborough, though it can be assumed that these soils had still been susceptible to tunnelling.

Other factors which influence the movement of soil moisture are also important. These include the water retention characteristics, and conductivity/permeability relationships particularly the presence of a layer of restricted permeability. The strength characteristics of a soil are also of importance as these influence whether gullying occurs which is the most problematic stage of tunnel-related erosion.

3i Soil shrinkage and cracking

a) *Shrinkage*

Desiccation induced shrinkage cracking has been regarded as important in the initiation of tunnelling because of the consistent occurrence of cracks in tunnelled soils and the development of models that accounted for this relationship (Gibbs 1945; Downes 1946; Laffan and Cutler 1977b).

Most soils exhibit a decrease in volume (which can also be viewed as an increase in dry bulk density) upon loss of moisture. This volume change is largely dependent on:

1. the amount of clay in the soil;
2. the type of clay in the soil.

Clay minerals are important because of their large surface area in relation to mass which allows large quantities of water to be physically bonded, and their molecular structure which allows water to also be chemically bonded.

There are three locations where water can be held in a soil:

1. in pores between particles - capillary water
2. on the surface of particles - adsorbed water
3. within particles - absorbed water.

Water as a liquid has an affinity for the pores within a soil. This results from the surface tension which develops when water enters a pore. To then remove water from that pore requires energy sufficient to break the surface tension (Hillel 1980). This is the main mode of water retention in coarse (sandy) soils. However in soils with a clay component water is also attracted and held by the electrostatic charges associated with the clay particles.

Adsorbed water is held on the surface of clay particles by weak forces associated with Van der Waals bonds and also by much stronger electrostatic forces, while absorbed water is held within particles by electrostatic attraction.

Sridharan and Allam (1982) described two mechanisms which control the volume change behaviour of clays:

1. where the volume change is primarily controlled by the shearing resistance at the near contact points, i.e., shrinkage occurs when capillary water is removed from between the particles so allowing them to move closer together;
2. where the volume change is primarily controlled by the osmotic (double layer) repulsive forces i.e., shrinkage occurs when water is removed from within and from the surface of particles decreasing their size. This is a result of changed electrostatic relationships between particles and the soil solution.

These two mechanisms can be respectively described as interparticle and intraparticle shrinkage. There are some clay minerals which can have large volume changes depending on their water content. This large volume change is primarily due to the loss or gain of large quantities of water bound within particles. These minerals are termed the "swelling clays" although the term "shrinking clays" would be just as valid. Those minerals which shrink or swell only because of the loss or gain of interparticle water do not have as large a volume change as the swelling clays. This is because less water can be held between and on their particles than can be held within, between, and on the particles of the swelling clays.

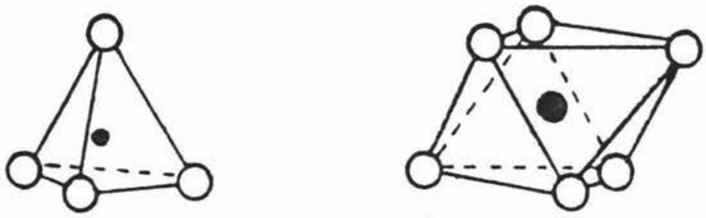
To explain how such large amounts of water can be bound it is necessary to consider the structure of clay minerals. The typical lattice structure of clay minerals is built up from two basic units. These are:

1. a tetrahedron of four oxygen atoms surrounding a central cation, usually Si^{4+};
2. an octahedron of six oxygen atoms or hydroxyls surrounding a larger cation of lesser valency, usually Al^{3+} or Mg^{2+}.

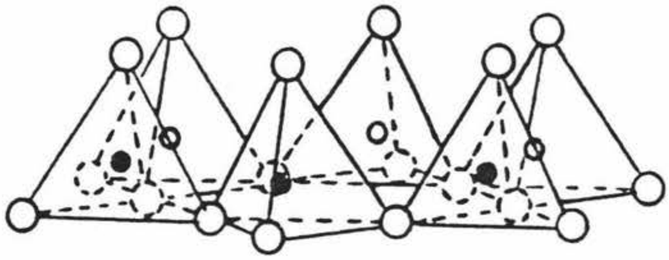
The tetrahedra are joined together by sharing the oxygen atoms in their basal corners. This gives a hexagonal silicate lattice about Å 4.93 thick. The octahedra are also joined together by sharing the oxygens along their edges to form an alumina lattice about Å 5.05 thick (see fig. 3.1) (Hillel, 1980a). A clay particle is composed of sheets stacked upon one another with the different clay minerals varying in their ratio of tetrahedral to octahedral sheets. There are also variations due to the 'isomorphous replacement' of the Si^{4+} or Al^{3+} ions by ions of different, usually lower valency (Hillel, 1980a). This results in a negative charge imbalance in the clay lattice. An additional charge imbalance may result from the incomplete charge neutralisation of ions on the sheet edges.

These charge imbalances are met by the absorption of ions, usually cations such as Ca^{++}, Mg^{++}, and Na^{+}, which are not part of the lattice but occur on the outer surfaces and also between the layers of the clay particles. These cations can be removed and replaced and so are known as exchangeable cations (Hillel, 1980).

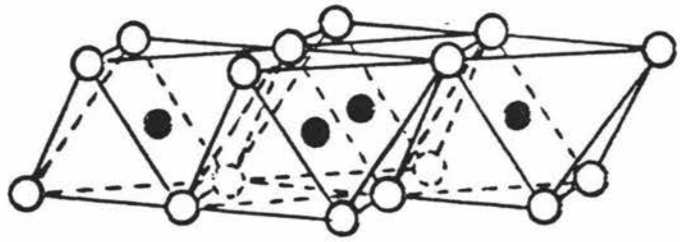
When these clay particles are dry the exchangeable cations are bound tightly to the negative clay particle surface. When the clay is wetted some of the exchangeable cations dissociate from the particle surface and enter into the solution. This results in the formation of what is termed a "double layer". The first of these consists of the negative layer on the clay surface. The second is composed of two parts; an inner layer (Stern layer) comprised of those cations that are still directly bound to the lattice surface, and an outer layer (Gouy layer) comprising the other neutralising cations which are diffused in the solution close to the clay surface (Russell, 1980).



The basic structural units of aluminosilicate clay minerals: a tetrahedron of oxygen atoms surrounding a silicon ion (left), and an octahedron of oxygens or hydroxyls enclosing an aluminium ion (right).



Hexagonal network of tetrahedra forming a silica sheet.



Structural network of octahedra forming an alumina sheet.

Fig. 3.1
The basic structural units of clay minerals, (after Hillel, 1980a)

The cations in both the double layer and those within the lattice itself can bond with water by hydration. The oxygen atom in water has a slight negative charge and this is attracted by the positive charge of the cations. The attraction is greatest by ions of a higher charge density, either smaller ionic radii or more importantly a greater ionic charge. Of the three commonest exchangeable cations Ca^{++} and Mg^{++} bond water much more tightly than Na^{+} because of their greater charge density.

As noted above, volume change of clay minerals occurs in two dimensions - interparticle and intraparticle. A proportion of intraparticle swelling occurs when the cations in the outer double layer are hydrated. Water will only become available when ionic concentrations are lower in the soil solution than in the clay mineral. This creates an osmotic pressure which water movement attempts to equalise. With the swelling clays water is admitted into the lattice in addition to being bound on the outer surface. Water is bound within these clays by two mechanisms. The first of these is analogous to bonding on the outer surface in that hydration occurs around any free cations present within the lattice. The second mechanism occurs when the slightly positive hydrogen atoms of the water molecule bond, via hydrogen bonds, with the slightly negative oxygens within the layer structure of the clay. This initial layer of polarised water molecules may attract further layers of ordered polarised water molecules between the layers of clay. This growing structure of polarised water molecules is only disrupted by the presence of the tightly bound hydration shells around any Mg^{++} or Ca^{++} ions due to the strong charge associated with these hydration shells. The strong charge means that the orientation of the water molecules in their vicinity is determined by the randomly orientated cations rather than the other water molecules in their ordered structure. Contrastingly where Na^{+} occurs the hydration shell is only weakly charged and does not disrupt the orientation of the growing layer of polarised water molecules to the same extent as the hydration shell around Mg^{++} or Ca^{++} ions. This means that where Na^{+} is the predominant cation more water can be bound within the lattice than where Ca^{++} or Mg^{++} are predominant.

The observation has often been made that the presence of organic matter in soils reduces their capacity to shrink and swell. This organic matter includes undecomposed residues from dead roots and recent stubble, However the important fraction is that known as humus. Hillel (1980a, p 76) uses the term humus for the "more or less stable fraction of the soil organic matter remaining after the major portion of residues have decomposed". Humus, like clay is colloidal and its particles are negatively charged. This charge is not due to the isomorphous substitutions of cations as in clays, but to the dissociation of carboxylic (-COOH) and phenolic (⌬–OH) groups contained in the wide range of organic compounds that make up humus (Hillel, 1980a). Humus reduces volume change by bonding to the sites of positive charge, such as the exchangeable cations in preference to water. Because humus is often composed of large polymers it can bond several particles at once and forms a protective layer around the grouping of particles which is now known as an aggregate (Hillel, 1980a).

Humic compounds are decomposed further by bacterial action and lose their stability. Unless these compounds are continually replaced by further decomposing organic material the percentage of humus will decline rapidly.

Hillel (1980a) mentions that certain inorganic materials can also reduce volume change of clays. Calcium carbonate in particular, as well as iron and aluminium oxides can bond to the clay and reduce its ability to adsorb water.

Shrinkage of clays occurs when water is drawn out of, or away from the clay particle. This is due to:

1. a rise in the cation concentration of the surrounding

solution (usually due to water loss by desiccation) resulting in an osmotic pressure differential which water movement attempts to equalise,

2. desiccation giving sufficient negative moisture potential to break the bonds holding water both within and on the surface of the clay.

Where desiccation occurs these two processes would act simultaneously.

Summary

1. Coarse particles can swell slightly as water has an affinity for interparticle pores. This capillary water can cause only a slight rearrangement of particles as if particles move apart, the pore size increases and the water would be held less tightly.

2. "Non-swelling" clay particles can swell additionally to capillary attraction by hydration of cations on their outer surface.

3. "Swelling" clay particles can swell additionally to capillary attraction and outer surface hydration by hydration layers building up within the clay lattice.

4. Volume change related to hydration layers within clay lattices is potentially the cause of the greatest volume change (hence the term "swelling" clays).

5. Volume change related to hydration layers within clay lattices is enhanced by the presence of Na^{+} ions and lessened by the presence of Ca^{++} and Mg^{++} ions.

b) Cracking

Volume change induced by water loss occurs in three dimensions, except in some highly plastic soils which can accommodate volume change in one dimension (Ravina, 1983).

Consider a field soil, with a capacity for volume change, in its saturated condition. Any water loss by desiccation will result in shrinkage of the surface layer. Vertical shrinkage can be accounted for by subsidence, however horizontal shrinkage will leave a void, commonly an elongate crack.

Ravina (1983) reviewing the effects of vegetation on volume change concluded that only a small amount of (qualitative) information was available on soil cracking. Ravina (1983) observed that more cracks develop when the initial moisture content is higher, presumeably because more initial swelling occurred. He also suggested that cracks form where the cohesion of the soil is lowest, as the drying soil will shrink away from those areas. Cohesion is usually lowest either where the soil is wetter or where there are less roots. This indicates that in a dry area cracks will form in those parts that dry out last, such as hollows, or in those areas where there are few or no roots. Once a plane of weakness has formed further drying will result in shrinkage away from the existing cracks. If there are no or few planes of weakness, i.e., even drying from an even vegetative cover, gross cracking would not occur. Rather, a great many small cracks would form (Ravina, 1983). The extent to which a soil can transmit the volume change of shrinkage to a crack some distance away, a property also dependent on cohesion, determines the spatial distribution and size of cracks. Once a crack has formed drying of the soil in the vicinity of the crack is increased because of the increase in exposed surface. Adams and Hanks (1964) reported a cracked clay soil that had three to four times the exposed soil surface than in the non-cracked condition. The increase in the level of evaporation is not as great as this because there is less exposure to desiccating factors, particularly wind (Adams and Hanks, 1964). The lack of air movement results in cracks having high relative humidities which restricts evaporation. Adams and Hanks (1964) study indicated that evaporation from crack surfaces varies between 35-91% of that from a comparable area of surface soil of a similar water content.

This evaporation from depth results in a zone of dry soil in the vicinity of the crack (see fig. 3.2) even where a crack may have formed in an initially moister area. Hillel (1980b) suggested that because of drying in their vicinity cracks may be self-propagating. Hillel (1980) also noted that cracks tend to reform in the same place. Ravina (1983) attributed this to the formation of a sheath of oriented clay platelets on the crack walls. This forms a plane of weakness which remains when the crack is closed during wet periods.

The effects of soil structure on volume change are somewhat contradictory. Well structured soils are likely to have a larger capacity for volume change than poorly structured soils because their greater porosity gives a larger moisture holding capacity. However gross cracking is perhaps less likely as aggregates could shrink away from the interaggregate voids, with these voids enlarging and acting as zones of weakness forming microcracks. The stability of the aggregates upon contact with water can influence how much cracking occurs. This was illustrated by Hillel (1977) (see fig. 3.3) who treated soil aggregates to make them hydrophobic. Such coarse stable clods at the surface would also lower the rate of evaporative loss in dry weather, as the coarse pores would slow water movement through the surface layer. Alternatively infiltration would be increased by the stable open pores at the soil surface. Taken together these two points indicate that a well structured soil retains more moisture.

Soil aggregates are often naturally stabilised by humic compounds, which, as has already been stated above, reduce

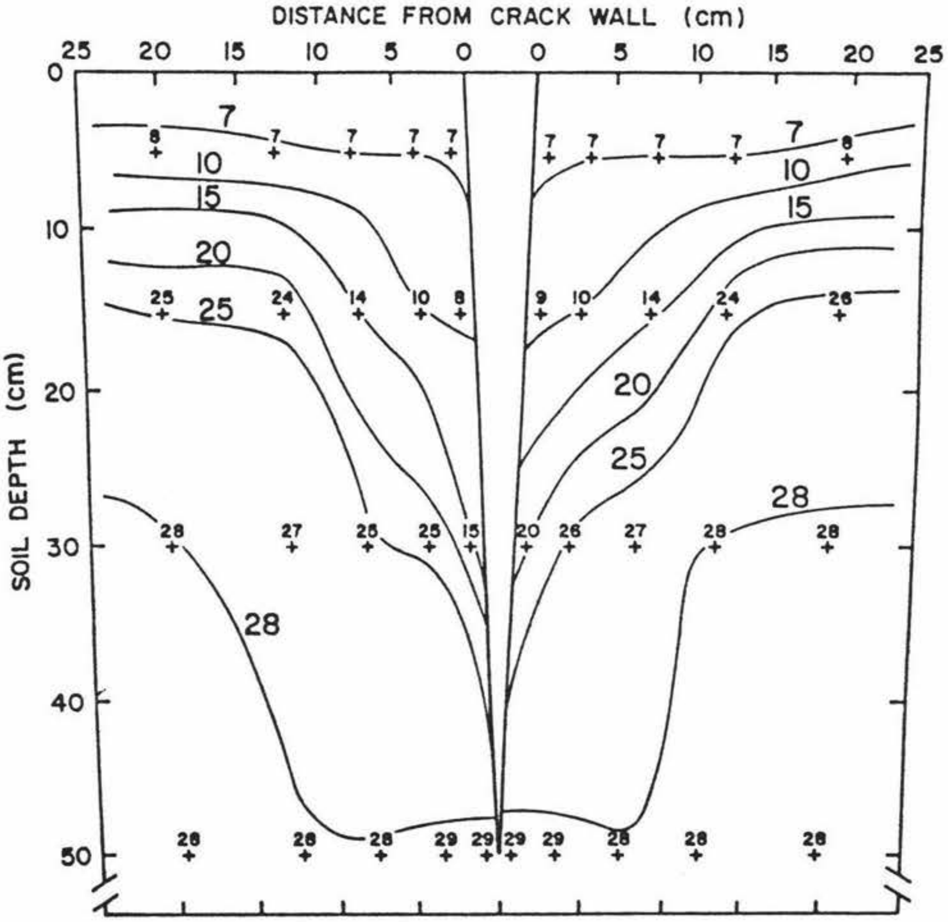
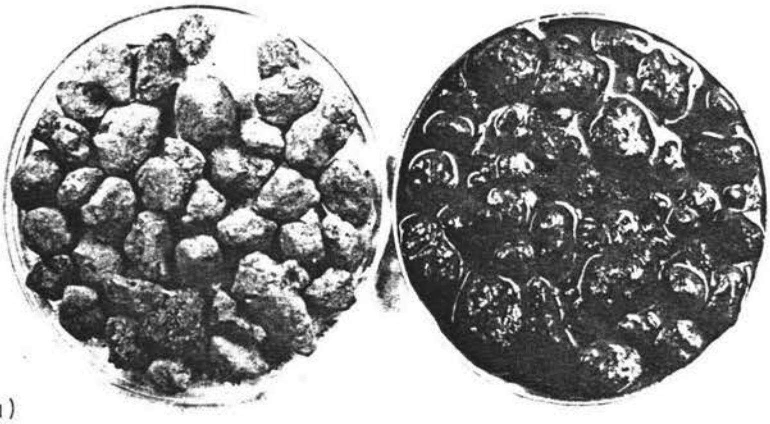
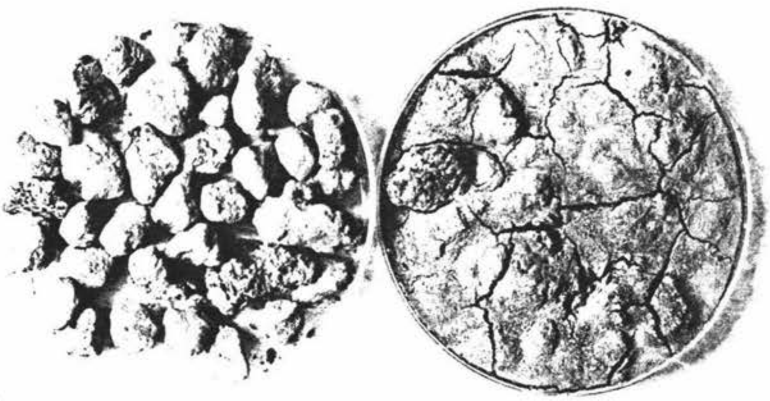


Fig. 3.2
Two dimensional gravimetric water content distribution for soil near a shrinkage crack showing drying of soil in vicinity of crack, (after Ritchie and Adams ,1974).



(a)



b)

Fig. 3.3
The stability of two aggregates upon contact with water, (a) during wetting and (b) after drying. Unstable natural clods on the right imbibe water and slake down to a muddy suspension which cakes upon drying to form a dense crust. The clods on the right were silicone treated and remained discrete and stable upon contact with water, (after Hillel 1977).

shrinkage. The reduction in cracking associated with high levels of organic matter therefore proceeds on two levels.

In summary, cracking is reduced in:

- soils with small fluctuations in moisture levels,
- well structured soils,
- soils with a vegetative system having good root development,
- homogeneous soils,
- soils with a high level of organic matter.

3ii Dispersion

Dispersion was described by Sherard *et al* (1972) as the process which occurs when the repulsive forces between clay particles exceed the attractive forces, so that when the clay mass is in contact with water, individual clay particles are progressively detached from the surface and go into suspension. If the water is flowing the dispersed clay particles are carried away. This is the process usually invoked to describe particle release leading to the formation of tunnels.

Analysis of the dispersive process reveals that it is very similar to the process by which clays expand on wetting. As outlined in 3ia above, where Na^{+} ions are predominant over Ca^{++} and Mg^{++}, and there is a very low concentration of salts in the soil solution, the strongly developed osmotic pressure will result in water moving into the lattice of some clay minerals. If the percentage (not the concentration) of Na^{+} of the exchangeable cations is high enough and the soil solution dilute enough, expansion will continue to a point where the clay pieces will have insufficient attraction to maintain coherence. The clay will initially break up into loosely bound small flocs and then into individual clay plates. The first of these two stages is known as disaggregation or deflocculation, while the second stage is dispersion (Russell, 1980). Dispersion can be simply viewed as swelling that has continued beyond the point of stability. Hence it is no surprise that soils which have tunnelled and are dispersive, are also soils which crack when dry due to their related shrink/swell potential.

This similarity to the swelling process explains why dispersion of the sodic soils (rich in Na^+) where tunnelling has been observed occurs, and also why infiltrating rainwater (a very dilute solution) has often been cited as causing tunnelling. Sherard *et al* (1977) observed that water containing dissolved salts, such as ground or soil water, may be in equilibrium with the salts on the exchange complex of the clay. As such, no osmotic pressure would develop and no dispersion would occur.

Flowing water is usually invoked as the means by which particles are removed from the site of their dispersion. This ignores two other means by which particle transport may occur. The first of these is diffusion wherein water would tend to move to where there is a high concentration of dispersed clay particles and the dispersed clay particles would tend to move through the water to where there is a lower concentration of dispersed particles. Additionally, water tends to move to places with a lower negative pressure potential than its current location. This may drag water from the site of dispersion to a site of lower potential possibly taking dispersed particles with it.

3iii Slaking

Slaking is the disintegration of unconfined soil (or rock) after exposure to the air and subsequent immersion in a fluid, usually water. No external confining pressure is assumed to act over the material prior to immersion (Moriwaki and Mitchell, 1977). Wilms (1979) offered a

further simple description:
"the breaking up of aggregates into discrete fragments".

Moriwaki and Mitchell (1977) observed four modes of slaking:

1) *swelling slaking* - disintegration due to excessive swelling resulting in weaker material;
2) *dispersion slaking* - disintegration caused by dissolution of structure due to dispersion, this is usually preceded by swelling slaking;
3) *surface slaking* - disintegration of aggregate by removal of macroscopic particles from aggregate surface;
4) *body slaking* - disintegration of aggregate into large pieces as processes operate throughout the body of the aggregate.

Moriwaki and Mitchell (1977) observed that which of these modes of slaking occurred depended on the same three factors as dispersion, namely: clay type, ionic concentration in the solution, and which ions are in solution.

Holmgren and Flanagan (1977) described four processes which operate when slaking occurs:

1) *hydration* - when rewetted dry soils are disrupted violently as water molecules return to their energetically favoured sites on particle surfaces;
2) *deaeration* - occurs in conjunction with hydration, as the wetting front penetrates into a soil aggregate air is pushed ahead and collects within the interior under positive pressure. This pressure can be enough to disintegrate an aggregate;
3) *osmotic swelling* - as described in 3i;
4) *dispersion* - as described in 3ii.

The factors influencing swelling and dispersion have been outlined in previous sections. Surface and body slaking depend on the rates and proportions of hydration and deaeration acting on the soil aggregate. This in turn depends upon the particle and pore sizes of the aggregate, aggregate structure, initial moisture content, and bonding by various agents.

Susceptibility to slaking is maximised in:

1) initially dry soils as there is a large volume of air contained;
2) in clay rich soils as they are more likely to swell or disperse;
3) in soils with weak interparticle and intraparticle bonding.

These soils susceptible to slaking are often those same soils prone to cracking and to dispersion.

3iv Soil Permeability and Moisture Characteristics

The occurrence of a layer of limited permeability below a relatively permeable soil is the factor usually thought to cause lateral flow of subsurface water (Jones, 1981). The level of impermeability required is dependent on the rate at which percolating water is supplied to that level compared with the rate at which it can transmit water. Alternatively Goldsmith and Smith (1985) mention that a layer of restricted permeability may not be essential as subhorizontal tunnelling processes could be controlled by hydraulic gradients related to flow outlets. They describe the tunnelling process as proceeding no deeper than is required to obtain a suitable outlet into a drainage channel that offers a lower resistance to flow than the soil in which the tunnel is developing. However in all reported cases of tunnelling in New Zealand a layer of restricted permeability is present at tunnel bases and it is inferred that subsurface flow has occurred at that level. Goldsmith and Smith (1985) mention that tunnelling may have been initiated above that level and then eroded downwards until the impermeable layer was reached.

Of the four distinct environments in New Zealand where tunnel-gullying occurs described in 2iii above, all four had layers of restricted permeability defining the zone of tunnel development. These were:

1. soils derived from strongly weathered sedimentary rocks where the tunnels occur along the interface between a well-developed B horizon and a less permeable C horizon;
2. tephra deposits where tunnels have developed over a different less permeable tephra or an underlying ignimbrite;
3. colluvial footslope deposits in Tertiary sandstone and siltstone deposits where tunnels have developed along the interface of colluvial debris and a former surface.

(Lynn and Eyles, 1984)

In the fourth environment, that of loess and loess colluvium, tunnels have formed over a fragipan, as described by Laffan (1977b), (see 2iv above).

Smalley and Davin (1982) reviewed the literature concerned with fragipan horizons. There appears to be little consensus on defining fragipans or describing genesis. However, Smalley and Davin (1982) listed four characteristic properties apparently universal in fragipan horizons:

1. fragipans are hard layers particularly when dry;
2. fragipans are compact layers;
3. fragipans tend to be relatively impervious;
4. fragipans tend to have a massive polygonal structure.

The hardness of fragipan horizons is thought to be due to one or more of three processes:

1. interparticle cementation by aluminium compounds;
2. interparticle cementation by silica compounds;
3. interparticle connections by clay bridges.

Any of these cementation processes may be responsible for lowering the erodibility of the fragipan's upper surface particularly when the soil is dry. This would also encourage tunnel development over the pan. Wilms (1979) noted that compaction may reduce the erodibility of a layer by reducing the active surface area of soil particles. Nevertheless both Laffan (1973) and Wilms (1979) found that the soil within fragipans was usually highly dispersive. It would seem that it is the low rate of hydraulic conductivity of the fragipan that restricts its erosion rather than other factors.

The location of moisture within a soil is largely dependent on three factors:

1. the entry point of water to that soil;
2. the conductivity of that soil;
3. the attraction of water by the soil.

Water is redistributed from the point where it enters the soil by a number of factors, among them gravity, moisture tension, osmosis, and diffusion. In unsaturated soils the major force is that of moisture tension. This is also described as the pressure (or matric) potential or soil moisture suction and is related to the affinity that water has for small pores within a soil, (see 2iv above). The rate at which this demand for water is satisfied depends on the hydraulic conductivity of the soil. The hydraulic conductivity is a property that is also largely dependent on porosity - the volume of pores, the tortuosity, and most importantly the size of pores are important in determining the hydraulic conductivity. For lateral flow of water to occur a slope and an imbalance between supply and demand, are required. When more water is being supplied than a particular layer can either hold or transmit downwards then water may move in response to the gravitational potential and flow downslope, with its maximum rate of flow determined by the hydraulic conductivity of that layer. If the supply of water exceeds this conductivity a perched water table would form, from which lateral flow could continue after external water supply had ceased.

Summary

1. Lateral flow is dependent on the supply of water to some depth exceeding the rate at which that layer can transmit it downwards;
2. Sufficient slope needs to occur for lateral flow to commence;
3. Lateral flow is encouraged in hillslope soils containing a relatively impermeable layer.

3v Soil Strength

Traditionally tunnel roofs have been thought to collapse due to downward pressure by stock or because tunnels have enlarged laterally to the extent that the roof no longer has sufficient strength at its weakest part to support itself. Hicks (in press) raises the additional possibility that water pressure in the tunnel, particularly after heavy rain may be sufficient to burst through the tunnel roof, forming what looks like collapse holes.

Soil strength is an important parameter in this phase of tunnel roof destruction rather than in the earlier phase of tunnel initiation. The importance of tunnel roof destruction to subsequent gully development has been largely ignored in published studies concerned with tunnelling. However considerable research has occurred into the factors determining soil strength. A description of these factors and of the process of root destruction follows.

a) *Arch strength and tunnel roof collapse*

The well known strength of arches is related to the typical incompressibility of the materials that arches are constructed of. Tunnel roofs are structurally analogous with arches. However tunnel roofs can collapse, this usually being the first sign that gullying is about to develop.

Roof collapse of tunnels in loessial soils occurs principally in winter, when the soil is wet. Downward pressure by stock hooves can initiate roof collapse when the soil is in a susceptible condition. The downward pressure of a stock hoof compresses the soil overlying the tunnel, either bending the arch and reducing stability, or breaking right through the roof. Further hoof impacts on a weakened area may then be sufficient to break the tunnel roof. Roof collapse may also be initiated by tunnel enlargement due to flowing water. Collapse would result when the strength of the roof is insufficient to support the mass of soil. These two influences - downward pressure and undermining - could occur simultaneously when wet tunnelled slopes are grazed. Destruction of tunnel roofs by bursting would also be encouraged in these conditions.

Roof collapse could also result from desiccation. Tunnel roofs would be prone to desiccation as the removal of soil in tunnels lowers the moisture storage capacity in that area of soil. This would result in shrinkage cracking which if great enough could cause a roof to collapse upon application of downward pressure, as it would then be more compressible.

Summary of factors related to tunnel roof collapse:

- hoof pressure
- level of compressibility
- amount of tunnel flow
- restrictions to tunnel flow
- resistance to stress
- amount of shrinkage.

b) Animal hoof pressure

Willatt and Pullar (1983) estimated hoof pressures for cows of 192 kPa, and sheep of 83 kPa. These figures were obtained on the basis of weight per projected unit area of contact. These were acknowledged underestimates, as animals may make ground contact with only two or three hooves at a time, or hooves may not necessarily be placed flat on a soil surface. Willatt and Pullar mention that when an animal is in motion kinetic energy is also imparted to the soil. They cited hoof pressure values from other sources of 100 kPa and 64 kPa for sheep, and 160 kPa for cattle, while pressure values given for tractors were <100 kPa and 30-150 kPa.

Because of these pressure differences a single cattle beast would be more likely to cause tunnel roof collapse than a single sheep. However at the same stocking rate approximately six times as many sheep as cattle are present. Whether six times as many sheep exercising about 40% of the hoof pressure are more or less likely to collapse a tunnel roof would depend on the pressure needed to cause roof collapse, and the chance of a hoof being in the right place.

It is probable that the pressure required to collapse a tunnel roof decreases as the tunnel size increases. If this is the case then it is probable that cattle would cause roof collapse at an earlier stage of tunnel development than sheep would. Mason (1981) noted that cattle pug the ground severely in winter and this had a beneficial effect by breaking in small gullies which did develop (see plate 3.1). The author has observed roof collapse on the Wither Hills apparently caused by cattle, which resulted not in breaking in of the tunnel, but in leaving an open hole (see Plate 3.2). Nevertheless it is expected that the earliest possible identification of tunnel and potential gully sites is in the best interests of farm management. If sheep are grazing roof collapse would not take place until tunnels are larger, so that any gullying that does develop could be expected to be more serious.

c) Shrinkage and tunnel roof collapse

Whether the soil over a tunnel roof is weakened by

Plate 3.1
Pugging of ground in winter by cattle at Wither Hills, Blenheim.

Plate 3.2
Collapsed tunnel roof apparently caused by cattle at Wither Hills, Blenheim – August 27 1986.

desiccation-induced shrinkage cracking depends on; the amount of shrinkage, and the relationship between the strength and dryness of the soil. The weakness induced in the arch structure by the cracking may be compensated for by the increased strength associated with the dryness of the soil (see 3ve). However if a crack forms right through the tunnel roof a point with an extremely high infiltration rate would be formed. The flow of water in a rain event may scour the crack and enlarge a hole to the point where the tunnel roof is no longer stable.

d) Compressibility

This is related to the soils pore distribution. Soils with open pores are susceptible to compression on the application of pressure; this allows the soil particles to move closer together. A soil is more likely to have open pores in its dry state, although when wet the soil may still be compressible if pressure can expel the water from the pores. In wet soils there is likely to be less friction between particles, and less likelihood of cementing agents being present. Qualitative observations on the Wither Hills have indicated that the loessial soils are more compressible when wet.

e) Tunnel Roof Bursting

Hicks' speculation on the occurrence of tunnel roof bursting instead of collapse seems plausible, when the pressures that can be reached by a head of water due to retarded flow are considered. Water backed up for a vertical fall of 8.5 m would supply a pressure of 83 kPa at the point of blockage, roughly equivalent to the pressure from the hooves of one sheep. A 19.6 m head of water would supply 192 kPa pressure to the blockage point roughly equivalent to the pressure from the hooves of one cattle beast. On a typical tunnelled slope of say 20° water would need to be backed up 25 m to supply 8.5 m head, or be backed up 57 m to supply 19.6 m head. These figures are of a magnitude such that it seems plausible to suggest that roof destruction may occur by two mechanisms:

i) by downard pressure - collapse,

ii) by outward pressure - bursting.

f) Resistance to stress

A soils resistance to tunnel roof collapse can be changed by altering two parameters which affect the cohesion between soil particles. These are:

1. the water content;
2. the level of root binding.

Water acts as a lubricant by increasing the interparticle distances within a soil. This results in a reduction of the frictional component of cohesion. Wetting a soil may also result in solution of any carbonate cements that are present.

Owen (1981) measured shear strength on Wairarapa soils where both slipping and tunnel-gully erosion occur. He found that increasing water content significantly reduced soil shear strength on soils from both sunny and shady aspects (see fig. 3.4). He was attempting to specify reasons for an aspect-mass movement relationship. Owen found that sunny slopes despite being considerably drier were nevertheless weaker. This indicated a marked soil difference between sunny and shady slopes, which was confirmed by a pedological survey. This reduction in strength as water content increases may provide a reason for the apparent increase in tunnel collapse in winter when the soil is wet.

The presence of roots in a soil increases cohesion by binding soil particles closer together. The soils shearing resistance is also increased, as to shear the soil the roots also have to be broken. The first of these effects is due to the 'pullout' strength of the roots. This is dependent upon the surface area of root in contact with the

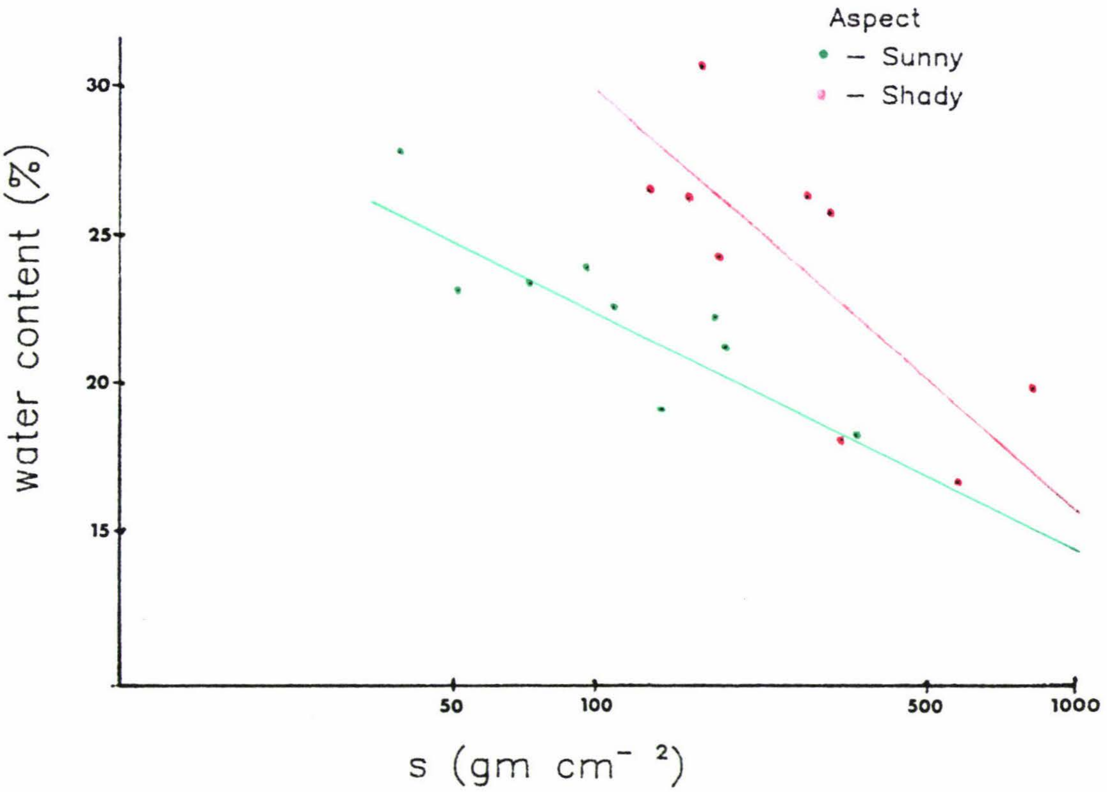


Fig. 3.4 The relationship of shear strength (s) to sample water content for a yellow–grey earth soil formed from mudstone (after Owen, 1981).

soil. The surface area of roots is proportional to the length times the circumference ($2\pi r$) of roots. The second effect, that of increasing the shearing resistance is due to the roots tensile strength and is dependent upon the length times the cross-sectional area (πr^2) of roots. These two effects - pullout and tensile strength - are proportional to the length of roots and either their radius or radius^2.

An increase in the level of cohesion could influence tunnel-related erosion in two ways. The first is by reducing the rate of tunnel enlargement. The extra cohesion would reduce the rate of removal of macroparticles from the tunnel walls, and also the rate at which soil would fall in from the tunnel roof. Secondly both the rate and style of tunnel roof destruction could be altered. A larger tunnel would be necessary before the roof would either collapse or burst. This may then lead to more serious gullying. Alternatively roof subsidence, rather than collapse or bursting, may occur. Although this would lead to the formation of a surface depression, open gullying may be less likely as highly erodible subsoil has not been exposed. Some confirmation of this last idea is provided by observation of tunnelling in loessial soils in the humid environment of the Manawatu compared with the seasonally dry Wither Hills. Tunnels on the Massey University farm, Tuapaka, appear to have subsided with the rootmat remaining intact (see plate 3.3), while on the Wither Hills collapse often appears to be by a whole section of roof falling in and leaving a sharp-sided hole (see plate 3.4).

Plate 3.3
Tunnel roof subsidence with rootmat remaining intact — Tuapaka, Palmerston North.

Plate 3.4
A collapsed tunnel roof where rootmat has broken — Wither Hills, Blenheim.

CHAPTER 4 THE HYDROLOGICAL EFFECTS OF OVERGRAZING

The soil-atmosphere interface has many impacts on the location and movement of water throughout the environment. Water is exchanged between the soil and atmosphere in the processes of infiltration and evapotranspiration; it is lost to streams by throughflow, pipeflow or overland flow; it is lost to groundwater by seepage; or it is held in storage and gradually both released and replaced. Vegetation extends the soil-atmosphere interface both above and below the soil surface. When vegetation is removed or altered by grazing the soil-atmosphere interface is changed and the effects extend throughout the hydrological cycle.

This study was initiated because it was thought that overgrazing of pasture grown on soils susceptible to tunnelling caused these soils to crack excessively due to increased water loss by evaporation. There is little doubt that removal of vegetation increases the level of evaporation from the soil surface, however this is only one component of a much larger system, and it is necessary to consider the other components before conclusions can be drawn about increased water loss due to overgrazing.

A number of studies have noted some of the hydrological effects of overgrazing. However no widely applicable model has been developed that can account for the variability in effects due to the important catchment properties of vegetation, soils, and climate. It is therefore necessary for any particular environmental conditions, to make field measurements before the actual hydrological effect of overgrazing can be described.

Overgrazing directly affects the processes of; evaporation, transpiration, evapotranspiration, interception, stemflow and throughfall, infiltration, and runoff. Indirectly overgrazing may affect the whole hydrological cycle, though its effects would be imperceptible in the storage components of the atmosphere and the oceans.

4i Evaporation

The exchange of gases between soil and atmosphere can occur by two mechanisms:

1) convection (mass flow),
2) diffusion.

With convection, the moving force is the total gas pressure which results in the entire mass of air streaming from a zone of higher pressure to one of lower pressure. Pressure differences can result from barometric pressure changes in the atmosphere, temperature gradients, wind gusts over the surface, infiltrating water displacing antecedent soil air, a fluctuating water table pushing air up or pulling it down, extraction of soil water by plants, and by compaction of the soil (Hillel, 1980a). However this method of exchange is thought to be important only at shallow depths and in soils with large pores (Hillel, 1980a).

In other soils diffusion, where the moving force is the partial pressure (concentration) of any gaseous constituent is thought to be the dominant mechanism. Diffusion may occur both through the air filled pores and also through water films where the supply and removal of gases is particularly important for plant respiration (Hillel, 1980a). When water vapour is removed from a point its partial pressure will be reduced. This will cause water from elsewhere to move towards that point to equilibrate the pressure. Thus the removal of water vapour from the soil surface into the atmosphere will draw more water vapour up from below. The effects of grazing on evaporation and transpiration will be described together in section 4iii.

4ii Transpiration

The loss of water vapour by plants is caused by vapour pressure gradients between the normally water saturated leaves and the often quite dry atmosphere. This could be resisted except that plants absorb CO_2 (which is required for growth) through cavities in their leaves. These cavities known as stomates may be opened or closed depending on whether CO_2 is required. When stomates are open and CO_2 is taken in, water usually diffuses out because the atmosphere is drier than the leaves (Hillel, 1980). When water is lost, tension within the plant causes water to move toward the stomates. This tension is continued through to the root zone where water is transferred from soil to plant (Hillel, 1980). When plants are transpiring, water is removed from near wherever roots are present. As roots deplete the soil of water in their immediate vicinity water moves from the surrounding soil in response to this moisture tension. Plants can only remove water from the soil until a tension of about -15 bars is reached in the soil. At this point plants still lose water to the atmosphere when stomates are open but it is not replaced. This results in plants having insufficient water to operate physiologically and they wilt.

4iii Evapotranspiration

The usual situation is for both evaporation and transpiration to be occurring simultaneously, hence the compound process termed evapotranspiration. Water evaporates from the soil surface and also from the walls of any cracks present, while plants may remove water from wherever roots are present in the soil.

Evapotranspiration may occur at a potentially maximum rate determined by meteorological factors or at a lower rate determined by the ability of the soil and plants to supply water. The meteorological factors which encourage evapotranspiration are:

1) high levels of sunshine and high temperatures, which both impart energy to water at the soil-atmosphere interface encouraging vaporisation;

2) low atmospheric pressure which encourages vapour to move from the soil to the atmosphere by convection;
3) low atmospheric humidity which encourages vapour to move from the soil to the atmosphere by diffusion;
4) high surface winds which remove vapour as it moves into the atmosphere maintaining humidity levels at the soil-atmosphere interface at the lowest possible level which encourages vaporisation.

Whether the soil can supply water to the atmosphere at the rate demanded depends on the relationships between the soils wetness, water retention and hydraulic conductivity. As a soil dries out, the water that remains is harder to remove as the easily removed water has gone first, and conductivity lowers as the larger pores are now air filled which blocks liquid transport. The ability of plants to supply water also declines as the soil dries out.

The proportion of evapotranspiration that can be attributed to each of the separate processes depends upon the amount of surface cover which controls evaporative demand, and both the rooting depth and soil's dryness which control the amount of water available for transpiration. The relative importance of evaporation increases with decreasing vegetative cover and decreasing soil moisture levels. Ward (1975) cites research which compared evapotranspiration from forest, pasture grass, and cultivated crops and showed that evaporation accounted for 10, 25, and 45 percent respectively of the total evapotranspiration losses. When a soil's moisture content reaches the wilting point transpiration effectively ceases and any further water loss is due to evaporation. The relationships between evaporation, transpiration, and water loss depend on the soil and the variables of vegetation and atmospheric demand.

Barker and Chu (1985) reviewed the effect of grazing intensity on soil moisture levels. They concluded that water can be conserved by keeping pastures short. The decrease in transpirative loss offset any increase in evaporative loss except right at the soil surface. This moisture conservation was accompanied by a loss in pasture production. This pasture density/water use relationship was also shown by Johns and Lazenby (1973) in Australia with a positive correlation in the summer months between increasing leaf area index and water use. Evans (1976) showed that for a ryegrass-white clover sward on yellow-brown earth soil at Palmerston North, that soil at 50 cm depth under a laxly grazed area became dryer than at 10 cm depth under a hard-grazed area (see fig. 4.1). However this study did not take place in a cracking soil (Evans, Pers. Comm.). This type of relationship has not been shown in an area with cracking soils where it is expected that some evaporation from depth would occur increasing the effective depth of evaporation.

4iv Interception, Stemflow, and Throughfall

These related processes may determine the immediate location of precipitated water but they have little overall impact on the eventual location of that water. Lull (1964) points out that intercepted rainfall which is subsequently evaporated, is effectively no different from rainfall which penetrated the leaf canopy and was then brought up through the plant by evapotranspiration. This is because the energy used by the former process is then not available for the latter. The interception storage capacity of grasses appears to be about 1-3 mm (Burgy and Pomeroy, 1958). For particular species this capacity is related to their leaf area which is controlled by the level of grazing. Although interception may delay the speed and decrease the volume of water reaching the soil surface this would only be of

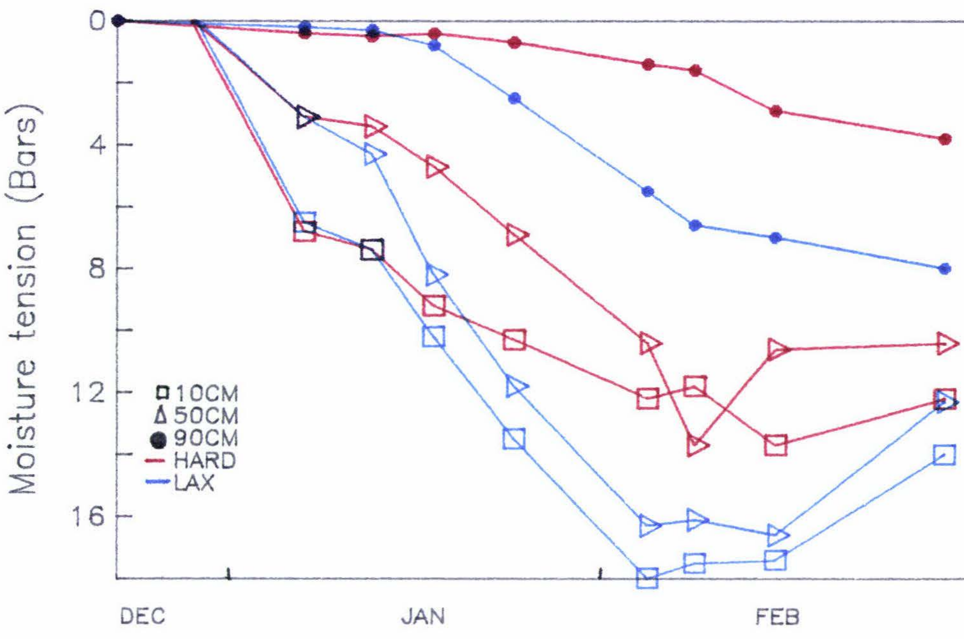


Fig. 4.1
The effect of management
on moisture tension.
– after Evans (1976).

importance with small rainfall events where 1-3 mm was a significant proportion of the total fall. With larger events of, for example, 30 mm, the level of interception has little effect on the amount of water reaching the soil surface - this would range between 27 and 30 mm depending on the level of defoliation.

The more important effect associated with increasing leaf area is the restriction of raindrop impact with the soil surface. Such impact destroys surface soil structure blocking voids and lowering the infiltration capacity (Ward, 1975).

4v Infiltration and Runoff

In addition to destroying soil structure by increasing raindrop impact, overgrazing may also result in loss of structure because of increasing compaction by stock treading. Willatt and Pullar (1983) noted the effect of increasing stocking rate on both the bulk density and hydraulic conductivity of the top 6 cm of a silt loam soil (see fig. 4.2). Compaction reduces the infiltration rate by reducing the porosity of the soil. This loss of structure has two related effects when rainfall exceeds the reduced infiltration capacity:

1) decreasing soil moisture levels;
2) increasing runoff.

Campbell (1954) conducted tests on the Wither Hills silt loam soil measuring the infiltration capacities under a number of management and pasture systems (see fig. 4.3). Campbell made an additional comparison of infiltration capacity between:

Native cover	3.5 in hr^{-1}	=	90 mm hr^{-1}
Well farmed	0.65 in hr^{-1}	=	17 mm hr^{-1}
Badly farmed	0.23 in hr^{-1}	=	6 mm hr^{-1}

The rainfall of ten minutes duration with a two year return period for Blenheim is 5 mm, while the one hour rainfall with a two year return period is 11 mm (Tomlinson 1980a).

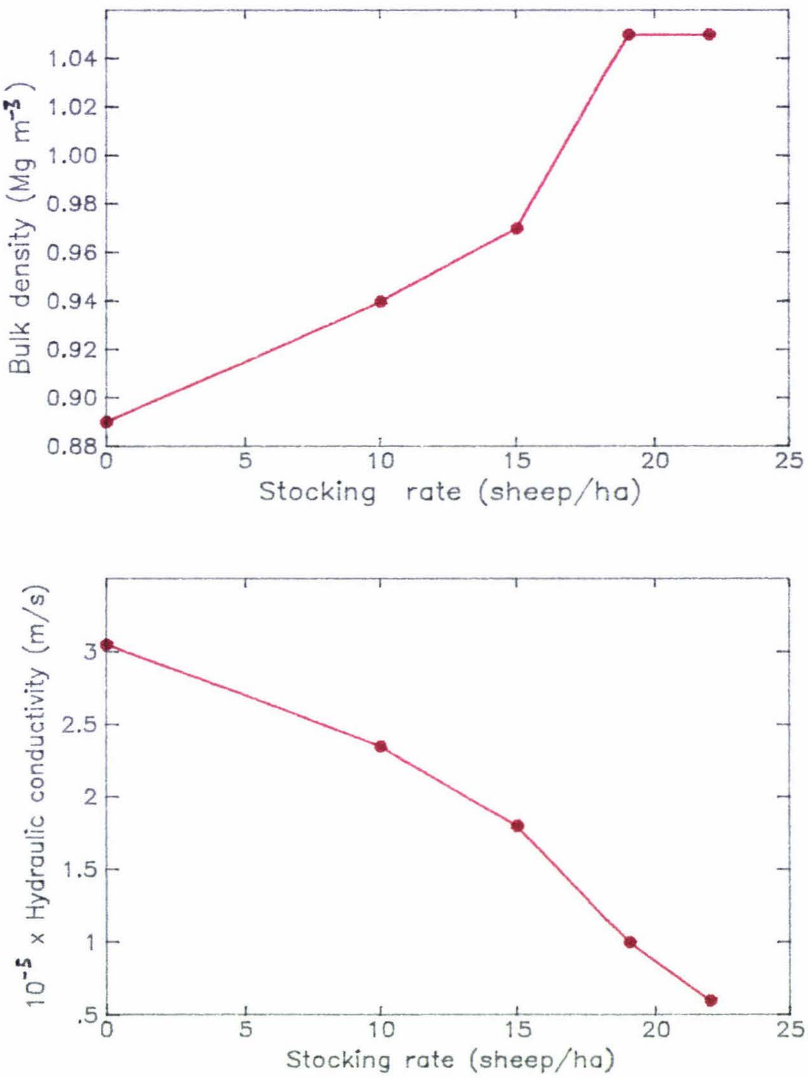


Fig. 4.2
The effects of stocking rate on bulk density and hydraulic conductivity on the top 6cm of a silt loam – after Willatt and Pullar (1983).

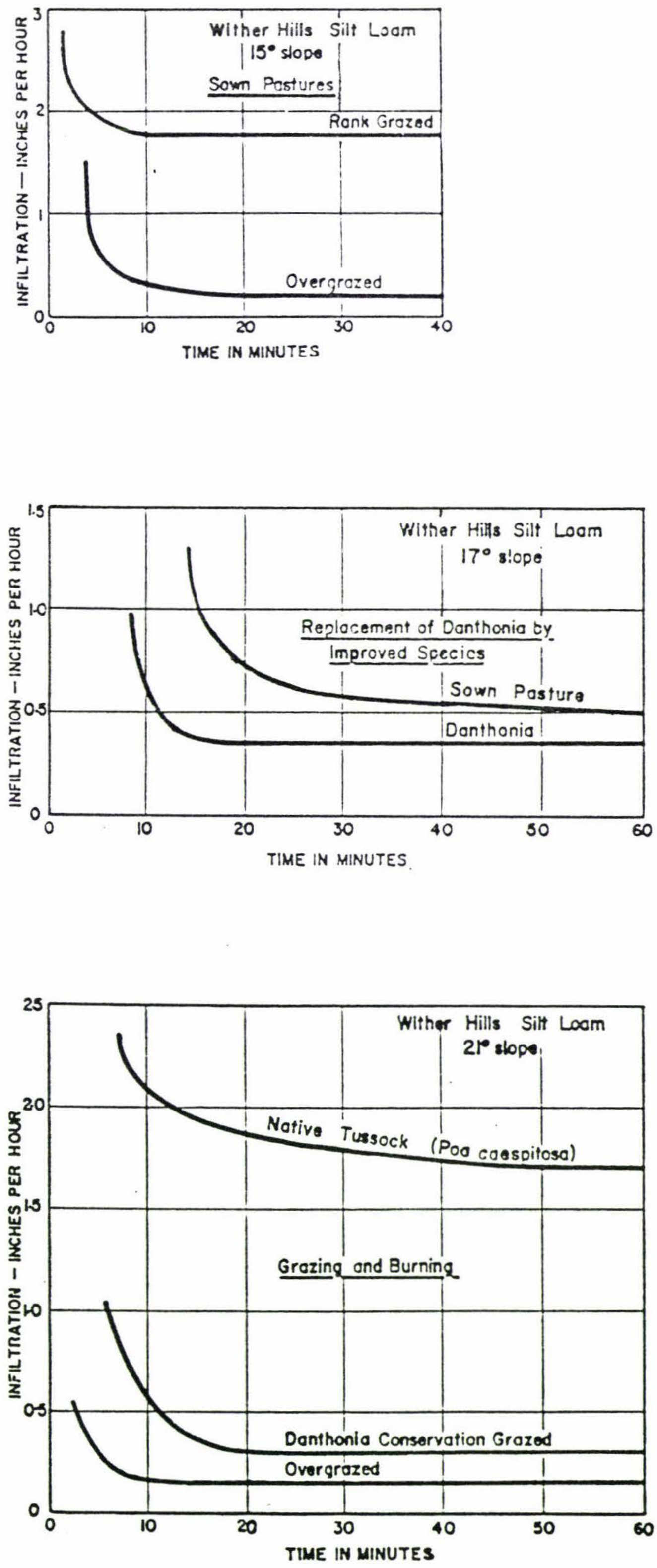


Fig. 4.3
Effect of pasture management on infiltration rate, (after Campbell, 1954).

Rainfall intensities vary considerably within individual events with most rain tending to occur in pulses separated by periods of low intensity (see fig. 4.4). On this basis it would be expected that an instantaneous infiltration rate of 6 mm hr^{-1} could be exceeded within many rainfall events even if only for short periods while infiltration rates of 17 mm hr^{-1} and possibly even 90 mm hr^{-1} would only be exceeded within a very few rainfall events.

It was noted in 2vii that excessive runoff was a problem associated with tunnel-gullying. In addition to the reasons outlined then another cause of runoff would be the loss of soil structure due to compaction.

4vi Summary of Effects on the Soil Moisture Balance

The major hydrological effects of overgrazing are:

1) a reduction in evapotranspiration;
2) a decrease in infiltration and a corresponding increase in runoff.

As levels of evapotranspiration are seasonal the overall effect on the levels of soil moisture would also have a seasonal relationship. It would also depend on particular events so that a low intensity rainfall of say 20 mm would have a different effects than a high intensity rainfall of 20 mm. To accurately describe the effects at a particular site would require extensive data gathering. The simplest solution would be measurement of soil moisture levels under different grazing intensities over a period of time including a range of climatic conditions (see chapter 7).

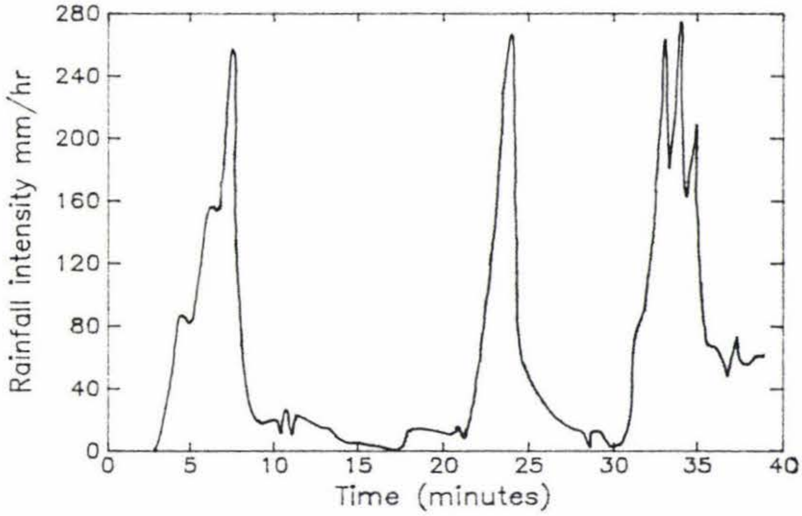


Fig. 4.4 The variation of rainfall intensity within a single rain event (after Semplak, 1966).

CHAPTER 5 THE EFFECTS OF OVERGRAZING ON PASTURE CONDITION

Animals may defoliate, selectively graze and trample pastures, deposit dung and urine, and disperse seeds (Watkin and Clements, 1978). These individual effects will be outlined in this chapter. However the exact causes and effects of excessive grazing are difficult to describe as these depend on the site dependent relationships between the soil, plants and animals. For example the Wither Hills could be described as having been overgrazed in 1958 with a stock carrying capacity of 2.66 LSU ha^{-1}, and not being overgrazed in 1980 despite an increase in the stock numbers to 5.02 LSU ha^{-1}.

5i Defoliation

Reducing the active leaf area of pasture not only affects the plant, but also changes the microenvironment in the plants vicinity including the soil and atmosphere close to the soil surface (Watkin and Clements, 1978).

Defoliation reduces water loss by transpiration as there are less stomates to lose water. Contrastingly defoliation increases water loss by evaporation because the reduction in cover increases the exposure of the soil surface to both radiation (see table 5.1) and wind (see Chapter 4). A less direct effect on soil moisture levels is that resulting from compaction of the soil surface which reduces infiltration and promotes runoff. Surface compaction is due to increased raindrop impact upon the soil surface or increased treading damage (see 5ii) due to a decrease in the cushioning effect of foliage.

Defoliaton has been noted as reducing root development by a number of researchers e.g. Jacques (1937), Carter and Law

Table 5.1: Mean monthly soil temperatures (°C) at two depths and at three different stocking intensities, (after King and Hutchinson, 1976).

Sheep/ha	**10**		**20**		**30**	
	1 cm	**4 cm**	**1 cm**	**4 cm**	**1 cm**	**4 cm**
January	17.78	17.89	18.08	18.00	19.29	20.02
February	18.54	18.52	18.43	18.44	19.63	20.00
March	17.02	16.85	18.37	18.18	19.54	19.83
April	13.98	14.20	15.73	15.56	16.07	16.56
May	11.85	12.01	12.66	12.55	12.48	12.86
June	10.45	10.81	10.92	10.79	10.67	10.45
July	7.39	7.40	7.77	7.55	7.86	7.76
August	10.37	9.75	11.04	10.93	10.90	10.97
September	12.64	12.48	13.44	13.32	14.08	14.35
October	15.52	15.27	16.06	15.60	16.91	17.09
November	17.61	17.51	17.98	18.08	19.16	19.13
December	18.78	18.59	19.82	19.75	21.68	21.25

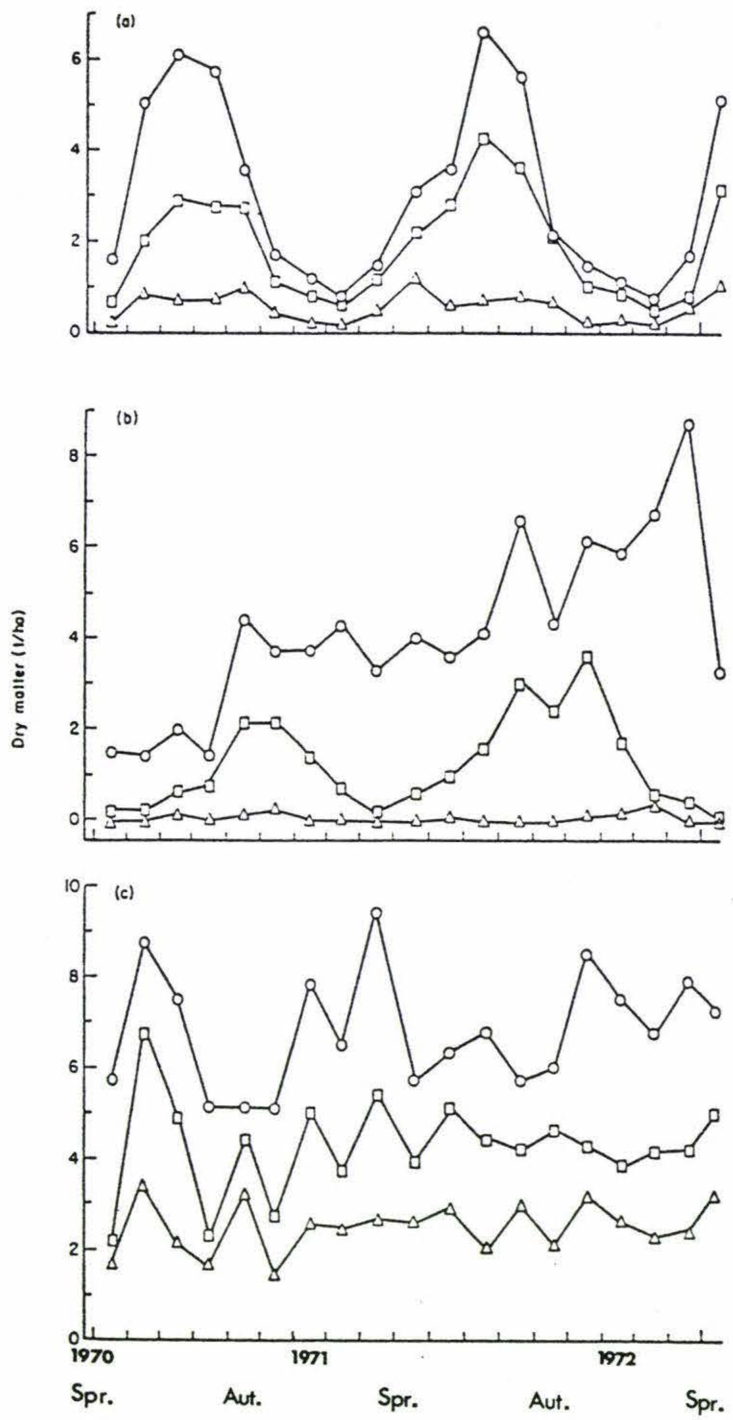


Fig. 5.1 Effect of stocking intensity:

o 10 sheep ha^{-1},

□ 20 sheep ha^{-1},

Δ 30 sheep ha^{-1};

and seasonal changes on:

(a) green herbage,

(b) dead herbage,

(c) washed roots;

(after King and Hutchinson, 1976).

(1948), Jameson (1963), and King and Hutchinson (1976) (see fig. 5.1). However Richards (1984) qualified this generalisation by observing that with at least one grass, *Agropyron spicutum* (Eurasian bunchgrass) defoliation did not always noticeably reduce root development. This is a grazing sensitive grass whose response was in marked contrast to that of the very similar but grazing tolerant *Agropyron desertorum* (North American bunchgrass). The response of *A. desertorum* was to allocate relatively more resources to aboveground regrowth re-establishing the root-shoot balance whereas the response of *A. spicatum* was for root elongation to continue following defoliation to the detriment of foliage regrowth.

Deinum (1985) measured root distribution in a grazed pasture dominated by perennial ryegrass. Deinum found that total root mass was less under the long grass of the dung patches, than in the shorter grass between these patches. This effect was particularly noticeable at the 0-10 cm depth where most roots (approximately 85%) were found. At greater depth somewhat more root mass was found under the long grass of the dung patches.

These contrasting observations indicate that to accurately describe the response of a pastures roots to grazing it is necessary to measure root response for that pasture under a particular set of grazing conditions (see chapter 9). However the usual situation when pasture is continuously overgrazed is for there to be an overall reduction in root mass as explained by Shearer (1986). Plant growth following winter dormancy or defoliation uses reserves of nutrients and energy stored in the root system. As the leaf area increases the plant is able to utilise sufficient energy for continued growth, as well as replacing the reserves used for the initial growth. If leaf removal occurs before these reserves are replaced, future root growth and condition will be detrimentally affected (Shearer, 1986). If these root reserves are depleted the rate of recovery of leaf growth will be reduced. Further leaf growth is also reduced because of the lowered photosynthetic capacity and because of the roots' reduced ability to take up water and nutrients. This is why excessive defoliation reduces overall pasture production (see fig. 5.2). Sheath and Bryant (1984) note that losses of pasture production occur under both overgrazed and excessively undergrazed conditions. In rank pasture dry matter losses occur and opportunities for growth are lost.

Selective defoliation occurs because of the differing palatability and availability of pasture species. Pasture species also differ in their response both morphologically and physiologically, to defoliation and will regrow at different rates. These effects may result in quite different distributions of pasture species depending on the intensity and mode of defoliation (Watkin and Clements, 1978).

King and Hutchinson (1976) also measured the relationship between green and dead herbage for three stocking intensities (see fig. 5.1). They found that the mass of dead herbage decreased with greater stocking intensity, as more pasture was utilised by stock. Consequently more plant litter was returned to the soil at the lower grazing intensities benefitting the levels of soil organic matter. The greater return of excreta as the stocking rate increases would not make up for the lower return of plant litter, as part of the extra pasture consumed was utilised for animal growth and metabolism and lost to the soil-pasture system.

5ii Treading

Brown and Evans (1973), reviewing earlier work by D B Edmond, noted that the detrimental effects of treading in wet conditions were obvious and have been well documented. However no such obvious effects of treading on pasture

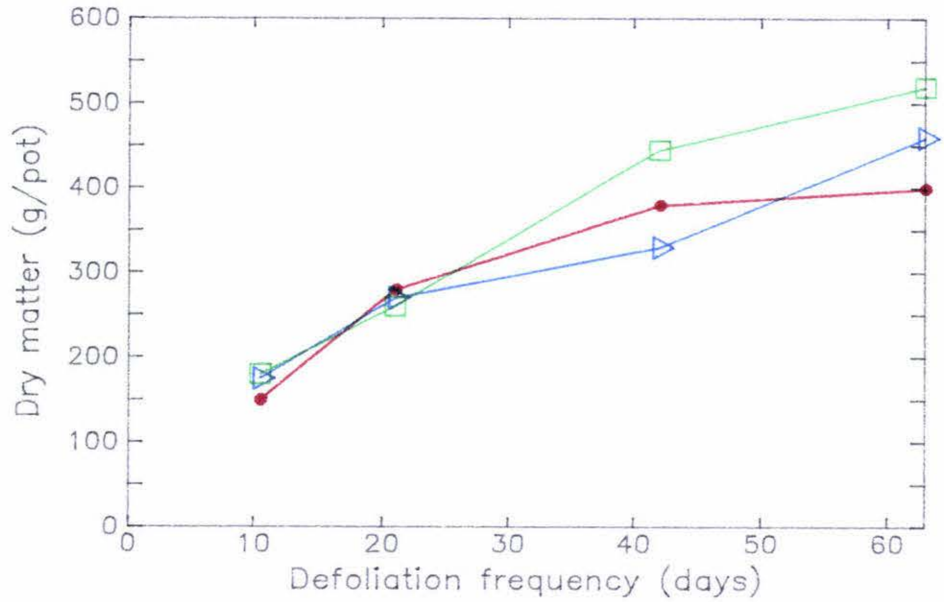


Fig. 5.2
The effect of defoliation frequency on accumulated dry matter yield.
(● tall fescue, □ ryegrass, △ mixture) – after Bell 1985.

production in dry weather were apparent and had not been investigated. The main concept they mention is that, "all treading damages pasture irrespective of soil type, soil moisture level, plant species, or kind of animal". Treading may damage pasture; directly by crushing or bruising foliage on dry soil or burying foliage and covering it with mud in soft wet soil (Brown and Evans, 1973), and indirectly by compacting the soil which restricts root growth.

Edmond (1970) had shown that there was little difference in the effect on herbage production between sheep and cow treading although both were deleterious. However some treading damage has to be accepted when grazing occurs. The recommended way of reducing treading damage is to reduce the amount of walking by grazing animals to obtain water or by limiting the duration of grazing. Keeping animals off pasture during and immediately after rain and more generally restricting grazing time per day during the winter were also seen as beneficial management techniques (Brown and Evans, 1973). Pasture composition may also alter because of differential resistance to treading. Management to minimise treading damage may be necessary to maintain less resilient species such as red clover and cocksfoot (Brown and Evans, 1973).

Damage to soil structure by treading was noted in chapters 4 and 5i. Compaction will increase mechanical resistance to root penetration, reduce aeration, reduce moisture availability, reduce infiltration, and increase runoff (Watkins and Clements, 1978). Any of these factors may depress pasture growth, and alter composition because of selective effects on species. Willatt and Pullar (1983) showed an increase in penetration resistance by between 20 and 30 percent for grazed plots over ungrazed plots and they concluded that this could produce a significant reduction in root growth (see fig. 4.2).

5iii Excretion

Curll and Wilkins (1983) investigated the effects of excretion in conjunction with a study of defoliation and treading. They found that the return of excreta to the pasture system ameliorated some of the accompanying effects of defoliation and treading due to increased levels of soil nitrogen available to plants. Herbage growth rates and root weights were increased with the return of excreta. The botanical composition also changed with ryegrass being encouraged and clover being depleted where excreta was returned. They found that at a moderate stocking rate of 25 yearling wethers per hectare the return of excreta compensated for the detrimental effects of defoliation and treading on herbage growth. However at a stocking rate of 50 yearling wethers per hectare herbage growth was depressed as the beneficial effect of the return of excreta was outweighed by the negative effects of treading and defoliation.

5iv Seed Dispersal

Seeds can be transported in the digestive systems of grazing animals, and may also be transported when attached to hooves and the hide of animals (Watkins and Clements, 1978). This is only of minor importance in pastures where species are already well established. However where cover is patchy seed dispersal by grazing animals may be important in recolonisation (Watkins and Clements, 1978).

5v Summary

Although the exact effects are dependent on the site properties of soil, pasture species, and type and number of animals, some conclusions can be offered on the effects of overgrazing:

1) Herbage production will be reduced;
2) Palatable species will be reduced;

3) Root mass and length will be reduced;
4) Soil structure deteriorates;
5) Water loss increased at surface but decreased at depth;
6) Infiltration reduced and runoff increased;
7) Soil organic matter reduced.

These effects will lower the soils actual productive capacity and also increase its susceptibility to erosion. Put more simply - overgrazing is inadvisable.

CHAPTER 6 A REVIEW OF TECHNIQUES FOR CONTROLLING TUNNEL-RELATED EROSION

Viewing tunnel-related erosion as a soil conservation problem implies the desire to either: remove the problem, remove the factors which caused the problem, or reduce the impact of the problem. The soil conservation works that have been carried out in areas of New Zealand affected by tunnel-related erosion over the past forty years have attempted each of these objectives. In practice these objectives are met by carrying out both repair work and control work, which are often not easily distinguishable.

In New Zealand the serious soil conservation problem is tunnel-gullying, with the initial stage of tunnelling not much of a problem in itself. The problems associated with tunnel-gullying in dryland loessial areas were outlined in 2ii above. This chapter will outline the techniques that have been developed to control these problems. Many of these control techniques were first applied and tested at the Wither Hills Soil Conservation Reserve which was established in 1944 primarily for this purpose.

6i Early works

These initial works are outlined in a Soil Conservation and Rivers Control Council publication (Wilkie, 1951). They included:

1. stock removal so that natural reseeding of native grasses occurred;
2. repair and construction of fences to ensure stock control;
3. provision of adequate stock water supplies;
4. fertiliser application - both lime and superphosphate;
5. establishment of new pastures;
6. contour cultivation to control the rate of runoff;
7. tree planting on badly eroded sites and in shelterbelts;

8. construction of grassed waterways;
9. gullies filled in by discing;
10. gully control by debris dams and live silt traps;
11. continuing experimentation into pasture species, fertiliser, sowing and cultivation techniques, grazing levels, and erosion rates.

The effects of these measures was to:
1. completely control sheet erosion which had been rife over the area;
2. control small gullies;
3. partially control larger gullies;
4. increase moisture retention on the hills promoting more growth, better erosion control and increased production;
5. protect debris dams and other structural works in the creek beds which would have been severely damaged but for the retarding of runoff and soil loss by increased vegetative cover.

(Wilkie, 1951).

Tree planting and some pasture establishment had been unsuccessful due to the lack of moisture and in some places a lack of soil. Contour furrowing increased pasture production during the late spring - early summer period when the retention of runoff water benefitted growth. This benefit did not extend into the summer period when the soil was too dry for growth whether furrows were present or not (Wilkie, 1951). Unfortunately furrows also encouraged tunnel redevelopment as they concentrated water in particular areas of the slope.

Runoff and soil loss measurements were made under a number of management systems which showed the beneficial effects of conservation farming (see Table 6.1).

Treatment (0.01 acre plots)	Average volume of runoff (gallons)	Average % silt by volume	Average volume of silt (gallons)
Improved pasture, moderately grazed, which had been contour furrowed	9½	1.2	0.11
Improved pasture, moderately grazed, with no contour furrows	6¼	1.1	0.07
Bare, overgrazed, native pasture	18	1.3	0.23
Well grassed conservation grazed native pasture	11¼	0.8	0.09
Conservation grazed native pasture	4	1.5	0.06
Native pasture, burnt at intervals	21	4.8	1.01

Table 6.1 Effects of pasture management on runoff and soil loss - August 1948 to June 1950, (after Wilkie, 1951).

Wilkie (1951) outlined the costs and benefits of the scheme and on the basis that current income was much greater than historical income he concluded that future seasons would see all expenditure recovered and an overall profit made providing good land management practices were maintained. The block was described as having been changed from a "deteriorating problem area" to a "permanent asset with high future production capabilities".

6ii More recent works

The three main developments since 1951 have been:

1. the technique of destroying gullies by bulldozing the ground smooth;
2. improving pastures;
3. improving grazing management.

The bulldozing technique is described by Mason (1981): "The current method adopted in Marlborough is to doze in severely eroded tunnel-gully areas between July and October. Starting at the base of the slope a track is bulldozed at a 45° angle across the slope. The operator backs the bulldozer up the track and comes down the same track taking a one-third blade width of soil with an angled blade, tipping this off the downhill side of the track. The dozer works down to a depth below the floor of the existing gullies to completely doze out the gully." (see plate 6.1).

Bulldozing has two main effects:

1. smooths the surface removing paths for the concentration of runoff;
2. destroys the fragipan, which is the zone that concentrates sub-surface lateral flow.

These are not necessarily permanent effects. Runoff water will tend to reconcentrate with time forming surface channels, and a compact layer at depth may reform though it has not yet done so.

Plate 6.1
The technique of removing tunnel-related erosion and smoothing land by bulldozing.

The next step following dozing is the establishment of pasture (see plate 6.2). Mason (1981) describes this process: "After the face is completely dozed the land is chisel ploughed on the contour. This may require one or two workings depending on the condition the soil is left in after the first pass. The operator aims to keep the seedbed as rough as possible.

If the cultivation is completed early enough seed and fertiliser are applied by air. If the cultivation work is completed too late (after the end of October) to sow the permanent pasture an immediate cover crop is sown. The seed and fertiliser are not harrowed in but sheep may be run over the block being developed to tramp the seed into the soil."

The cover crop recommended by Mason (1981) is either barley, oats or rye corn. The recommended permanent pasture is a mix of lucerne and phalaris with lesser amounts of cocksfoot, white clover, and subterranean clover, while Sheppard and Lambrechtsen (1983) additionally recommend perennial ryegrass. The major problem in establishing and maintaining pasture in Marlborough is the lack of moisture. Lucerne and phalaris are both relatively drought resistant species with lucerne in particular being very deep rooting and able to draw moisture and nutrients from a large volume of soil. It is both palatable and highly productive (NWASCO, 1973). However lucerne responds badly to hard grazing, with production and ground cover both greatest when grazing is lenient. When grazed too hard bare ground is exposed and weeds can colonise. The other pasture species sown are meant to cover any bare ground between the lucerne plants. However it has proven difficult to establish plants here because of competition from the lucerne for moisture and nutrients (NWASCO, 1973).

The third development in conservation farming has been the

Plate 6.2
One year old pasture established following bulldozing.

move away from grazing by sheep to grazing by cattle. The immediate effect of this has been to maintain a greater level of ground cover as cattle cannot defoliate pasture to as great an extent as sheep. The provision of sufficient fencing and adequate water supplies has also allowed greater control of grazing intensity to be made. These factors have enabled pasture to be maintained in good condition benefitting both production and erosion control. The effects of grazing intensity on pasture condition and hydrology were outlined in the two previous chapters.

6iii Current Works Status

Five factors of critical importance in achieving a satisfactory and lasting treatment (aside from any climatic influences) are listed in the Marlborough Catchment Board's Scheme Review (1981). These are:

1. the standard of the initial mechanical treatment;
2. the application of sufficient fertiliser and seed;
3. sufficient fencing to allow control and utilisation of pasture growth, i.e. the ability to concentrate stock;
4. provision of an adequate stock water supply;
5. adequate grazing management and stock type.

The first of these factors depends for its success on the skill and experience of the bulldozer operator in removing the tunnels, destroying the fragipan and retaining topsoil. The third and fourth factors depend largely on sufficient finance being available. However the second and fifth factors depend on appropriate choices being available, and correct decisions being made. The success of soil conservation works depends on this complex web of physical, social, and economic factors. Research has been concentrated on attempting to find the best techniques for soil conservation, seemingly with the assumption that once this has been done these techniques will be adopted. However it is rarely that simple, as approval and adoption of techniques by farmers depends on their perception of prospective benefits, which may be rather different from the actual benefits. This would be particularly important where initial effects are negative, say through lost production, while the positive effects are not evident until some future date. To the five factors, outlined above, can be added a sixth - adequate communication, both between researchers and catchment board staff and between catchment board staff and farmers. Without this communication, choices would be made without a full appreciation of current knowledge. This may result in incorrect and inadvisable decisions being made which lowers the effectiveness of those works and also lowers peoples perceptions with regard to the desirability of future works.

With regard to determining the effectiveness of the Wither Hills Catchment Control Scheme an economic evaluation was carried out by Hadfield (1981). This evaluation considered the on-site benefit of increased production with the carrying capacity having gone from 2.66 livestock units per hectare in 1958 to 5.02 in 1980, and the off-site benefit of decreased sedimentation blocking watercourses. The costs of the works involved and those of increased stock numbers and fertiliser application were considered, and these costs along with the benefits were updated to 1981 dollars. With these tangible costs and benefits considered the scheme had an internal rate of return of 8.2%. Hadfield recognised that the real internal rate of return was rather higher than this because of the intangible nature of some of the benefits which were not considered in this analysis. Some of these are:

1. protection given to the flats below the hills has contributed to an expansion of horticulture;
2. protection given to the flats has contributed to urban expansion onto this land which is less productive than where expansion would otherwise have occurred;

3. decreased flood risk giving a greater sense of security;
4. improved appearance of the hills making parts of Blenheim more attractive places to live.

Hadfield considered the economic return from the scheme to be "relatively high", especially when these intangible benefits were taken into account. He also noted that on a livestock unit basis cattle were at this stage only about half as profitable as sheep and concluded that "serious consideration should be given to utilising management techniques which could go some way to reducing the predominant cattle fattening policy (see fig. 6.1) in favour of increasing sheep numbers." It was recognised that an all sheep policy could not be sustained because of the increased risk of erosion.

The reduction in erosion associated with the scheme is shown by table 6.2 (Marlborough Catchment Board, 1981). This data was gained by analysis of aerial photographs and shows a general trend towards less severe erosion since the scheme began.

The soil conservation techniques used on the Wither Hills have reduced erosion and led to a dramatic increase in production. This has been done at reasonable cost to New Zealand so that the Catchment Control Scheme has been a worthwhile project. Nevertheless any complacency could be dangerous: a new system of tunnels which could later become gullies may be deeloping. If this is so, the treatment is only temporary, and it would have to be admitted that a method of pastoral management which may be continued in perpetuity has not been found. Mason (1981) expected some gully redevelopment and saw it as necessary that these roof collapse sites be filled up with straw or hay and seed seconds. This would only be effective at a small scale, so detection of these problem areas at the earliest possible stage is necessary if situations such as

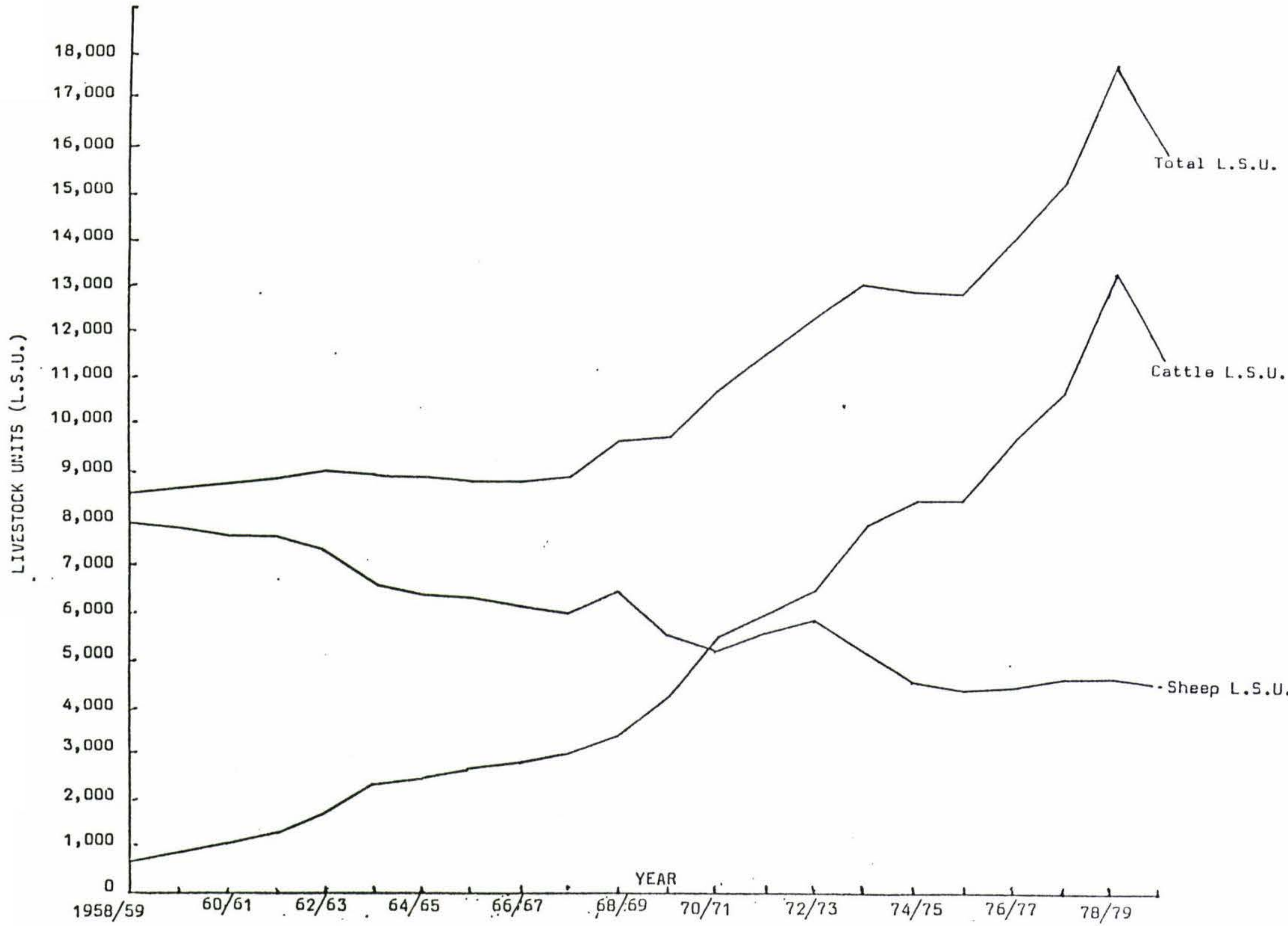


Fig. 6.1 Changes in cattle, sheep, and total livestock units on the Wither Hills, 1958 – 1980, (after Hadfield ,1981).

	1958 (ha)	1969 (ha)	1980 (ha)
Nil	1,344	2,280	2,345
Slight	183	280	304
Moderate	249	200	138
Severe	178	256	252
Very severe	74	115	107
Extreme	78	69	55
TOTALS	2,100	3,200	3,200

Table 6.2: Analysis of erosion status using land use capability assessment, (after Marlborough Catchment Board, 1981).

that shown in plate 6.3 are not to become common. Tunnelling does reoccur on slopes that have been treated (see plate 6.4). It is possible that visible collapse may only identify a small proportion of tunnels actually present. Tunnel initiation and enlargement have not been stopped although it is probable that the rate of such development has been slowed. The major effect of the conservation works on soil erosion has been the reduction in gully formation as they have not redeveloped to a significant extent.

Plate 6.3
Tunnel gully erosion at
Wither Hills, Blenheim.

Plate 6.4
Tunnelling that has redeveloped on a previously treated slope of Wither Hills, Blenheim.

CHAPTER 7 SOIL MOISTURE-PASTURE CONDITION EXPERIMENT

An experiment was designed to test the effects of pasture condition on the soil moisture balance and the development of desiccation cracking. Soil moisture levels under three different pasture conditions were measured at two sites susceptible to the development of tunnel-related erosion, over the summer of 1985-86. It had been intended that the influence of pasture condition and soil moisture levels on crack development would be ascertained. Unfortunately no significant soil cracking occurred at either site under any pasture condition at any stage of the summer (see chapter 8). This chapter outlines that part of the experiment designed to test the effect of pasture condition on soil moisture levels.

7i Methodology

Two sites susceptible to tunnel-related erosion were selected - one on the Massey University Sheep and Beef Unit, Tuapaka, near Palmerston North, and the other site on the Wither Hills Reserve near Blenheim. The prime requirements for site selection were: an area of at least 75 m x 24 m with an even slope angle, reasonably similar soil throughout the site, reasonably similar vegetation over the site, reasonably similar drainage, and accessibility by vehicle.

a) *Tuapaka Site* - This was located at NZMS1 N149 220375 on a colluvial footslope of about 5° slope approximately 90 m above sea level (see plate 7.1). The soil at this site is an intergrade between the Tokomaru silt loam on the terrace and the Halcombe hill soil on the hillslope (see Cowie, 1972 for pedological information). Cowie classifies the Tokomaru silt loam as a weakly leached moderately to strongly gleyed yellow-grey earth from loess, and the Halcombe hill soil as a weakly leached weakly to moderately gleyed yellow-grey earth from sandstone, conglomerate and loess. The paddock in which the study site is located has been ploughed at intervals for many years mixing the upper

Plate 7.1
The Tuapaka site for the soil moisture – pasture condition experiment.

horizons.

The drainage both into and out of this site appears reasonably homogeneous across the site - as shown by the similar moisture contents across the site before any pasture variability was applied (see fig 7.1). The pasture on the site was initially dominated by perennial ryegrass (*Lolium perenne*) with smaller amounts of white clover (*Trifolium repens*), Yorkshire fog (*Holcus lanatus*) and browntop (*Agrostis capillaris*).

b) *Blenheim Site* - This was located at NZMS1 S28 237945 also on a colluvial footslope of about 12-15° slope approximately 50 m above sea level (see plate 7.2). The soil at this site is a complex mixture formed from both loess and gravel deposits which have been reworked by colluviation and in places by human action. Over most of the site there was a hard layer at 0.7-1.0 m depth which proved virtually impossible to dig or auger through when dry. The site contained a band running upslope through the middle of the area which was significantly drier than the rest of the site. This appeared to be due to a lack of organic matter and soil structure at the surface which has resulted in a low moisture holding capacity and provided an inhospitable environment for plant growth. The areas on either side of this band seemed quite similar and provided a more amenable area for plant growth.

The pasture on the site was a mixture of *Phalaris tuberosa*, cocksfoot (*Dactylis glomerata*), and white clover, with smaller amounts of such species as perennial ryegrass, barley grass (*Hordeum murinum*), Wing Thistle, and Docks.

c) *Pasture Treatments* - At both sites the 75 x 24 m area was divided into three 24 x 24 m areas. At the Tuapaka site three treatments were used. These were:

i) mown regularly to 2-3 cm height;

ii) continuously grazed by set stocked cattle usually to 5-10 cm height;

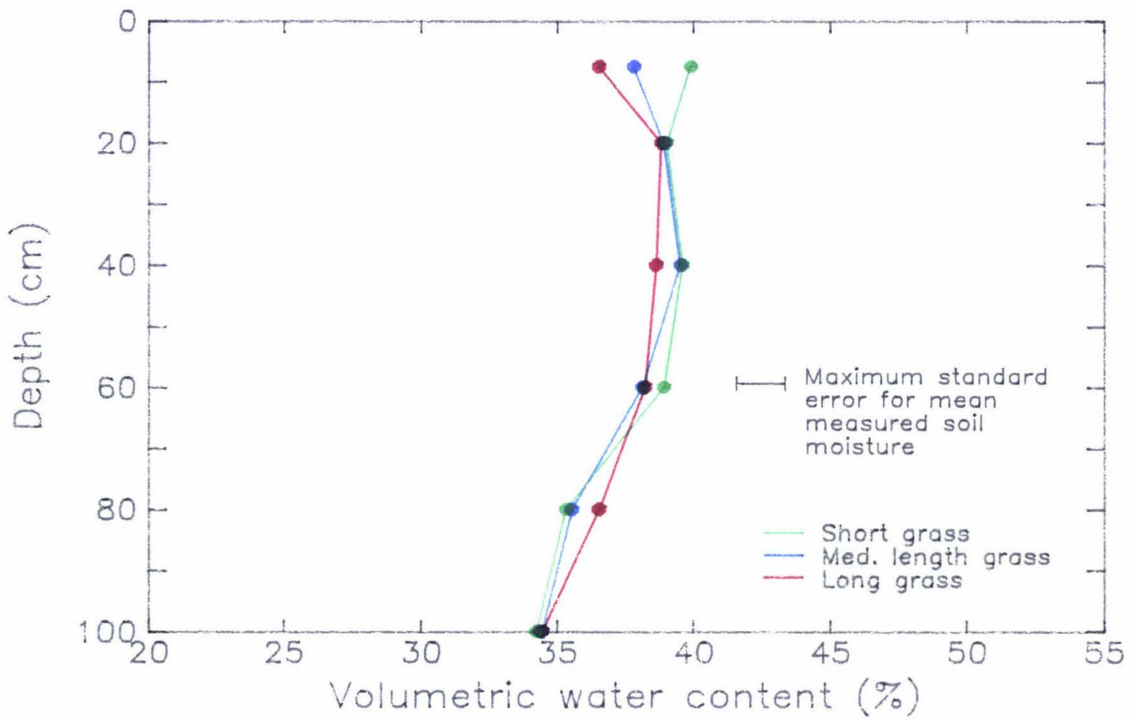


Fig. 7.1
Soil moisture levels at Tuapaka before pasture treatments were in place – November 15 1985.

Plate 7.2
The Wither Hills site for the soil moisture – pasture condition experiment.

iii) ungrazed, uncut rank pasture usually 30-50 cm in height (see plate 7.3).

At the Wither Hills site only two pasture treatments were applied.

These were:

i) mown regularly to 2-3 cm height;

ii) ungrazed, uncut rank pasture usually 30-40 cm in height.

This second treatment was replicated on the initially drier, more sparsely vegetated zone. (see plate 7.4).

7ii Soil Moisture Measurements

In each of the six pasture treatments 5 access tubes for the neutron depth probe were installed running upslope and spaced 4 m apart (see fig 7.2). The area surrounding these rows of access tubes was used for the removal of soil samples for gravimetric water contents, and was intended for viewing of the cracks that subsequently did not develop.

The neutron probe used was a Campbell Pacific Nuclear model 501 Hydroprobe combination density/moisture gauge. The access tubes, which were 2 inch (50.8 mm) aluminium irrigation piping, were installed to allow moisture readings to 100 cm at Tuapaka. At Wither Hills moisture readings in most tubes were obtained to 80 cm depth though some were only obtained to 60 cm. Tubes at Wither Hills could not be installed to greater depth because of the presence of the hard layer which could not be augered through when the tubes were installed in October 1985.

At Tuapaka the pasture was mown every 7-10 days over the summer and autumn of 1985-86 while soil moisture measurements were taken every 6-16 days depending on rainfall and soil moisture conditions. Soil moisture

Plate 7.3 The three pasture treatments at Tuapaka on April 20 1986:

1 Short - regularly mown,

2 Medium length - grazed by cattle,

3 Long - ungrazed and uncut.

i The pasture treatments at Wither Hills, Blenheim on February 12 1986:

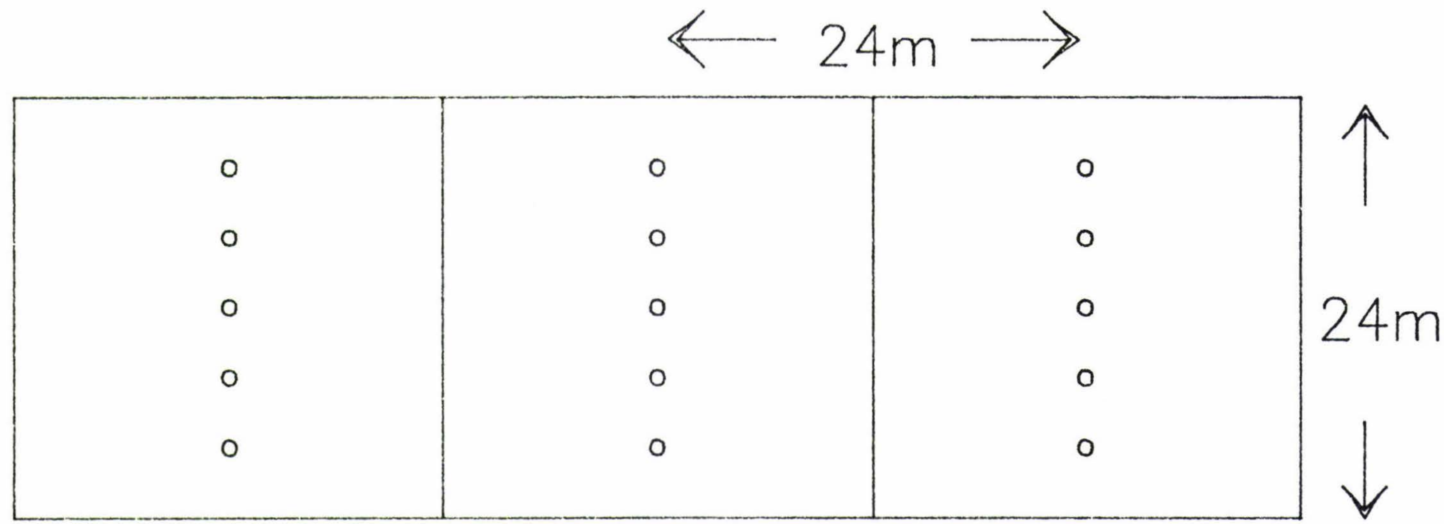
1 Short – regularly mown,

2 Long – initially drier zone,

3 Long – initially moister zone.

ii The difference between long and short pasture treatments at Wither Hills on January 15 1986.

Plate 7.4



o Probe tubes spaced 4m apart

Fig. 7.2 The layout of three groups of five neutron probe access tubes at each site.

levels were measured twice before any treatment was in place on October 22 and November 15 1985 and in saturated winter conditions on September 15 1986. These readings acted as controls to ensure that any difference which occurred between treatments was not simply due to site inhomogeneities between those areas where different treatments applied. These readings show the initial homogeneity over this site of soil moisture levels (see figs 7.1 and 7.3).

At Wither Hills the pasture was mown every 28 days over the summer of 1985-86 - the grass grew very little in this period because of dry soil conditions. Soil moisture measurements were also made every 28 days from October 21 to March 15. The initial readings in October were made before any treatment had taken place (see fig 7.4), while readings were also made in August 1986 when the soil was in a saturated condition (see fig 7.5). These readings shown on fig 7.4 and 7.5 indicate the similarity between rows 1 and 3 and the differences between rows 1 and 3, and row 2.

a) *Gravimetric Moisture Content Measurements* - Samples for gravimetric analysis were taken from both sites usually on the same days as readings were taken with the neutron depth probe. Ten samples of 30-40 grams in weight were collected from each pasture treatment at 5-10 cm depth, stored in sealed tins, transported to the laboratory, weighed, dried, and weighed again. From these measurements the gravimetric water contents were calculated as follows:

$$\frac{\text{Moist Weight} - \text{Dry Weight}}{\text{Dry Weight}} \times \frac{100}{1}$$

The ten samples were averaged to give the gravimetric water content at 5-10 cm depth for that treatment. These results can be converted to volumetric water contents by multiplying the gravimetric water content by the dry bulk density of the soils at 5-10 cm depth. The dry bulk density was calculated by removing undisturbed soil samples of a known volume and ascertaining the mass of dry soil

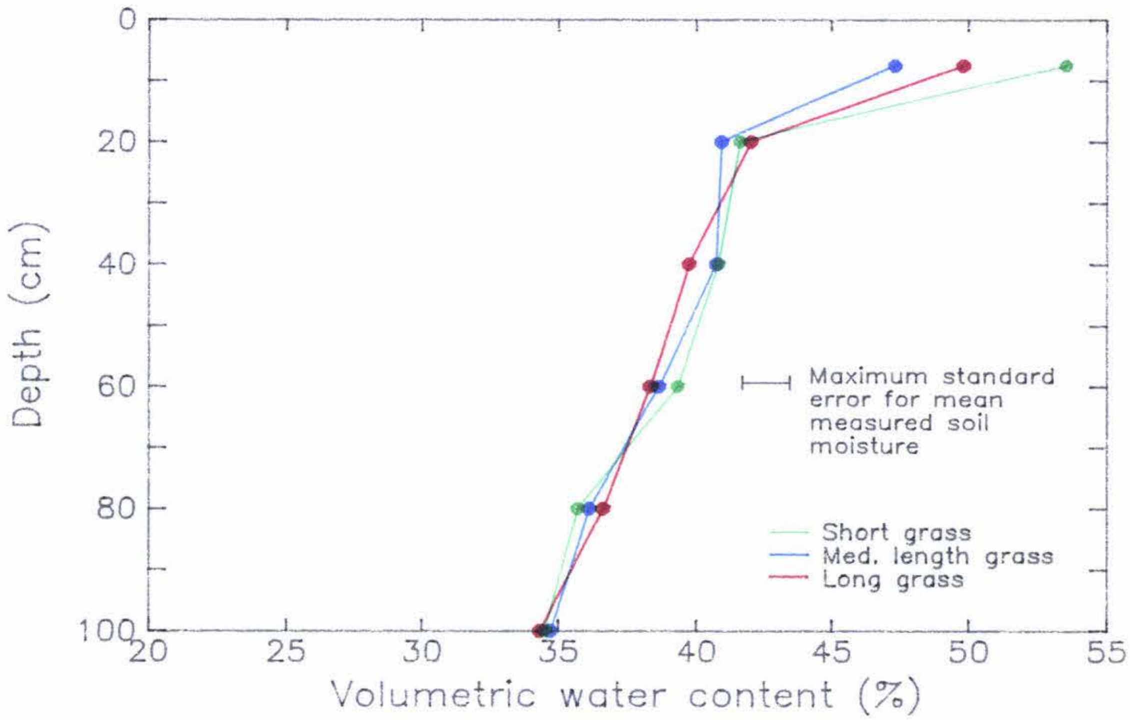


Fig. 7.3
Soil moisture levels at Tuapaka in saturated conditions after treatments were removed – September 15 1986.

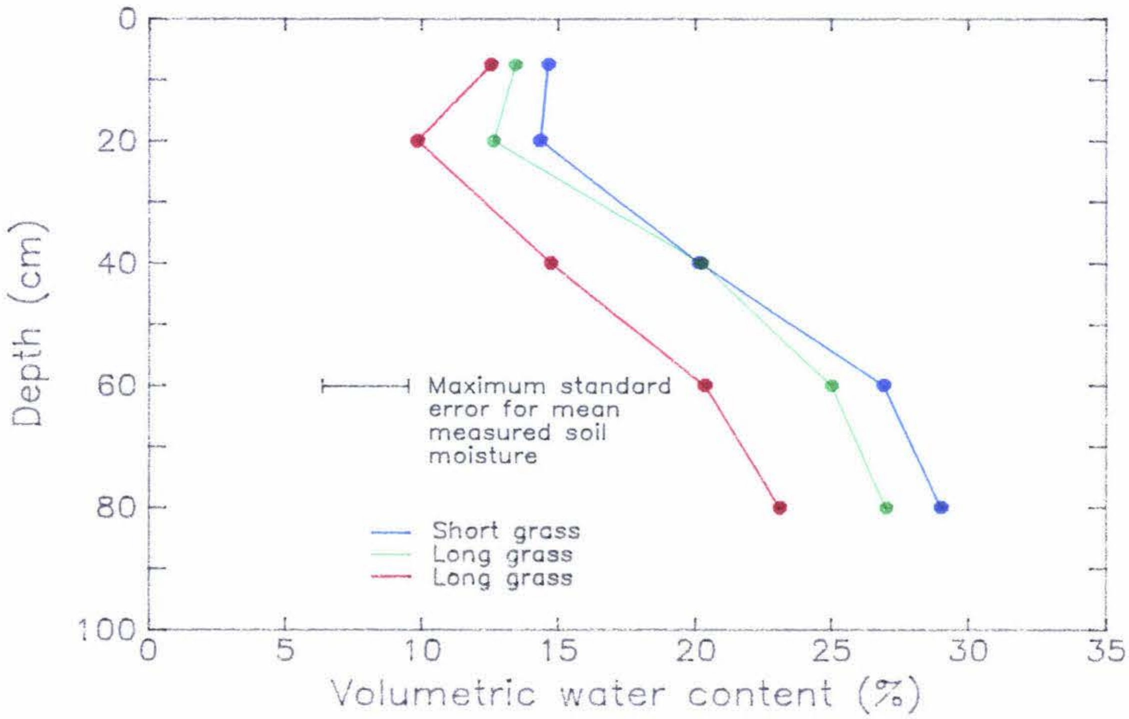


Fig. 7.4
Soil moisture levels at Wither Hills before treatments were in place – October 21 1985.

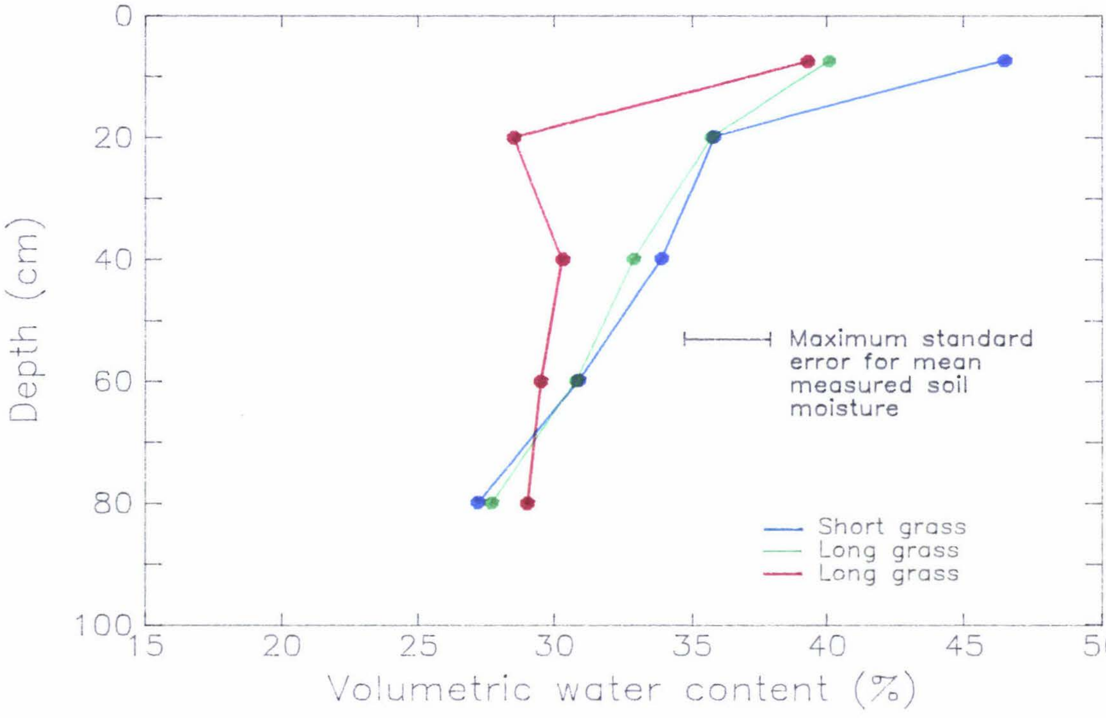


Fig. 7.5
Soil moisture levels at Wither Hills in saturated conditions after treatments were removed – August 28 1986.

present. At Tuapaka the dry bulk density at 5-10 cm depth was approximately 1.3 Mg m^{-3}. At Wither Hills the dry bulk density was approximately 1.5 Mg m^{-3}.

At Tuapaka the samples for gravimetric analysis were collected using a 1 inch (2.5 cm) diameter tube type corer. This corer could not be used at Wither Hills due to the hardness of the ground in summer. A 2 cm diameter screw auger was used to remove soil at Wither Hills. Soil from 0-5 cm depth was not used for measuring water contents because of the large volume of roots and other organic matter which would give inaccurate measurements of the soils moisture content. The 0-5 cm material was returned to the augered hole. The 10 samples for each pasture treatment were collected up to 8 m either left or right of the row of access tubes (5 groups of 2 samples). The location of each sample was preselected randomly and was the same for each pasture treatment.

b) *Volumetric Water Content Measurements* - These measurements were gathered with the neutron depth probe. The probe's Am-241/Be source emits fast high energy neutrons which are slowed largely by collisions with hydrogen nuclei in the soil (primarily contained in water). The slower neutrons are scattered after these collisions and some of these scattered slow neutrons are sensed by a detector attached to the probe. The level of slow neutrons sensed is proportional to the hydrogen content and hence water content of the soil (Luckman *et al*, 1983). Three measurements each of 30 seconds duration were taken at 20 cm intervals downwards from 20 cm depth. The average of these three measurements was related to the soils volumetric water content by use of an equation particular to the probe used.

There are two calibration problems with the neutron depth probe - one is related to calibration of the probe itself while the other is related to the particular soil in the field. To calibrate the probe itself, it is usual practice to make two sets of standard measurements one before and one after field readings with the probe withdrawn into its housing, seated on the carrying box. To calibrate the probe for a particular soil it is necessary to gather samples while the access tubes are being installed and then find the relationship between the gravimetric water content of these samples and the volumetric water content and wet bulk density measured using the probe.

This second calibration was not completed in this study, initially because of ignorance, though it has in the end proven only a slight omission. At Tuapaka the soil on the site is reasonably uniform, and as this study is concerned with changes in moisture content onsite rather than comparisons with other sites, precision was the important parameter rather than accuracy. Precision of the readings is a function of the probe and its calibration and this was completed. At Wither Hills samples could not be gathered during installation of the access tubes because of the manner in which the soil 'powdered' as the auger drilled the hole for the tube. At this site the second calibration would have been useful because of the soils heterogeneity, however as is shown later in this section the gathering of this information at Wither Hills would have been of no help in making the results from there more useful anyway.

c) *Errors*

Gravimetric Water Contents

Provided that the New Zealand Standard (4402 Part 1 1980) is followed gravimetric water contents of individual samples are accurate to within 1% ($\pm$ 0.5%). The results in this study conform to the New Zealand standard. Where a number of samples are gathered from 1 site there is variability associated with the heterogeneity of the sampling site. At Tuapaka the standard deviation of the samples from each treatment was usually in the order of 2-3% of gravimetric water content.

Volumetric Water Contents
As stated above the accuracy of neutron depth probe measurement of volumetric water contents is not great. In fact according to Luckman *et al* (1983) even in a properly calibrated study accuracy is seldom better than ± 3%. However the precision of probe readings is subject to an error of less than ± 0.5% and as stated earlier it is precision that is the important factor as this study is concerned with any changes that may develop from an initially homogeneous situation.

The precision of the probe readings made at Tuapaka can be seen by considering table 7.1. This shows the consistency of readings at 100 cm depth under the short pasture where no change in water content was apparent over the summer of 1985-86 (except possibly on April 20).

7iii Results from Tuapaka

The soil moisture information gathered at Tuapaka (see figures 7.6-7.11) show conclusively that in this type of soil at these moisture conditions and under this pasture type, transpiration was a greater determinant of water loss over the summer than evaporation. From the initially homogeneous situation under all three treatments the longer grass dried the soil out more, at all depths 20 cm or greater, than the medium length grass which in turn dried out the soil more than the short grass. However at 5-10 cm depth water contents were always similar under the three treatments, indicating a balance at this depth between water lost by transpiration and that lost by evaporation. This indicates that greater water loss due to greater surface evaporation under short grass was probably restricted to the surface 5 cm or so.

a) *Statistical Analysis*

For the purposes of analysing the results in this study not all the readings will be considered. The readings

DATE	Nov 15	Dec 5	Dec 19	Jan 8	Jan 21	Feb 4
Volumetric Water Content	34.2	34.2	34.3	34.1	34.3	34.4

DATE	Mar 10	Mar 18	Mar 24	Apr 11	Apr 20	Sept 15
Volumetric Water Content	34.4	34.2	34.6	34.2	33.9	34.5

Table 7.1: Volumetric Water Content at 100 cm depth under short pasture (1985-86).

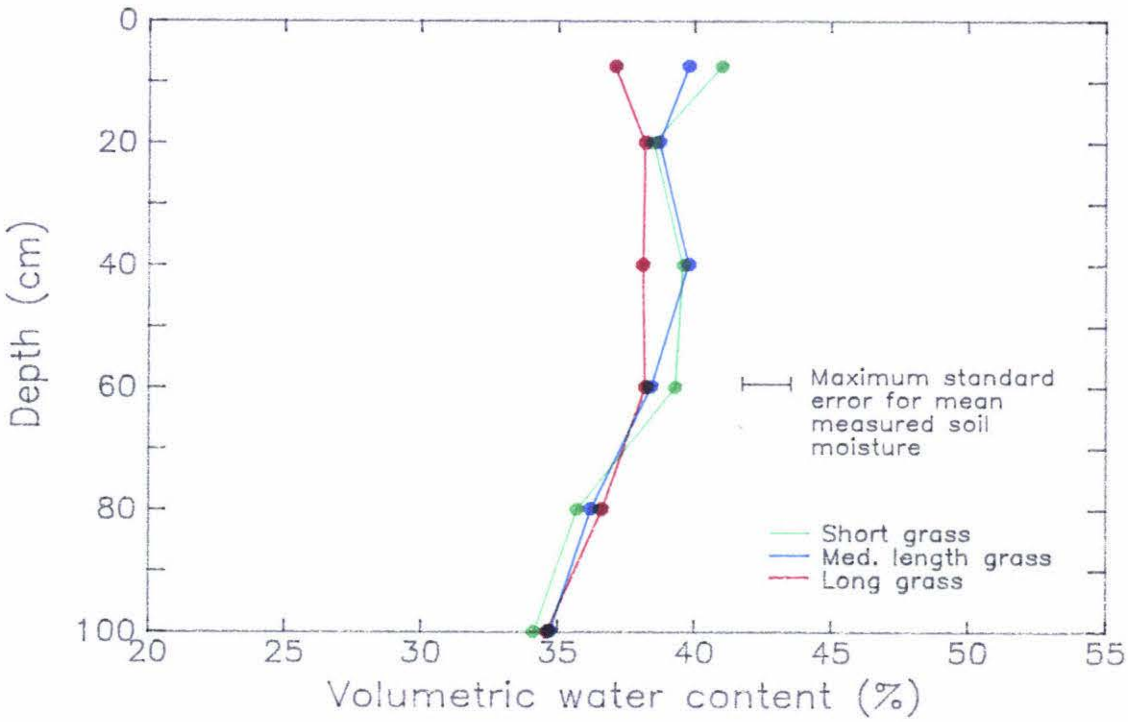


Fig. 7.6
Soil moisture levels at
Tuapaka - January 8 1986.

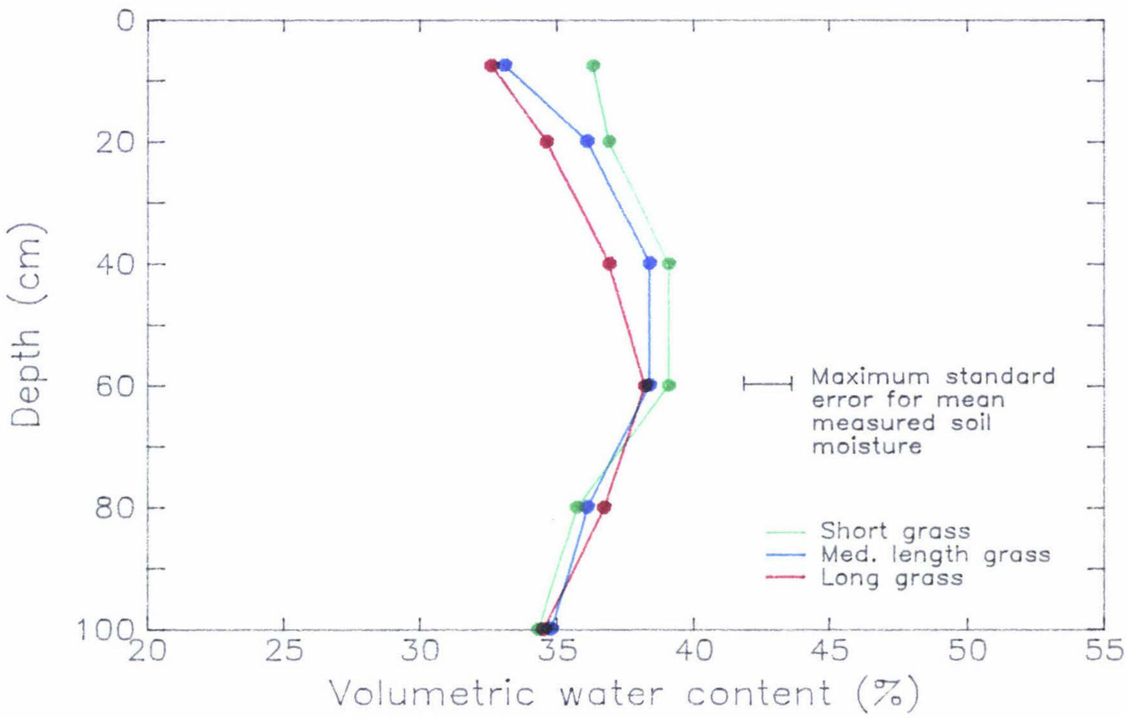


Fig. 7.7
Soil moisture levels at
Tuapaka – January 21 1986.

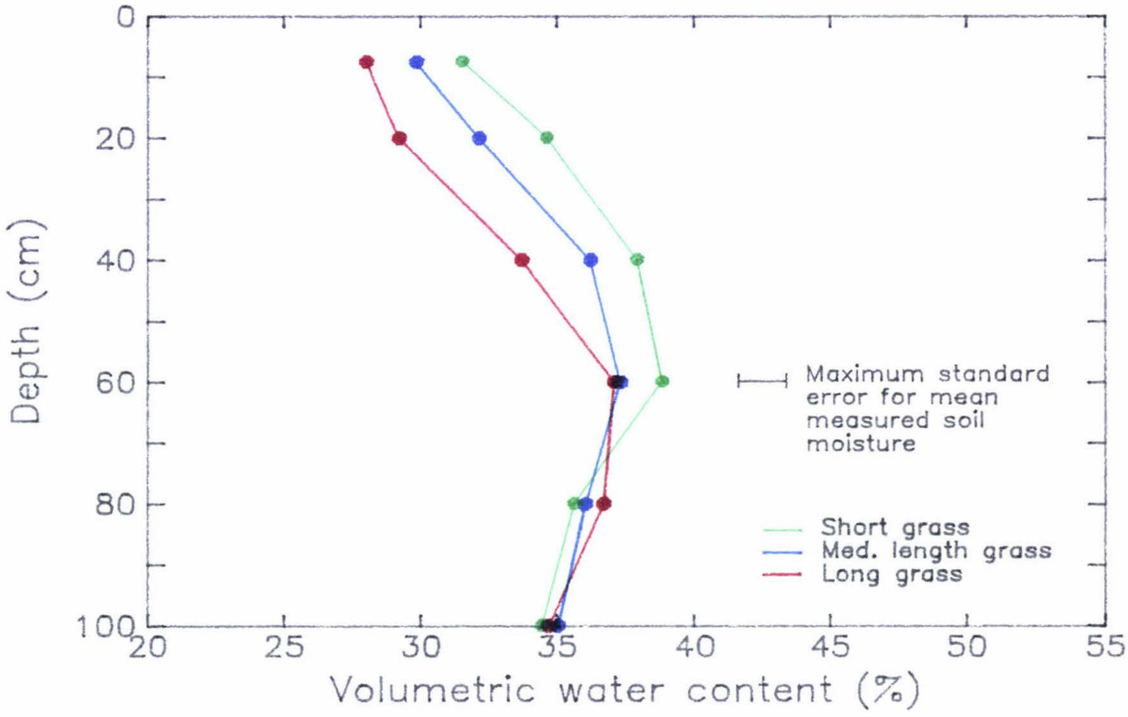


Fig. 7.8
Soil moisture levels at Tuapaka — February 4 1986.

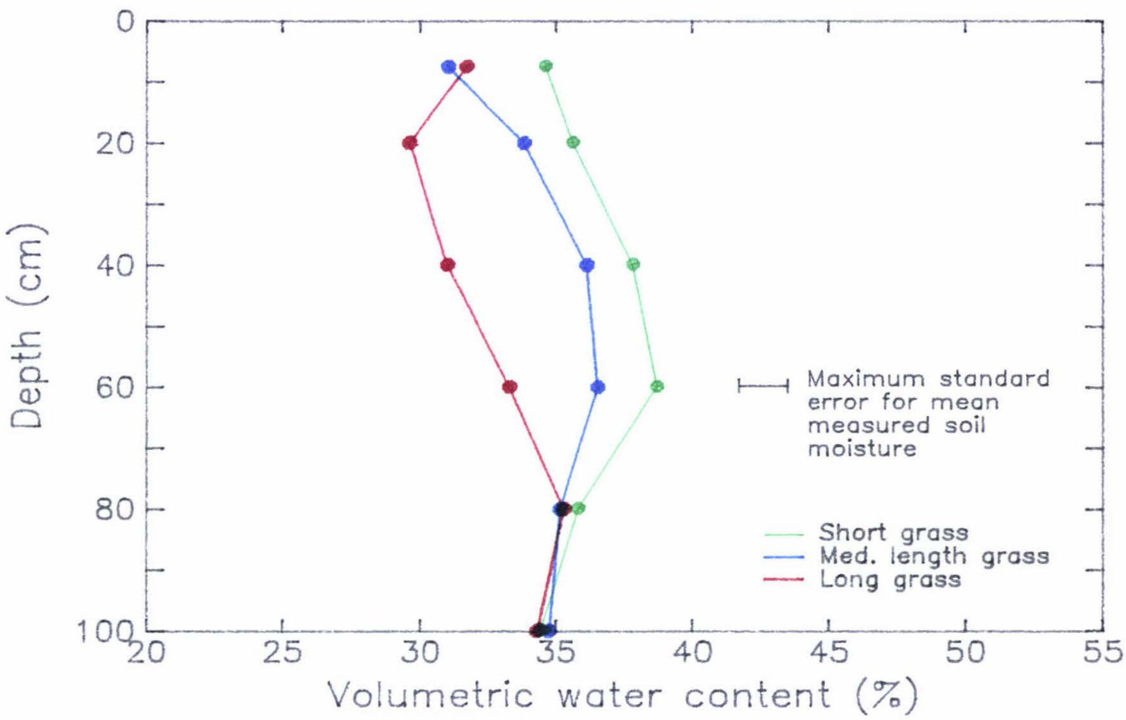


Fig. 7.9
Soil moisture levels at Tuapaka – March 10 1986.

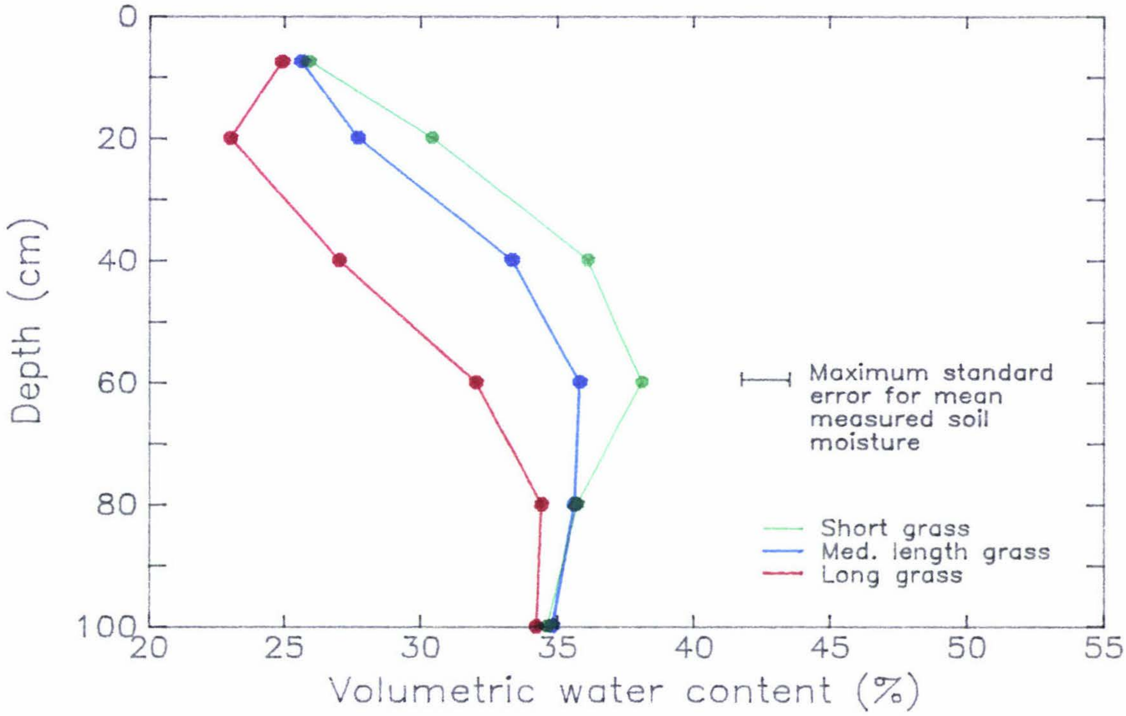


Fig. 7.10
Soil moisture levels
at Tuapaka –
March 24 1986.

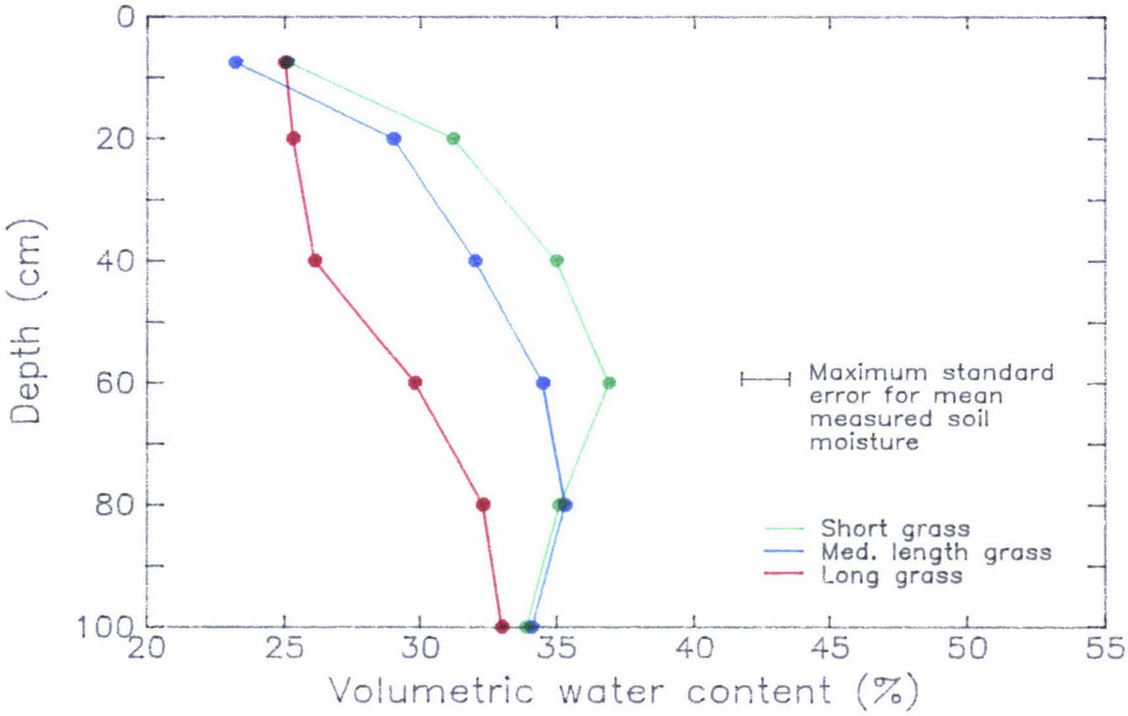


Fig. 7.11
Soil moisture levels at
Tuapaka – April 20 1986.

taken on November 15 1985 before any pasture treatments were in place will be used as a standard to which the progressive drying over the summer will be related. The moisture measurements made on: January 8 and 21, February 4, March 10 and 24, and April 20, all 1986 (shown in figures 7.6-7.11) will be used for analysis as they show soil moisture conditions becoming progressively dryer. These dates were usually separated by periods during which temporary increases in soil moisture levels occurred. As the three treatments used were on an originally reasonably homogenous area, the treatments can be analysed by considering the treatments as combinations of three pairs. These three pairs are short grass and medium length grass, medium-length grass and long grass, short grass and long grass. The differences in mean water contents and the different changes in water contents of these pairs can be tested for their significance by using 'Students' t-test. This is a test of the probability of the null hypothesis being true. In this case the null hypothesis is that there were no differences in moisture levels between the treatments. When the probability of the null hypothesis being true is less than 5% ($p < 0.05$) the result is said to be significant. When $p < 0.01$ the result is said to be highly significant and when $p < 0.001$ the result is said to be very highly significant. The results of a comparison of the water contents of pairs of treatments is contained on table 7.2. This table shows that the differential rates of water loss shown in figures 7.6-7.11 were unlikely to be due to chance. Because of this, the conclusion; that long grass dried out the soil at depths 20 cm or greater more than medium-length grass, which in turn dried out the soil more than short grass; seems justified.

Nevertheless there are a few question marks. There were differences unlikely to be due to chance at 5-10 cm depth on November 15 1985 and again on September 12, 1986 when no treatment differences were in place. The most plausible explanation for these differences is that there were

DATES (1985-86)	Nov 15			Jan 8			Jan 21			Feb 4			Mar 10			Mar 24			Apr 20			Sept 12		
TREATMENT PAIRS	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Depth (cm)																								
5-10	*		**										*								**	***		*
20										*	*	**		*	***		*	***			*			
40					**	*		**	**	**	**	***		**	***		**	***		*	***			
60										*			*	*	***	*	**	***	*	***	***			
80																				*	**			
100																								

KEY

Treatment Pairs

1 Short v Medium-length Grass
2 Medium-length v Long Grass
3 Short v Long Grass

* $p < 0.05$ - significant
** $p < 0.01$ - highly significant
*** $p < 0.001$ - very highly significant

N.B. no treatments were in place on Nov 15 1985 and Sept 12 1986

Table 7.2: Significant t values calculated from comparison of treatment pairs.

slightly different drainage patterns between the area of the short grass treatment and the other two areas. On both dates it was this area which was slightly wetter. However this difference between this area and the others seems unlikely to have been the reason for the higher levels of soil moisture under the short grass treatment over the summer of 1985-86. This conclusion is reached because the medium-length grass exhibited similar water loss behaviour to the short grass area in that both areas used considerably less water than the long grass area. Yet the area of the medium-length grass had shown no similar difference in soil moisture levels when no treatments were in place on November 15 1985 and September 12 1986. This indicates that the differences which did develop were primarily because of the treatments not any inherent heterogeneity between the areas.

The differences between treatments developed gradually over the summer of 1985-86 (see figures 7.6-7.11), occurring first between short and long grass treatments on medium-length and long treatments at 20 cm depth. The differences then became apparent at greater depth and also developed between the short and medium-length grass treatments as the summer progressed.

b) *Water Retentivity*

When comparing soil moisture information between different soils the most useful way of expressing this information is in terms of the level of soil moisture tension (soil water potential or suction). This is a measure of how tightly water is held and is expressed in terms of negative pressure (see Chapter 4c). To enable comparison of the results gained at Tuapaka with other soils, samples of soil from the site were tested for their water retentivity.

In this test positive pressure is applied to an undisturbed soil sample sitting on a porous plate within a pressure cell. This positive pressure forces water out of the sample through the porous plate. When the sample has reached equilibrium it is removed and its gravimetric water content determined. This procedure is repeated at a number of different pressures and the relationship between moisture suction and moisture content is gained. This is not a particularly accurate procedure as this relationship is normally different depending on whether the soil is drying or being wetted, and although undisturbed samples are used, some disruption to the structure of the sample is almost inevitable.

Two undisturbed 97.5 mm diameter cores were obtained from the Tuapaka site on June 4 1986 from opposite ends of the study site. Slices were taken from both of these cores at 20, 40, 60, 80 and 100 cm depth below the surface, and water retentivity measured on these slices at 0.1, 0.3, 0.5, 1.0, 3.0 and 15 bars pressure. The results of these tests are shown on figure 7.12. Despite the inaccuracies with this test the only anomalous values appear to be those at 0.1 and 3.0 bars pressure at 40 cm depth. Both the moisture contents determined at these pressures at this depth appear 3-4% too low. These anomalies can be seen when figure 7.12a is overlain on figure 7.12. If these values were correct they indicate that soil at 40 cm under the long pasture did not get as dry as at 60 cm which would be unusual, and that soil at 40 cm under all 3 treatments became wetter than the soil at 20 cm.

Considering figure 7.12 and 7.12a further, the extent of drying due to the different pasture treatments can be seen. The long pasture dried the soil out at 20 cm depth to approximately 15 bars which is the level commonly described as the wilting point. In contrast the medium length and short pasture treatments dried the soil at 20 cm depth to less than 3 and 1 bars respectively. These differences were reflected in the condition of the pasture at the end of March 1986 when the long pasture was showing signs of moisture stress.

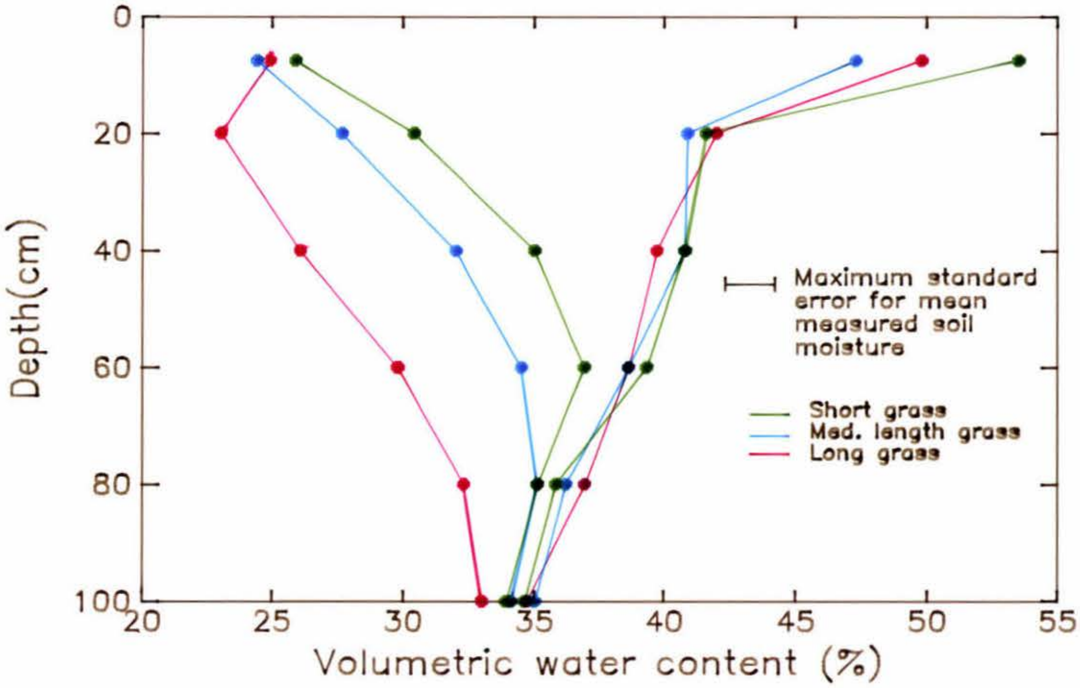


Fig. 7.12a
The dryest and wettest soil moisture readings at Tuapaka.

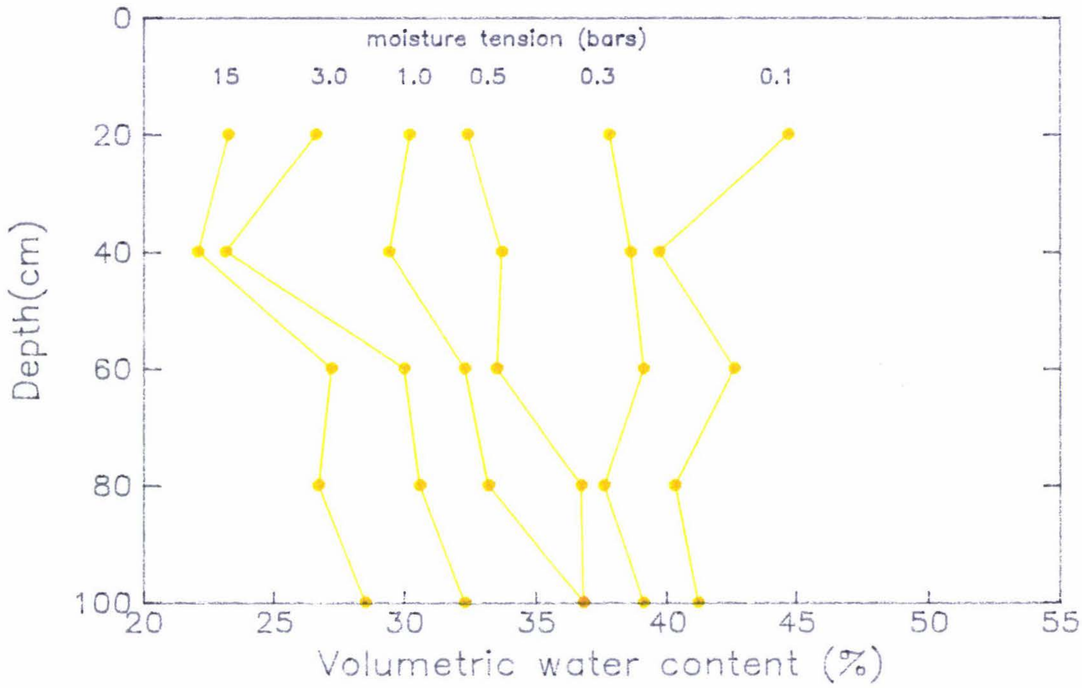


Fig. 7.12
Water retentivity for the Tuapaka soil.

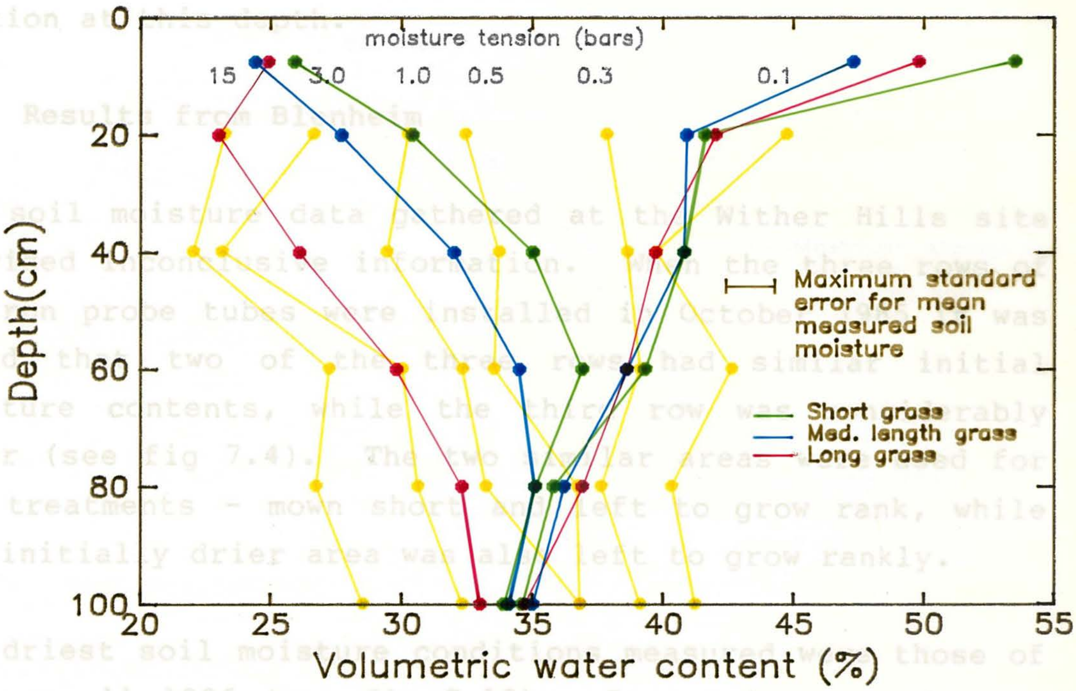


Fig. 7.12
Water retentivity for the Tuapaka soil.

Fig. 7.12a
The dryest and wettest soil moisture readings at Tuapaka.

If the water retention data are extrapolated upwards to 5-10 cm depth it would seem that all three treatments at some stage dried the soil out to between 3 and 15 bars of suction at this depth.

7iv Results from Blenheim

The soil moisture data gathered at the Wither Hills site provided inconclusive information. When the three rows of neutron probe tubes were installed in October 1985 it was found that two of the three rows had similar initial moisture contents, while the third row was considerably drier (see fig 7.4). The two similar areas were used for two treatments - mown short and left to grow rank, while the initially drier area was also left to grow rankly.

The driest soil moisture conditions measured were those of February 11 1986 (see fig 7.13). It can be seen that no significant differences in water use between the treatments had occurred in the period October-February. This lack of differentiation between treatments could have resulted from the already dry soil conditions in October 1985 when the treatments were put in place. Subsequent desiccation was probably controlled by the vapour conductivity of the soil rather than by the evapotranspirative demand. Such conductivity depends on the soil rather than the treatments used, hence little differentiation between treatments could be expected. If this was the case the important consequence would be that defoliation of pasture in summer on already dry soils at Wither Hills has little effect on soil moisture levels.

7v Rates of Water Use at Tuapaka by the Three Pasture Treatments

It is possible to estimate the rate of evapotranspiration by the three pasture treatments by construction of a simple moisture balance. Changes in soil moisture levels between

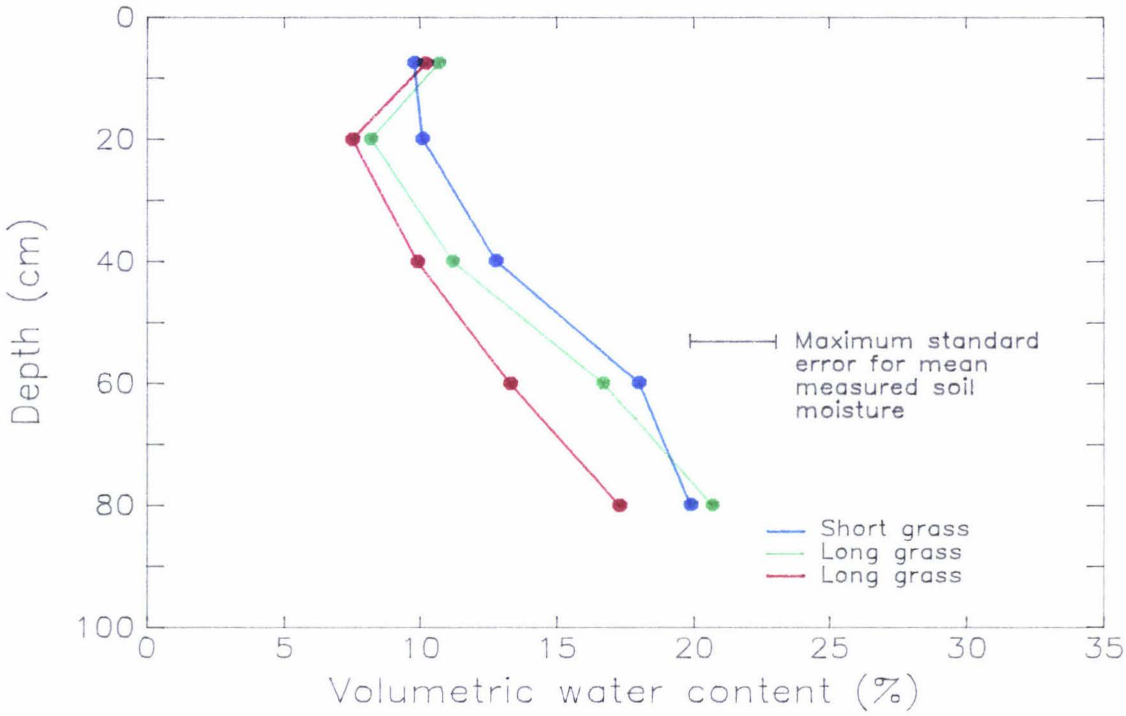


Fig. 7.13
The dryest soil moisture levels measured at Wither Hills — February 11 1986.

two dates can be considered a result of:

Rainfall - Evapotranspiration - Runoff

The possible loss of water through drainage is assumed to be negligible during the summer period at Tuapaka. A reasonable estimate of rainfall is gained by using data from a recording raingauge located at Tuapaka some 1100 m south of the study site at NZMS 1 N149 220364 maintained by the Department of Geography of Massey University. Unfortunately it was difficult to separate the two modes of water loss - runoff and evapotranspiration. A quick scan of the rainfall data contained on table 7.3 when considered in conjunction with the measured soil moisture levels suggests that runoff was possible on; November 20 and 24; December 2, 23, 26 and 29; January 3 and 12; February 16; and April 3.

Potential evapotranspiration was calculated by Penman's method (Doorenbos and Pruitt, 1977) using meteorological data gathered at Grasslands Division, DSIR, some 12 km southwest of Tuapaka. Evaporation pan data was also available from the DSIR site.

Table 7.4 contains rates of rainfall, water use, water loss, and potential evapotranspiration for the periods between dates when soil moisture levels were measured. If any substantial runoff had occurred off a soil during a period in which the soil was in a reasonably wet condition, it is expected that water use would be greater than potential evapotranspiration. In this case water use would be the sum of evapotranspiration which had been occurring at the potential rate because of the wet soil plus any runoff.

These conditions may apply to the two periods November 15 -December 5, and December 19 - January 8. In both cases water use is greater than Penman potential evapotranspiration. It is possible to calculate potential levels of runoff from these results as follows: (Water use

Table 7.3 Rainfall at Tuapaka 1985-86 (mm)

	November	December	January	February	March	April
1	9.0	2.8				1.5
2	2.8	21.0		3.0		0.1
3	7.0	13.1	35.6		8.5	29.8
4	10.0				3.5	
5	0.4	1.4				
6	23.1				0.3	12.3
7	3.5	9.2			1.9	
8			1.9			
9			10.3			
10						
11						
12	2.6		30.6	0.9		
13			5.5		9.8	
14			0.3			
15		0.6	6.0	7.8	0.8	
16		0.1		74.4	4.3	
17				0.2		
18				4.5		
19						
20	26.6			0.5		
21	2.4	3.0	0.3			
22	0.4	3.0	3.1			
23	1.9	34.4			0.2	
24	26.4		5.7	2.5	0.3	
25	2.5	1.0	19.2	2.9	0.2	
26	1.1	27.0	5.4	4.2		
27		0.7				
28					0.5	
29		30.7	3.2		1.7	
30						
31					1.6	
TOTAL	119.7	148.0	127.1	100.9	33.3	

Table 7.4: Rates of Rainfall, Water Use, Water Loss and Potential Evapotranspiration.

DATES (1985-86)	Rainfall at Tuapaka (mm/day)	Water Use at Tuapaka (mm/day)			Water loss at Tuapaka (mm/day)			Potential Evapo- transpiration (mm/day)	
		Short Grass	Med Grass	Long Grass	Short Grass	Med Grass	Long Grass	Penman	Evaporation Pan
Nov 15 - Dec 5	5.0	4.7	4.6	4.5	-0.3	-0.4	-0.5	4.0	4.1
Dec 5 - Dec 19	0.7	3.6	4.1	4.2	2.9	3.4	3.5	5.2	5.8
Dec 19 - Jan 8	6.9	5.0	4.7	5.0	-1.9	-2.2	-1.9	4.6	4.8
Jan 8 - Jan 21	4.1	4.8	5.2	5.2	0.7	1.1	1.1	5.1	5.5
Jan 21 - Feb 4	2.6	3.5	3.8	4.2	0.9	1.2	1.6	4.5	4.7
Feb 4 - Mar 10	3.3	3.1	3.3	3.6	-0.2	0.0	0.3	4.1	4.4
Mar 10 - Mar 18	1.9	3.5	3.3	4.0	1.6	1.4	2.1	4.2	4.6
Mar 18 - Mar 24	0.1	1.9	2.1	2.7	1.8	2.0	2.6	3.7	3.7
Mar 24 - Apr 11	2.7	1.8	1.9	2.0	-0.9	-0.8	-0.7	3.0	3.1
Apr 11 - Apr 20	0.3	1.9	1.9	2.5	1.6	1.6	2.2	2.2	2.2
Average Rates (Nov 15-Apr 20)	3.3	3.5	3.6	3.9	0.2	0.3	0.6	4.1	4.4

- Penman values) x the number of days. This has been done for the two periods mentioned above (see table 7.5). Runoff almost certainly also occurred on February 16 1986, although the overall rate of water use for the period February 4 - March 10 was less than the rate of potential evapotranspiration. The rain event of February 16 had been preceded by 12 days with only 0.9 mm of rain. Soil conditions were very dry and it is almost certain that actual evapotranspiration had declined well below the potential rate. This drop in rate of water use seems to have compensated for the runoff which would have occurred on February 16 so that the the overall rate of water use for the period was still less than the rate of Penman potential evapotranspiration.

Limited soil moisture data was gathered on February 17 1986. From this data it was not only possible to provide a reasonable guide to soil moisture conditions after the rain event, but also to provide a reasonable estimate of soil moisture conditions immediately before it. The soil at 60 cm depth was still dry after the rain event. This dryness could be used as a guide to earlier conditions. Additionally the February 4 soil moisture levels could be extrapolated to February 15 on the basis of the rate of evapotranspiration which had held during the earlier dry period of December 5-19. When expected February 15 soil moisture levels were subtracted from measured and assumed February 17 values the difference was about a 50-60 mm increase in soil moisture levels between the two dates. Since 82.2 mm of rain fell on February 15 and 16, the discrepancy of about 20-30 mm can be accounted for by attributing the loss to runoff.

The data on table 7.4 indicate that a reduction in the rate of evapotranspiration occurs during dry periods. Between December 5 and 19 only 9.9 mm of rain fell, with most of this on December 7. Over this period water use varied between 69-81% of the Penman estimate for the three

November 15 December 5 1985		December 19 1985 - January 8 1986	
Short Grass	14 mm	Short Grass	8 mm
Medium Grass	12 mm	Medium Grass	2 mm
Long Grass	10 mm	Long Grass	8 mm

Table 7.5: Calculated Potential Runoff Values at Tuapaka.

treatments. Similarly between March 18 and 24, only 0.5 mm of rain was recorded, and water use was between 51 and 73% of the Penman estimates. It seems that it is the dryness of the surface soil which restricts water movement preceding evapotranspiration rather than the overall soil moisture deficit. This is shown by considering the period April 11-20. Even though there were considerable soil moisture deficits under all three treatments, the surface soil would have been quite wet because of the total of 42 mm of rain which had fallen on April 3 and 6. Over this period water use (including any runoff which may have occurred) was between 86 - 114% of the Penman estimates. Runoff was unlikely in this period because of the dry soil conditions and the not particularly intense nature of the rainfall.

As shown on table 7.4 there was relatively little difference between the rates of water use by the three treatments. However in terms of the rate of water loss the relative differences are much greater though the absolute differences were still the same. Water loss at these rates had resulted in deficits for the period November 15 1985 to April 20 1986 of:

Short Grass - 38 mm,
Medium-length Grass - 52 mm,
Long Grass - 90 mm.

These were deficits for these areas from the winter saturation conditions recorded on September 15 1986 of:

Short Grass - 61 mm,
Medium-length Grass - 70 mm,
Long Grass - 112 mm.

The question which arises from these results is what the situation would be in a drier summer, say with rainfall averaging 2 mm/day instead of 3.3. If water use stayed at levels of 3.5, 3.6 and 3.9 mm/day the percentage differences in water loss would not be as great. However as was shown above the rate of water use in dry periods declines, such that water use would be less than the 3.5 -

3.9 mm/day of 1985-86, although water loss would still be greater than the 0.2 - 0.6 mm/day of 1985/86.

There were two dry periods of the 1985-86 summer that may provide useful comparison with an overall dry season. Between December 5 and 19 the rates of water loss for the three treatments were:

Short Grass - 2.7 mm/day,
Medium-length Grass - 3.4 mm/day,
Long Grass - 3.5 mm/day.

This period was not long after the grass treatments were emplaced, and little difference in foliage between the medium-length and long grass treatments had developed. The other dry period was from March 18-24. The rates of water loss for this period were:

Short Grass - 1.8 mm/day,
Medium-length Grass - 2.0 mm/day,
Long Grass - 2.6 mm/day.

This period was in the driest part of the summer and at this stage there was little difference between the foliage of the short and medium-length treatments.

On the basis of the admittedly limited information from these two drier periods it does seem as though there may be greater absolute difference between the treatments water usage in dry periods than in wetter periods. However if the results from the 1985-86 summer at Wither Hills are used as a guide it does seem that in very dry conditions, which were not reached at Tuapaka, the rate of water loss is controlled by the soils vapour conductivity rather than the level of foliage.

7vi Explanation of Differences in Rates of Water Use between Pasture Treatments at Tuapaka

The differences between the three treatments can be described and explained by referring to Hillel (1980). He describes three phases of drying (see fig 7.14):

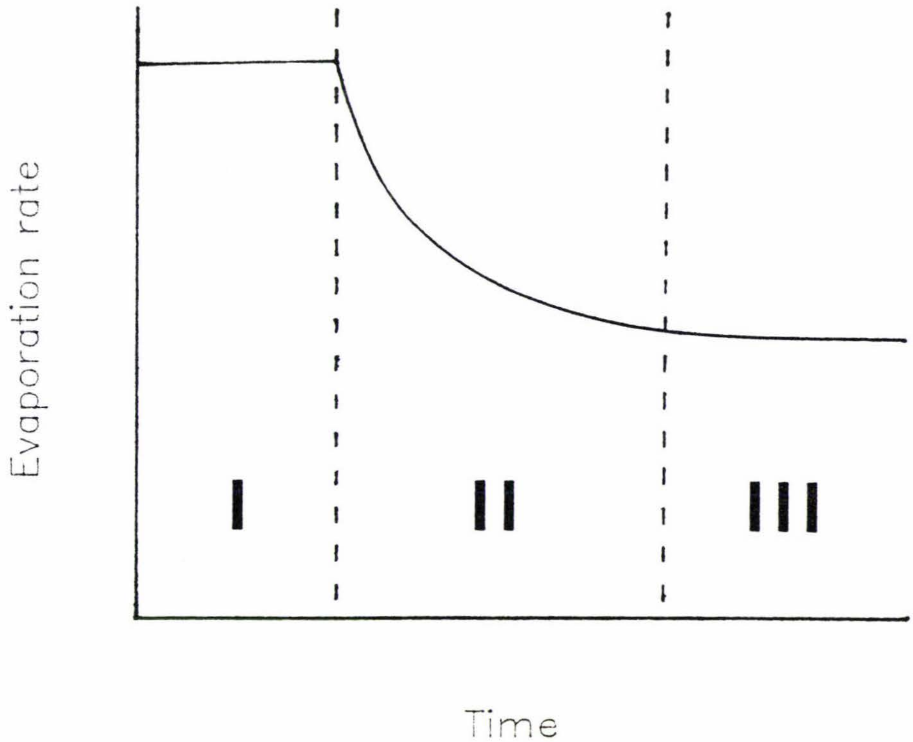


Fig. 7.14 The three phases of soil drying:

I an initial constant-rate phase when the soil is wet enough to supply water at a rate commensurate with the evaporative demand;

II an intermediate falling-rate phase when the evaporation rate is limited by the rate at which the gradually drying soil can deliver moisture to the evaporation zone;

III a residual slow-rate phase when liquid water movement through the soil's surface zone has ceased and any water movement is by the slow process of vapour diffusion;

(after Hillel, 1980b, p120-122).

i) an initial constant rate phase where evaporation is controlled by external meteorological conditions;
ii) an intermediate falling rate phase which is dictated by the rate at which the gradually drying soil profile can deliver moisture toward the surface;
iii) a residual slow rate phase which occurs when the surface zone is so desiccated that liquid movement effectively ceases and water loss only occurs by the slow process of vapour diffusion.

The different soil moisture conditions between treatments were probably due to different length of time being spent losing water in the three phases, particularly the time spent in phase two where the rate of water use is dependent on soil conditions. For example the differences between the rate of water usage by the different treatments could be considered as a result of such differences shown in fig. 7.15. The extension of phase II as grass length increases results in extra drying under longer grass at any stage once phase II drying has commenced. Even when two different treatments are both in phase III drying the longer grass will still always be dryer unless all possibly removeable water has been removed.

The lack of differentiation of treatments at Blenheim can also be explained by reference to fig 7.14. The treatments were probably not imposed until phase III drying had commenced, or late in phase II drying. This restricted the development of any differences as drying depended more on the soil than the different levels of vegetative cover.

7vii Summary and Conclusions

Soil moisture conditions were measured under three different pasture conditons at Tuapaka, and two different conditions at Wither Hills over the 1985-86 summer.

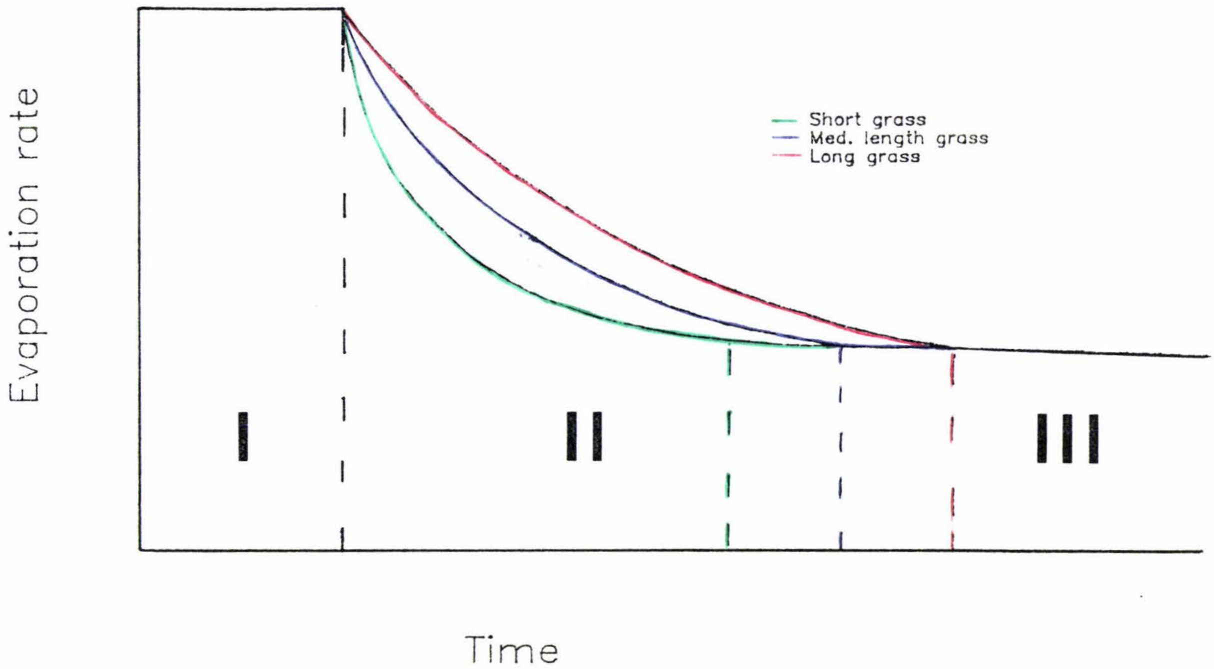


Fig. 7.15 Explanation of differential water use at Tuapaka by reference to three phases of soil drying (Hillel 1980b).

The three grass treatments would have identical rates of phase I drying but would differ in their rate of decline in water use during phase II. With short grass less water is readily available for evaporation, such that water use declines more rapidly than with longer grass. This can explain the similar rates of water use between treatments at Tuapaka during wet periods (drying in phase I) and the decline in water use with decreasing grass length during dry periods (drying in phases' II and III).

The soil at Tuapaka dried out more at all depths, 20 cm to 100 cm, with increasing pasture cover. Soil moisture levels at 5-10 cm were similar under all three treatments. Contrastingly at Wither Hills no significant differentiation of soil moisture levels under the different treatments occurred. However both these sets of results are consistent with a three phase description of soil drying as described by Hillel (1980).

If the results from Tuapaka are applied to the first stage of drying in spring at Wither Hills they would indicate longer pasture would dry the soil out more than shorter pasture. This difference may be maintained throughout the summer. However for most of the drying period water loss would be controlled by the soil rather than vegetation, which would result in surface soil moisture levels being similar under any pasture treatment. The difference in soil moisture levels would be expressed as different moisture levels at depth in the soil such as occurred at Tuapaka over the summer of 1985-86.

If the influence of soil moisture only, on soil shrinkage and crack development is considered, it does seem that conditions are more conducive for crack development under longer pasture, particularly for cracks to develop at depth in the soil. This is contrary to what has been accepted in the past. Either cracks are influenced by pasture in different ways, or good pasture condition has other positive effects which outweigh such negative effects, or else good pasture has been no aid in reducing tunnel development. Some of the other possible influences of pasture on crack and tunnel development have already been outlined in chapters 3 and 5. The influence of pasture condition on root condition is considered in chapter 9.

CHAPTER 8 OBSERVATIONS AND MEASUREMENT OF SOIL SHRINKAGE AND CRACKING

Surface cracks were observed on September 26 1985 in a soil covered with a sparsely vegetated four year old lucerne pasture on the farm owned by Waitaki NZR. These observations suggested that soil cracking on the Wither Hills occurred where vegetative cover was sparse. The cracks observed on September 26 1985 occurred in the bare ground between the discretely spaced pasture species (see plate 8.1). No cracks were observed intersecting the zones of soil occupied by plant roots. These observations confirm with the conclusion reached in 3ib from a review of the literature. When the study site for measuring soil moisture levels was set up in October 1985, points for observing the development of any soil cracking were put in place. There were 20 points on the short mown area 4 m and 8 m both left and right of the row of neutron probe tubes. A 1 square metre wire frame with wires running diagonally between the two sets of opposite corners was placed in a standard position on each of those points. It was intended that any visually obvious cracks which crossed these diagonal wires would be counted. Observations were made on every visit to Blenheim over the summer of 1985-86 however on no occasion were cracks observed even on February 12 1986 when the gravimetric water content at 5-10 cm depth under the short mown pasture averaged as low as 6.5%. It had been intended to make observations for crack development under the longer grass treatments once cracks had been observed under the short grass (where earlier development was expected).

This lack of crack development was surprising as at 6.5% gravimetric water content a considerable amount of water has been lost. The gravimetric water content of the same area was measured in saturated winter conditions on August 27 1986 and averaged 31.0%. So at 6.5% in February most water that can be lost has been lost and presumably most

Plate 8.1
Soil cracking between vegetation,
Wither Hills, Blenheim.

shrinkage that could occur has occurred. There is of course the possibility that most shrinkage may be caused by the loss of the last water present although the general conclusion reached in 3ia was that most shrinkage occurs with the loss of the first water. To test whether the water loss/shrinkage rate relationship may have been the reason why no cracking was observed at the Wither Hills site, samples were gathered in the field and subjected to the standard linear shrinkage test using whole soil in the natural state; with shrinkage and weight loss also being measured as the samples dried. These tests confirmed that most shrinkage occurred in the early stage of water loss and later water loss resulted in negligible shrinkage (see figs 8.1-8.6). However the samples taken are not entirely representative of the behaviour of the soil right at the soils surface. Samples were gathered at 5, 10, 20, 30, 40 and 50 cm depth, and showed similar behaviour at all depths. With the four samples taken at 5 cm depth maximum shrinkage was between 10 and 30%. It can be expected that shrinkage at the soil surface would be less than that at 5 cm depth because of the increase in organic matter near the surface. The procedure of mixing the soil with water until it is a smooth homogeneous paste, which is necessary sample preparation for the linear shrinkage test, may considerably alter the response of the soil to water loss as the influence of soil structure upon shrinkage is lost. For the reasons outlined in 3ib such disturbed samples are likely to have less capacity for volume change than the same soil in its natural state.

There are two further influences on cracking which need to be considered. Cracking could be inhibited by the plastic nature of the soil when wet. As noted in 4ib some highly plastic soils can accommodate volume change in one dimension. If most shrinkage occurs when the soil is still plastic horizontal crack development could be inhibited by vertical shrinkage and subsequent lateral flow. Field observation in August 1986 indicated that the surface soils

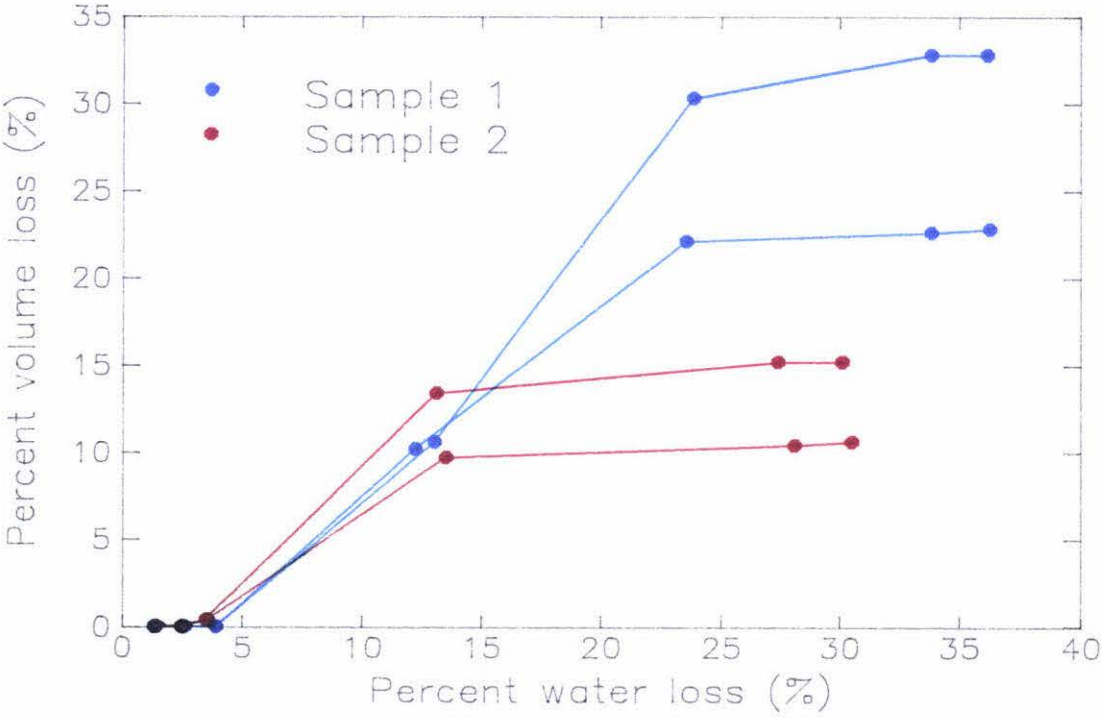


Fig. 8.1
The relationship between water loss and soil shrinkage at 5cm depth in a soil from the Wither Hills, Blenheim.

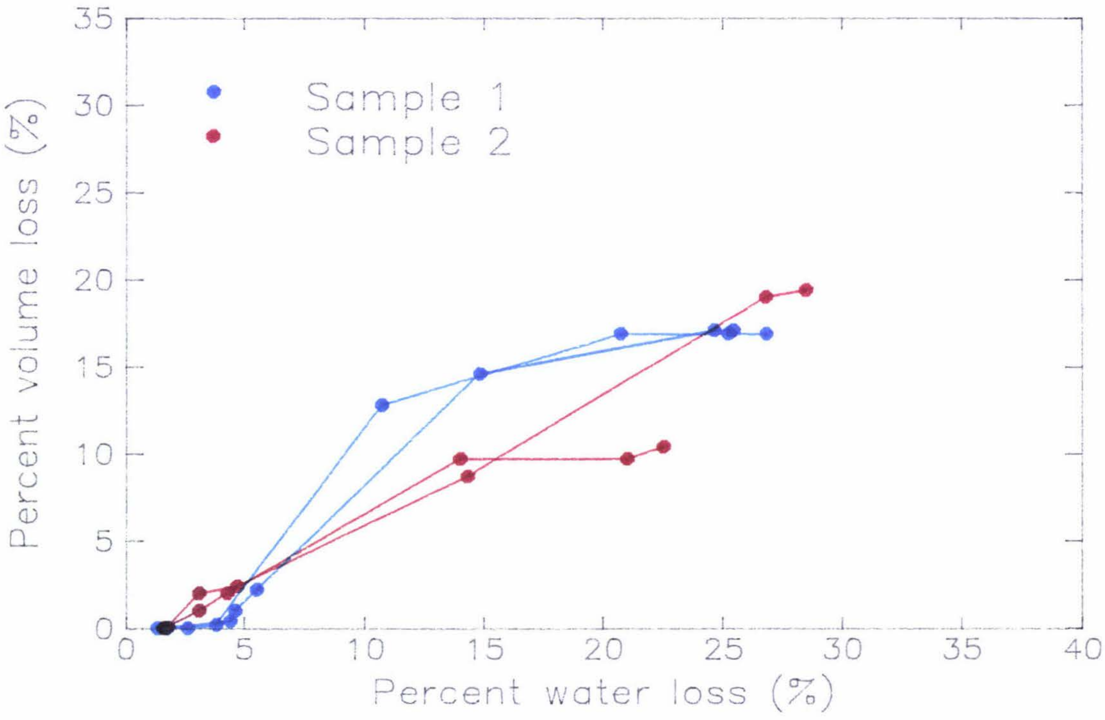


Fig. 8.2
The relationship between water loss and soil shrinkage at 10cm depth in a soil from the Wither Hills, Blenheim.

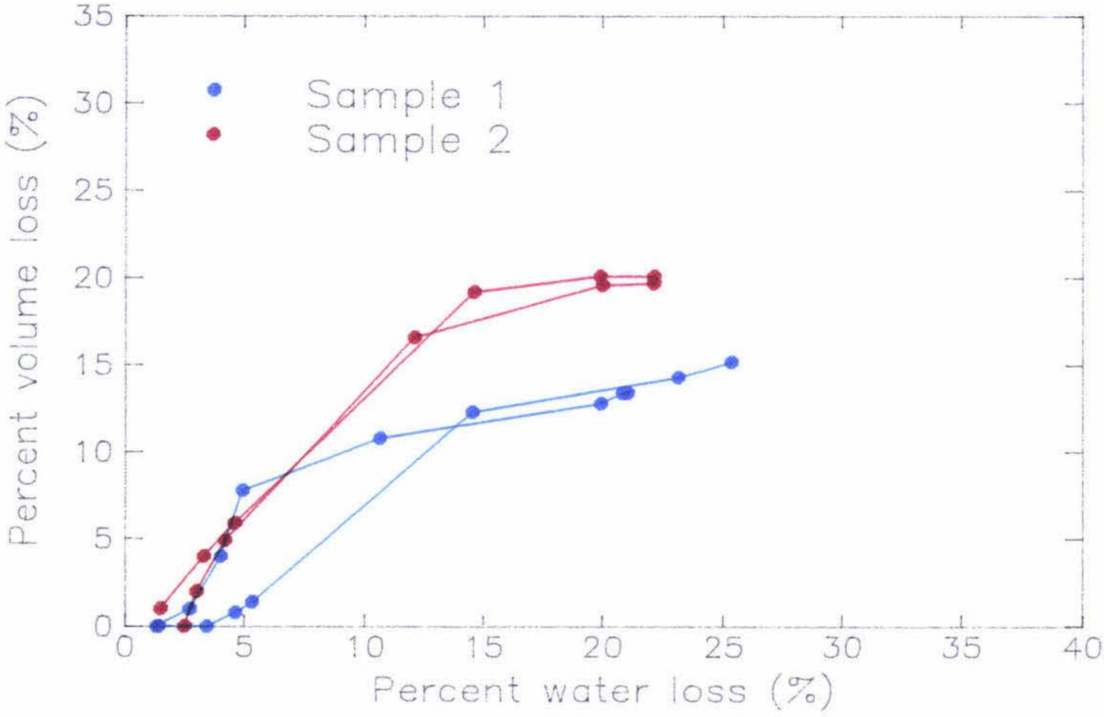


Fig. 8.3
The relationship between water loss and soil shrinkage at 20cm depth in a soil from the Wither Hills, Blenheim.

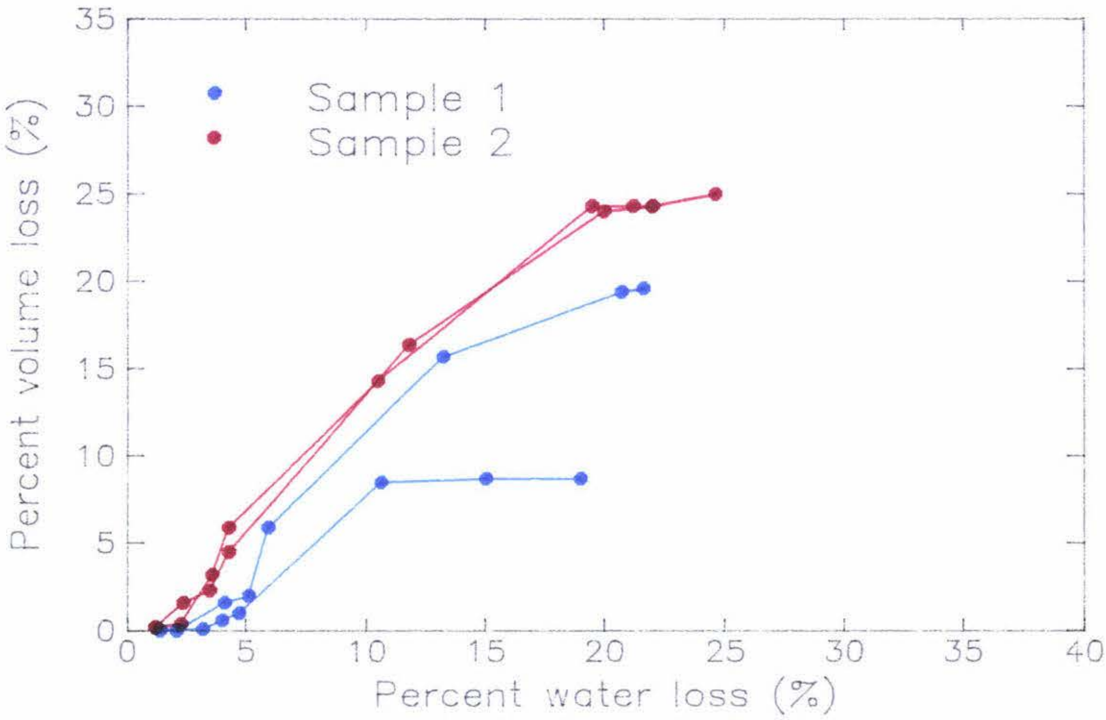


Fig. 8.4
The relationship between water loss and soil shrinkage at 30cm depth in a soil from the Wither Hills, Blenheim.

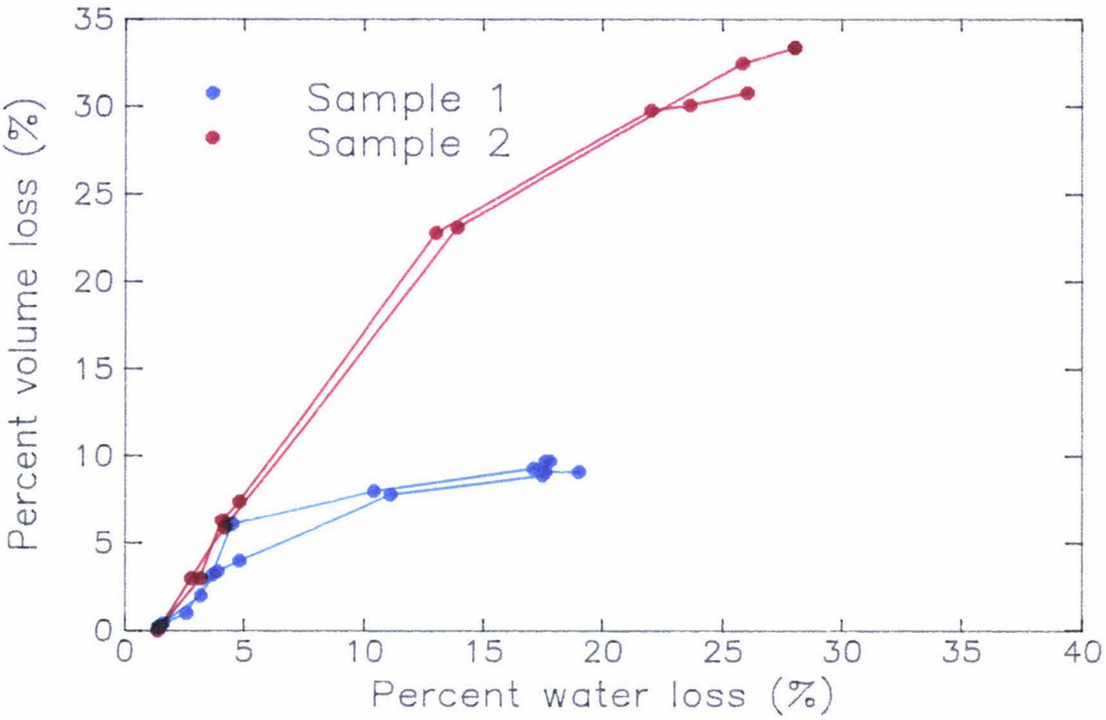


Fig. 8.5
The relationship between water loss and soil shrinkage at 40cm depth in a soil from the Wither Hills, Blenheim.

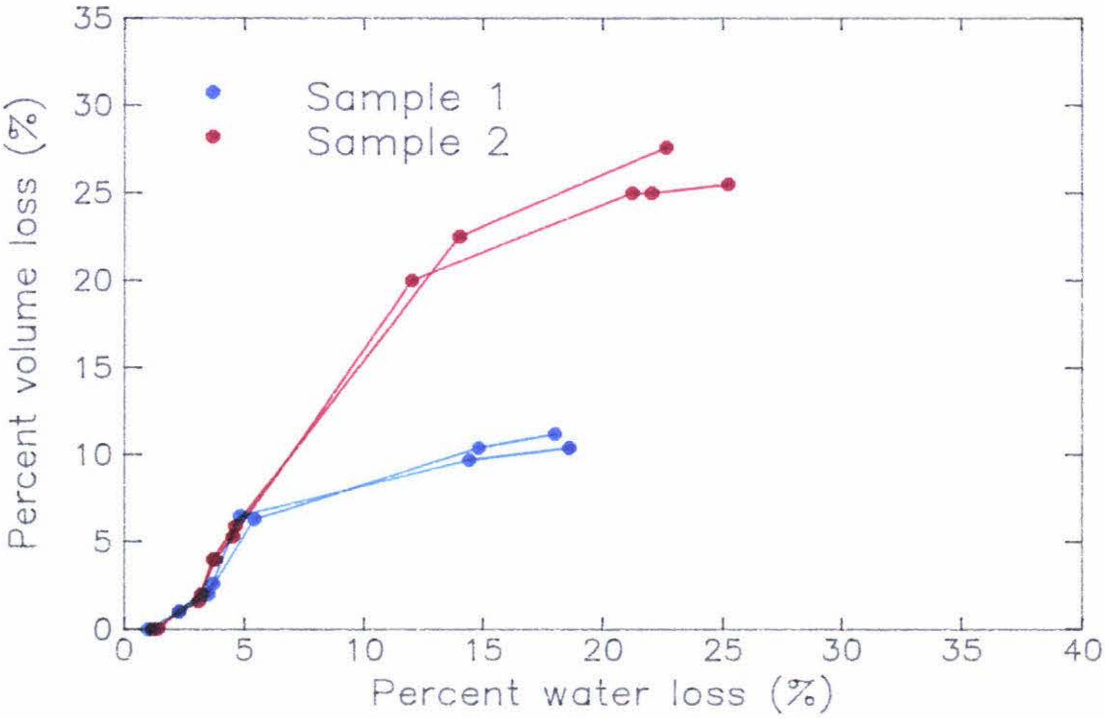


Fig. 8.6
The relationship between water loss and soil shrinkage at 50cm depth in a soil from the Wither Hills, Blenheim.

on the study site were soft when saturated though whether this could account for the lack of cracks is not known.

The second influence which needs to be considered is that of vegetation. The study site was covered in a well established pasture which is probably considerably denser than that which covered those areas where cracks have been observed in the past or indeed where cracks were observed in September 1985 on the Waitaki NZR property. Cracks were also observed less than 20 m upslope from the study site on a 'bald' area where the topsoil was completely lost during the bulldozing of the slope and has not reformed (see plate 8.2). The pasture cover over this area is sparse and cracks have developed. It is not clear whether this crack development is due to the poor pasture condition, excessive drying, or the lack of organic matter in the soil. However on the study site it does seem that the vegetative condition and particularly root development may have inhibited crack development as the soils would seem to be susceptible to cracking yet surface cracking did not occur. The possible absorption of shrinkage because of the plastic nature of the soils is unlikely because cracking has been observed in the past on the Wither Hills when it is assumed that the soils were similar in their plastic behaviour (or lack thereof).

Plate 8.2
Soil cracking observed near the Wither Hills experimental site on a 'bald' area.

CHAPTER 9 THE INFLUENCE OF PASTURE CONDITION ON ROOT DEVELOPMENT

9i Methodology

The effect of the three defoliation treatments used at Tuapaka on root development over the summer of 1985-86 was measured by gathering samples from each of the treatments and measuring the number and mass of roots present in these samples. This effect was not measured at the Wither Hills site because:

i) the hardness of the ground in the autumn of 1986 made sampling very difficult;

ii) the pasture on the study site had appeared to be suffering moisture stress for much of the summer resulting in little growth and as such, little differentiation of root development between treatments was expected.

These two problems did not occur at Tuapaka where samples were gathered on April 22 1986. Ten samples of 25 cm length were gathered with a 3 inch (78 mm) diameter corer from each treatment. These cores were divided into two sections, one from 0-7 cm depth and the other from 7-25 cm depth. The sampling sites were selected randomly and samples were labelled such that the author did not know which treatment the samples come from when samples were analysed. The samples were washed and sieved (1 mm sieve) removing the soil and leaving only root material. This material was weighed when wet and a subsample taken. It is important to remove the root subsample while still wet otherwise it is difficult to distinguish between dried live roots and decaying roots when counting. The number of roots in the subsample were counted using the line intersect method of Newman (1966), whereby the roots are spread onto a transparent dish and placed over a grid (see plate 9.1). The number of roots that cross the grid are counted and can be related to the length of roots present by use of a standard formula (Newman 1966). Calculation of

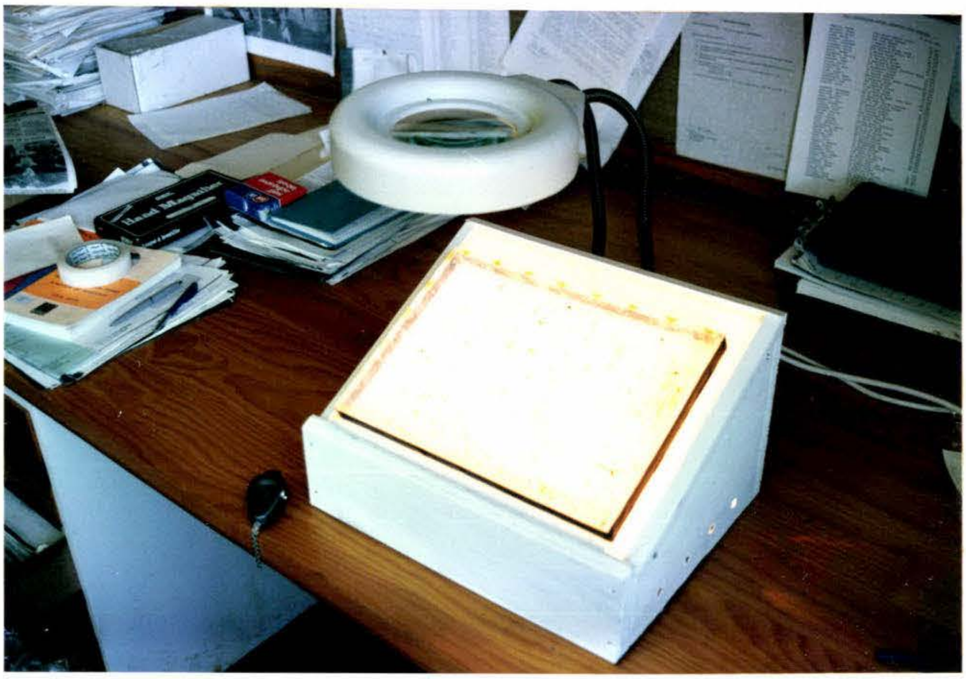


Plate 9.1
The root counting grid and accompanying apparatus.

the sample ratio then allows calculation of the length of root involved in the entire sample.

The root material not used in the subsample was dried and weighed. The intention of this procedure was to allow both the length and mass of root involved to be measured and hopefully any differences between treatments to become apparent. The cattle grazed medium length grass treatment was treated as a control, as this is the typical level of defoliation.

9ii Results and Discussion

The mass and lengths of root matter measured from the two depths, and from the three different pasture treatments are contained on table 9.1. This table also contains the associated calculations of mass/volume, length/volume, and length/mass. The significance of the differences between treatments in mass, length, and length/mass ratio was calculated - these results are presented on table 9.2.

None of the significant differences in root mass, length or length/mass ratio are between the short and medium length grasses. This is not surprising as these two treatments were quite similar when compared with the long 'rank' pasture. The differences in root characteristics may reflect the change in pasture composition evidenced in the rank pasture. This pasture became dominated by white clover as the summer of 1985-86 progressed whereas the short and medium treatments maintained dominance by perennial ryegrass.

Evans (1976) measured the root lengths of pure swards of a number of pasture species including perennial ryegrass and white clover (see table 9.3).

Assuming on average dry bulk density at Tuapaka for 0-25 cm depth of 1.3 Mg m^{-3} it is then possible to calculate the

Table 9.1 Mass and lengths of root matter and associated calculations for 0-7 cm and 7-25 cm cores from three pasture treatments of Tuapaka. (in all cases n = 10)

Mass of 0-7 cm core (3.34 x 10^{-4} m^3)			*Mass/Volume of 0-7 cm core*
Short Grass	$\bar{x}$ = 3.3 g	S.D. = 1.0 g	9.9 kg/m^3
Medium Grass	$\bar{x}$ = 3.4 g	S.D. = 1.5 g	10.1 kg/m^3
Long Grass	$\bar{x}$ = 2.2 g	S.D. = 0.9 g	6.6 kg/m^3

Mass of 7-25 cm core (8.61 x 10^{-4} m^3)			*Mass/Volume of 7-25 cm core*
Short Grass	$\bar{x}$ = 0.58 g	S.D. = 0.14 g	0.67 kg/m^3
Medium Grass	$\bar{x}$ = 0.53 g	S.D. = 0.10 g	0.62 kg/m^3
Long Grass	$\bar{x}$ = 0.69 g	S.D. = 0.15 g	0.80 kg/m^3

Length of root in 0-7 cm core			*Length/Volume of 0-7 cm core*
Short Grass	$\bar{x}$ = 109.7 m	S.D. = 24.8 m	327 km/m^3
Medium Grass	$\bar{x}$ = 94.1 m	S.D. = 31.0 m	280 km/m^3
Long Grass	$\bar{x}$ = 63.7 m	S.D. = 17.9 m	190 km/m^3

Length of root in 7-25 cm core			*Length/Volume of 7-25 cm core*
Short Grass	$\bar{x}$ = 43.1 m	S.D. = 13.7 m	50 km/m^3
Medium Grass	$\bar{x}$ = 33.9 m	S.D. = 10.5 m	39 km/m^3
Long Grass	$\bar{x}$ = 34.8 m	S.D. = 6.1 m	40 km/m^3

Length/Mass ratio in 0-7 cm core		
Short Grass	$\bar{x}$ = 34.6 m/g	S.D. = 6.4 m/g
Medium Grass	$\bar{x}$ = 29.6 m/g	S.D. = 5.3 m/g
Long Grass	$\bar{x}$ = 31.2 m/g	S.D. = 8.2 m/g

Length/Mass ratio in 7-25 cm core		
Short Grass	$\bar{x}$ = 75.4 m/g	S.D. = 17.4 m/g
Medium Grass	$\bar{x}$ = 63.4 m/g	S.D. = 13.6 m/g
Long Grass	$\bar{x}$ = 51.6 m/g	S.D. = 9.8 m/g

Table 9.2 Significance of the differences in root mass, length, and length/mass ratio calculated using the t test.

Mass	*0-7 cm*	*7-25 cm*
Short vs Medium	-0.12	0.86
Short vs Long	2.55*	-1.77
Medium vs Long	2.10*	-2.81*
Length	*0-7 cm*	*7-25 cm*
Short vs Medium	1.24	1.68
Short vs Long	4.76***	1.75
Medium vs Long	2.68*	-0.2
Length/Mass ratio	*0-7 cm*	*7-25 cm*
Short vs Medium	1.93	1.71
Short vs Long	1.04	3.78**
Medium vs Long	-0.53	2.24*

* $p < 0.05$	t (18 D.F.)	2.101	significant
** $p < 0.01$		2.878	highly significant
*** $p < 0.001$		3.922	very highly significant

Table 9.3: Root length (cm) per 1000 g soil (after Evans, 1976).

DEPTH (cm)	PERENNIAL RYEGRASS	WHITE CLOVER
0-20	12990	3310
20-40	2180	632
40-60	534	218
60-80	334	131
80-100	188	88
100-120	111	108
120-140	86	92

root length (cm) per 1000 g of soil for 0-25 cm depth. This is a comparable measurement to Evans 0-20 cm reading on table 9.3.

Table 9.4 Root length (cm) per 1000 g soil at Tuapaka.

DEPTH (cm)	SHORT GRASS	MEDIUM GRASS	LONG GRASS
0-25	9800	8200	6300

These results are what would be expected in changing from a ryegrass dominant to a clover dominant pasture. Unfortunately if this is the case then the effects of this species change, which is partly but not entirely related to defoliation, may be masking the intended singular effects of defoliation. An area grazed to similar level of defoliation as an ungrazed area may have less clover due to nitrogen being returned in animal excreta (see 5c).

As there were no significant differences between the short and medium treatments, and as the significant differences between the rank pasture and the other two treatments can possibly be explained by the change in composition no conclusions can be offered from the results of this experiment. However this conclusion is not a result of any limitations of the technique rather one of the root measuring sample site being an area designed for another experiment rather than this one.

CHAPTER 10 THE IMPACT OF CLIMATE ON THE EFFECTIVENESS OF SOIL CONSERVATION WORKS DESIGNED TO CONTROL TUNNEL-RELATED EROSION

In the Marlborough Catchment Board's Scheme Review a number of factors of critical importance in achieving a satisfactory and lasting treatment were described (see chapter 6c). This list deliberately excluded climatic influences, although these are important and may be the factor determining the success or otherwise of a soil conservation programme. The impact of the climatic influences has not been quantified despite the individual process being easily measurable. Salinger (1979) dubbed the period from 1950 to 1970 the "Green Years" as the climate throughout New Zealand was particularly amenable to high levels of agricultural production. There were very few droughts while temperatures were about 0.5°C higher than the long term average. Salinger concluded that "the instrumental record does not give the chances of more hospitable years a high probability". These "Green Years" coincided with the establishment of conservation works on the Wither Hills and may have provided fortuitous assistance to their success.

It is difficult to quantify the important climatic factors. For example wet winters encourage tunnelling by raising ground water levels and increasing the amount of tunnelflow. In contrast dry winters result in more rapid desiccation in spring which has detrimental effects on pasture condition. However most damage is by extreme events - either too much rain or too little - and any analysis should determine the occurrence of these events.

10i Methodology

This consisted of:

1) identifying the appropriate meteorological parameters;
2) identifying suitable records;
3) analysing these records with respect to their variability in time;

4) evaluating the effect any variability in the parameter may have had on the success of soil conservation works.

10ii Identification of the appropriate meteorological parameters

The success of soil conservation works in areas susceptible to tunnel-related erosion depends upon; sufficient summer rainfall for pasture not to deteriorate badly; winter rainfall conditions (see above); a lack of intense rainfalls which can result in sheet erosion, gully enlargement, and possibly tunnel formation; wind speeds and humidity levels which act as controls on the rate of evapotranspiration and so influence soil moisture conditions; and temperature as this partly controls the rate of pasture growth.

The following parameters were to be quantified if possible, usually on an annual basis, and any temporal trends noted:
1) annual rainfall
2) summer rainfall
3) winter rainfall
4) summer raindays
5) droughts
6) drought ending rainfalls
7) intense rainfalls
8) humidity levels
9) wind speeds
10) mean daily temperatures

10iii Identifying suitable meteorological records

To be of use in this study records are required to be of sufficient length, so that the 30 to 40 years since conservation works began can be compared with longer term trends. Daily rainfall records are available from the Wither Hills site (NZMS1 S28 247948) for the period 1946-1986, Blenheim (NZMS1 S28 237984) for 1941-1986, and

Sevenoaks (NZMS1 S28 123966) for 1902-1986. Only Sevenoaks gives a sufficient period of records for longer term trends to become apparent. Even though the Sevenoaks site is further up the Wairau Valley than the areas of severe tunnel gully erosion, and receives about 10 percent more rain per annum than the Wither Hills site, there is sufficient positive correlation between the sites, (for the period 1941-1984, r = 0.8802 for annual rainfall totals), for the Sevenoaks site to be used as representative of the Wither Hills area.

No long term records of either humidity levels or wind speeds were available from any site in the Blenheim area so any influence of these factors could not be ascertained.

Monthly and annual average temperatures are available for the Blenheim site since 1932. These were of some use in identifying the possibility of climatic fluctuations.

10iv Evaluation of Possible Climatic Influences

a) *Variation of Rainfall on an Annual Basis*

Tomlinson (1980b) has noted a relationship between annual rainfalls throughout New Zealand and sunspot cycles. His analysis showed peaks in rainfall every 11 years or so possibly associated with sunspot maximums, interspersed with troughs of rainfall. His curves of New Zealand wide rainfall are shown on fig 10.1. Of obvious interest are the three minima in rainfall centred on about 1913, 1922 and 1932. If these minima were associated with low rainfall levels in Marlborough they may have been a possible influence on the development of the tunnel gully erosion evident in 1945.

Five year floating averages of the annual rainfall, summer (November-March) rainfall, and winter (May-August), were calculated for the rainfall data from Sevenoaks. These were plotted on an annuial basis as per Tomlinson (1980b)

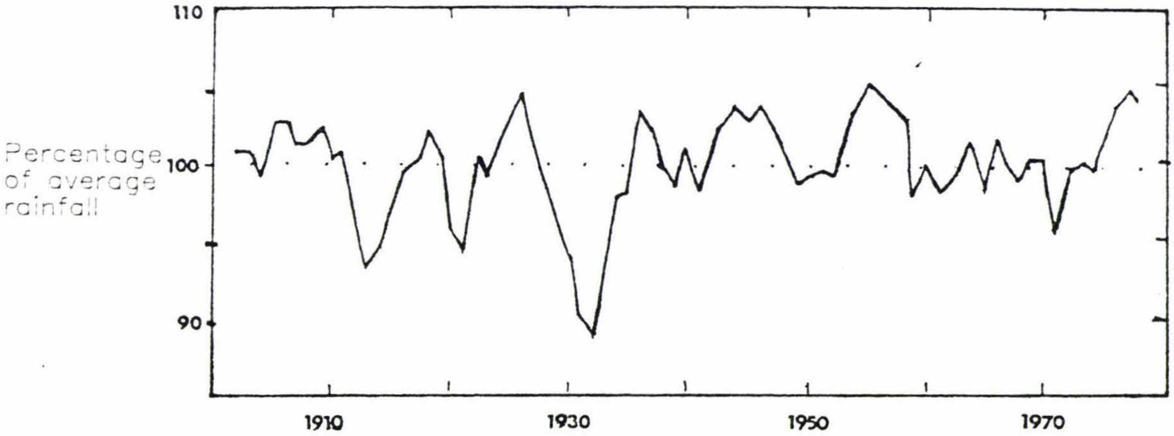


Fig. 10.1
Five year moving average of annual rainfall over New Zealand, (after Tomlinson, 1980).

(see figures 10.2-10.4). While the peaks and troughs do not conform exactly with Tomlinson's data they do confirm a rainfall minima in the early 1930s which was largely due to a series of dry summers.

Conditions since catchment control work was started in the late 1940s have trended towards slightly wetter than the long term average conditions, except for a series of dry summers in the early 1970s.

While it is difficult to assess the importance of such variations, a few speculations can be made. The dry years of the early 1930s were associated with an economic depression which would have provided prime conditions for overgrazing, and a general lack of farm maintenance in the Marlborough area. While probably not contributing significantly to the initiatation of tunnel gully erosion at Wither Hills, conditions were suitable for continuing the development of tunnel gullies into signficant problems. Secondly the moderate rainfall conditions since catchment control works commenced would certainly have had some benefit to pasture establishment and growth, as well as assisting a period of relative prosperity in the agricultural sector through the 1950s and 1960s. However these influences on the development and control of tunnel-related erosion do not seem to be exceptional events and would probably only be of assistance in either enhancing or restricting, rather than starting or stopping the development of tunnel-related erosion.

b) *Occurrence of Extreme Maximum and Minimum Rainfall Events*

As it seems that any fluctuations measurable on an annual basis probably do not contribute to stopping or causing tunnel-related erosion, rather reducing or increasing the rate of development, investigation of the occurrence of more extreme events is the other avenue open. Such extreme events as droughts or intense rainfalls may be

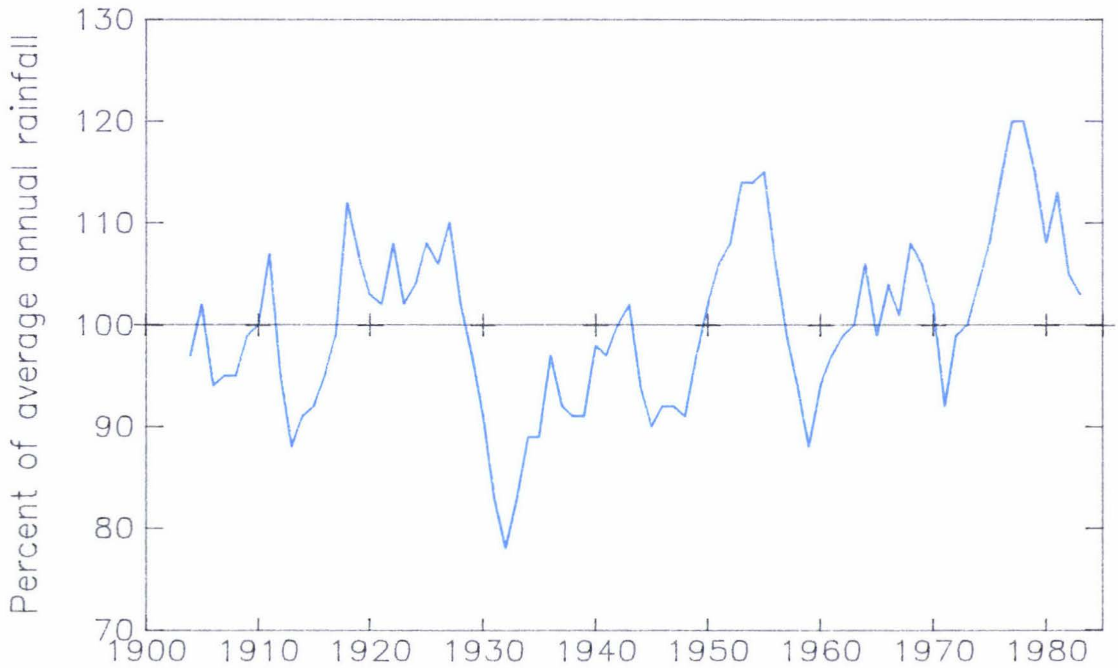


Fig. 10.2
Five year moving average of annual rainfall, at Sevenoaks, Blenheim.
Average annual rainfall (1902 - 1985)= 732mm

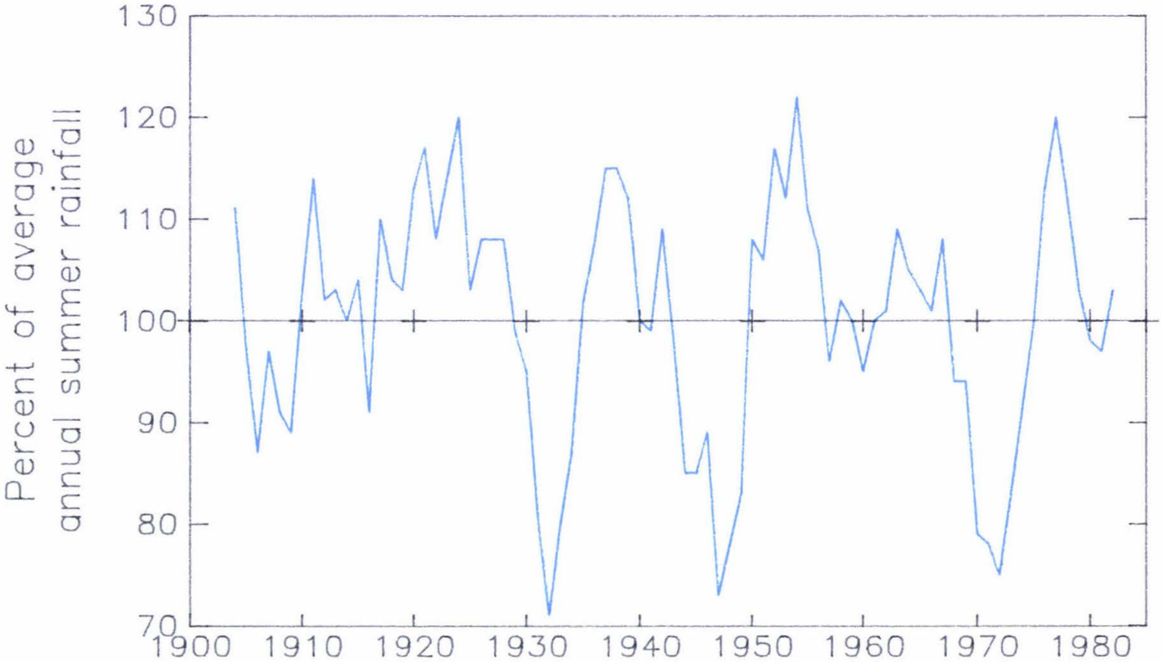


Fig. 10.3
Five year moving average of annual summer (Nov – Mar) rainfall.

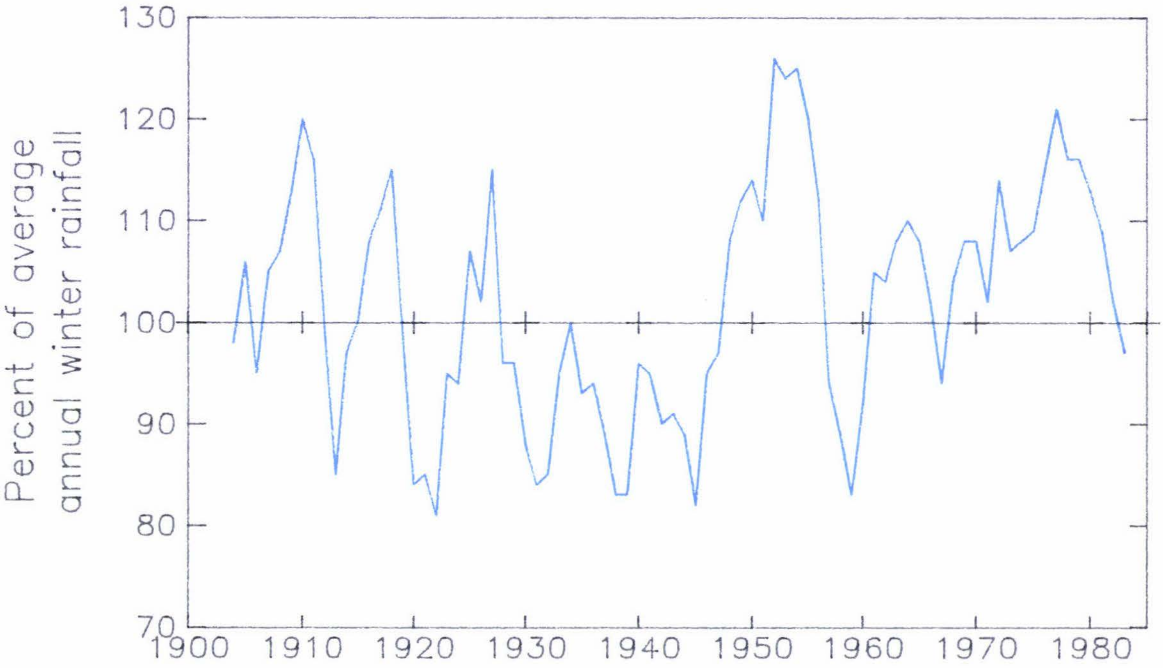


Fig. 10.4
Five year moving average of annual winter (May — Aug) rainfall.

infrequent but contribute significantly to tunnel development.

Droughts
The daily rainfall records from Sevenoaks were used to gain a rough estimate of the frequency of droughts in the Blenheim area since 1902. Drought severity depends on a number of factors, primarily a lack of rain, but also the rate of water loss which is influenced by the radiation input and wind.

Because rigorous analysis would be an extremely lengthy and complicated procedure, two rough but relatively simple methods of analysis were adopted.

Firstly, only completely rainless periods were considered. However the length of rainless period required for a drought varied depending on the rate of water loss for that particular time of year. In this analysis droughts were considered to be completely rainless periods long enough to induce 100 mm of potential evapotranspiration. The length of time required was estimated from evaporation pan data collected at the Wither Hills meteorological station since 1973 (see table 10.1).

The results on table 10.2 reflect the dryer years of the 1930s and 1940s mentioned earlier. However again there are no obvious climatic fluctuations. When the rainfall record is scanned for the really extreme events since 1902 the events listed on table 10.3 are noticeable. Once again the concentration of drought in the 1930s and 1940s is obvious with relatively few extreme droughts before 1910, in the 1920s and in the 1960s.

Drought-ending rainfalls
Traditionally tunnel gullies have been thought to initiate when heavy rain has fallen on a desiccated and cracked soil. Although the work reported in this thesis throws

Table 10.1 Drought lengths to cause 100 mm of potential evapotranspiration

Periods centred on the middle of each month	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Drought length (days)	40	28	22	17	16	19	25	40

Table 10.2 Number of droughts at Sevenoaks by decade

Decades	1902-1909	1910-1919	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969	1970-1979	1980-1985
Number of droughts	7	16	9	18	21	11	17	12	9

Table 10.3 Extreme Drought Events at Sevenoaks 1902-1985

Dates	Number of Days	Total Rainfall	Number of Raindays
Nov 14 1907 - Feb 29 1908	106	22.8	7
Jul 31 1914 - Feb 1 1915	185	97.3	22
Mar 25 1915 - Jun 11 1915	78	33.1	5
Nov 28 1916 - Feb 1 1917	65	20.1	3
Feb 1 1919 - May 16 1919	105	25.2	8
Jan 26 1921 - Apr 4 1921	69	25.7	3
Dec 29 1927 - Mar 5 1928	66	18.3	2
Jan 31 1930 - Apr 6 1930	65	16.2	2
Oct 2 1931 - Dec 13 1931	72	24.9	3
Feb 23 1932 - Apr 27 1932	64	9.1	1
Feb 5 1933 - Apr 2 1933	56	28.6	4
Nov 20 1934 - Jan 17 1935	58	13.5	2
Sep 13 1938 - Nov 25 1938	73	30.0	4
Dec 26 1938 - Apr 22 1939	117	8.1	2
Dec 14 1942 - Feb 15 1943	63	7.6	1
Feb 22 1944 - Jun 29 1944	128	23.6	3
Jan 10 1946 - Mar 12 1946	61	18.0	1
Nov 15 1946 - Jan 5 1947	51	3.0	1
Jan 17 1948 - Mar 19 1948	62	11.4	3
Dec 23 1951 - Mar 24 1952	92	18.1	2
Jan 11 1956 - Mar 17 1956	66	24.2	2
Dec 13 1956 - Feb 6 1957	55	0	0
Dec 25 1958 - Mar 15 1959	80	23.6	8
Jan 8 1967 - Mar 9 1967	60	33.3	5
Feb 2 1969 - Apr 2 1969	59	20.5	4
Jan 9 1970 - Mar 5 1970	55	17.5	4
Dec 26 1972 - Mar 1 1973	65	20.5	3
Nov 15 1974 - Jan 15 1975	61	16.6	4
Jan 29 1976 - Mar 26 1976	57	10.3	2
Jan 1 1978 - Mar 17 1978	75	20.4	2
Dec 24 1980 - Mar 1 1981	67	9.4	2
Jan 26 1983 - Apr 13 1983	77	25.8	6

doubt on this idea, heavy rainfall onto desiccated soil also leads to the deleterious effects of both compaction and removal of topsoil. As such, investigation of the occurrence of heavy drought-ending rainfalls is still useful.

The drought events used are those identified above as being sufficient to cause potential water loss of 100 mm. The number of these drought events that were ended by a rainfall event of 10 mm or greater are listed by decade in table 10.4.

This table does not show differences between decades that seem significant except perhaps for the large number of heavy drought ending rainfalls in the 1940s. However this is probably a factor of the larger number of droughts in this decade rather than an expression of heavy but infrequent summer rain.

Intense Rainfalls

The frequency of high intensity rainfalls in the Blenheim area is obtainable from NZ Met. Service Misc. Publ. 162 (Coulter and Hessell, 1980). The station nearest to Sevenoaks listed in this publication is Blenheim Aero. The rainfalls of 24, 48 and 72 hours duration which occur with varying frequency are listed on table 10.5.

The frequency of rainfall events of up to 7 days duration were gained by plotting the information contained on table 10.5 and extrapolating the curves.

The daily rainfall record of Sevenoaks from 1902-1985 was then scanned for the rainfall events which exceeded the approximate 2 year return period. In total there were 66 of these events. These events were then sorted into those which exceeded the approximate 5, 10, 20 and 50 year return periods (see table 10.6).

Table 10.4 Drought-ending rainfalls greater than 10 mm by decade

Decades	1902-1909	1910-1919	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969	1970-1979	1980-1985
Number of droughts	1	8	3	6	11	8	4	3	3

Table 10.5 Frequency of Heavy Rainfalls (mm) at Blenheim Aero (from Coulter and Hessell, 1980).

Duration (hours)	Frequency (years) 2	5	10	20	50	Limit
24	58	74	85	96	109	114
48	70	88	100	111	126	132
72	74	94	107	120	136	142

Table 10.6 Occurrence of High Intensity Rainfalls at Sevenoaks

	Approximate Return Period of Event (years)				
	2	5	10	20	50
1902-09	4	2	1	0	0
1910-19	7	6	3	3	2
1920-29	10	5	5	1	1
1930-39	4	1	1	0	0
1940-49	8	4	1	0	0
1950-59	7	2	2	0	0
1960-69	8	4	2	1	0
1970-79	10	3	1	0	0
1980-85	8	5	4	1	0
Total	66	32	20	6	3

The six events which exceeded the 20 year return period were:

February 24-26 1910	Total Fall 120.9 mm
May 26-30 1916	Total Fall 155.2 mm
February 16 1918	Total Fall 113.8 mm (140.3 mm over 3 days)
May 4-7 1923	Total Fall 163.3 mm
April 25 1966	Total Fall 100.1 mm
April 8-9 1980	Total Fall 116.1 mm.

The 1916, 1918 and 1923 events also exceeded the 50 year return period.

There are two interesting points that can be made about this data:

i) Four of the events, including the three most extreme, occurred between 1910 and 1923 before tunnel-gully erosion became a widely recognised problem and catchment control works began;

ii) All six events occurred in a 14 week period from February to May in the period when there was traditionally thought to be most risk from heavy rain falling on cracked soil. It is possible that this tradition arose because of the occurrence of the heaviest rains at this time of year.

Aside from the occurrence of the four extreme events between 1910 and 1923 there seem few fluctuations in the frequency of intense rainfalls, although there were relatively few intense rainfalls both between 1902 and 1909, and in the 1930s (see table 10.6).

c) Temperature Fluctuations

As noted above Salinger (1979) dubbed the period from 1950-1970 the "Green Years". Throughout New Zealand the temperatures averaged about 0.5°C higher than long term averages. Temperature data is available for the Blenheim site from 1933 onwards. The mean annual temperature for the period 1933-1984 is 12.7°C. Between 1933 and 1953 only 4 out of the 21 years averaged 12.7°C or greater, whereas between 1954 and 1984 25 of the 31 years did so. The average temperature for 1933-1953 being 12.4°C compared with an average for 1954-1984 of 12.9°C. When the two groups of mean annual temperatures were compared using the t test, the t value was 5.07, with 50 degrees of freedom. This indicated that the probability that there was no difference between the 2 periods temperatures was less than 0.001. In other terms a very highly significant result. It is not immediately obvious whether the period before 1953 was colder than the long term average condition or the period since 1953 warmer. However Salinger (1979) had indicated that the period since 1950 was warmer than the long term average (see fig 10.5) and it appears safe to conclude that the last 30 years has been up to 0.5°C warmer than average at Blenheim. These warmer than average temperatures, when accompanied by sufficient moisture, encourage vegetative growth, and when accompanied by insufficient moisture encourages soil desiccation and consequently reduces vegetative growth.

Because of this it does seem that the availability of soil moisture is a more important influence on vegetative growth than temperature, and the variation of annual temperatures within $\pm$ 0.5°C is probably less influential than the much wider variations in rainfall mentioned earlier in this chapter.

10v Summary

A number of climatological parameters of the Blenheim area were investigated for possible influence on the development and control of tunnel-related erosion. This analysis indicated the possible influence of a number of intense rainfall events before 1924, and of a series of droughty summers in the early 1930s, contributing toward the

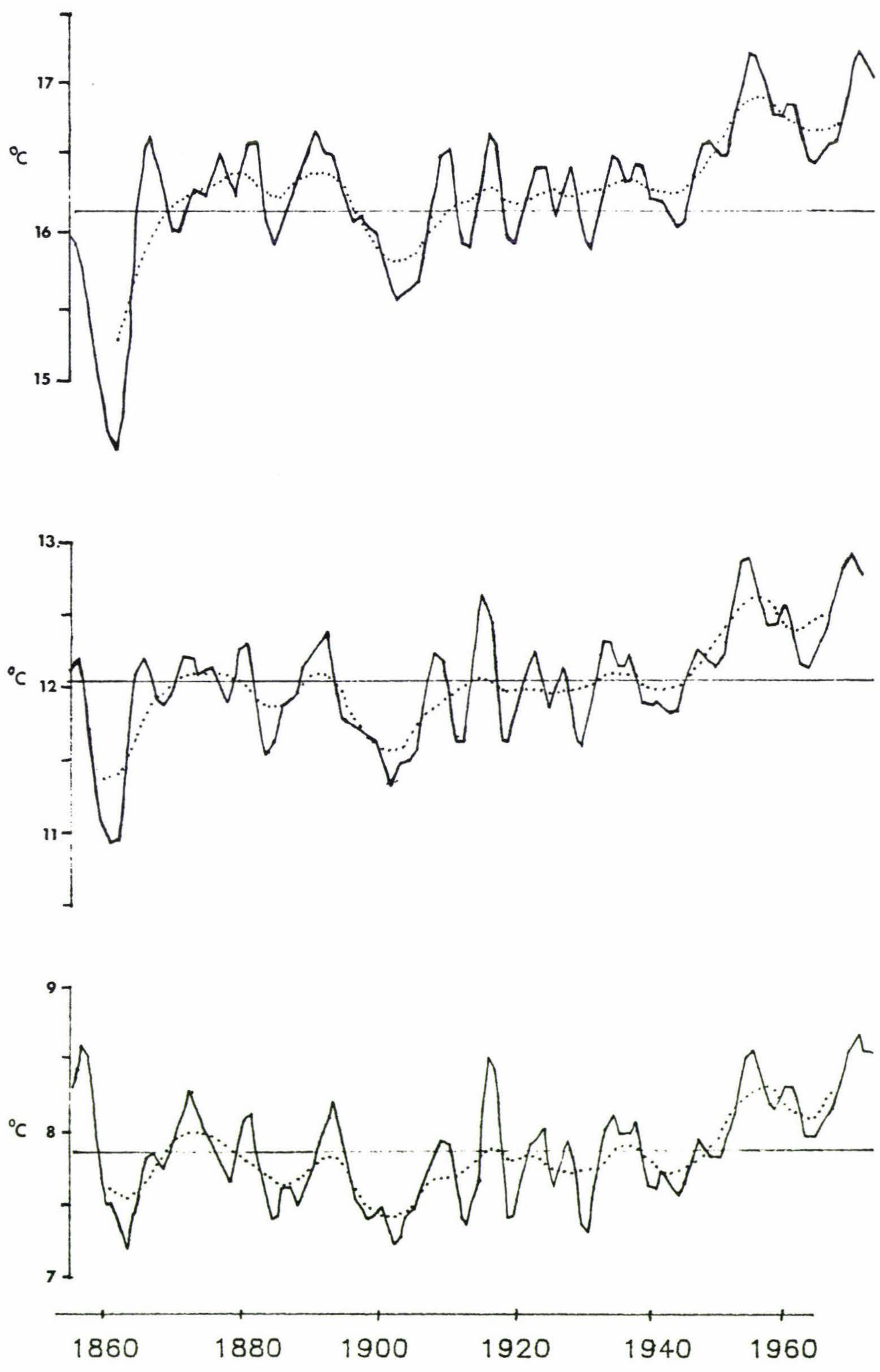


Fig. 10.5
Five year moving averages of annual maximum, mean, and minimum temperatures from composite New Zealand data — 1853–1975 (after Salinger, 1979).

development of tunnel-gully erosion into a serious problem by the 1940s. Contrastingly relatively favourable conditions have occurred throughout the past 35 years or so, which may have contributed to the success of catchment control works in reducing both the severity and reoccurrence of tunnel-related erosion.

CHAPTER 11 A SPECULATION ON TUNNEL ORIGINS

The evidence and arguments presented in this thesis throw some doubt upon the desiccation-cracking model of tunnel formation presented by Laffan and Cutler (1977b). The major drawback in this model is its inability to explain how voids which are formed link up to initiate a tunnel. This model also relies for support in part on the widespread occurrence of soil cracks in areas where tunnels have formed. It was shown in chapter 3 that soil which disperses will inevitably also shrink when dried. If it is accepted that soil particles are released by dispersion prior to removal and tunnel formation then the simple incidence of cracking is not evidence of a causative relationship.

A model for tunnel formation which can explain how voids may link up is outlined in this chapter. This model does not necessarily rely on the incidence of cracks and can explain the formation of tunnels in both saturated and unsaturated soils. However this model of tunnel formation is entirely speculative and is not yet based on any experimental work.

Most soils which tunnel contain structural voids which would enlarge when the soil dries, and shrink as it wets up again. In some soils these voids may be connected by shrinkage cracks to the soil surface. In these cases rainwater may penetrate directly to the void when precipitation occurs onto the soil when it is in a dry condition. In cases where cracks are not present water may still move into the void when the soil surrounding the void becomes saturated. Where water has penetrated to a void via a crack the soil surrounding the crack will presumably be dry. This dry soil will exert a 'suction' on the water and will draw the water out into the surrounding soil. Where water has reached a void only because the surrounding soil was saturated the water will stay in the void until the surrounding soil dries and draws the water out of the void.

If the water which had collected in the void has the potential to disperse soil particles from the walls of the void, i.e., it was an extremely dilute solution and/or containing a high proportion of Na^+ ions, then the dispersed particles may be carried from the void with the water as it is drawn out because of the moisture tension gradient.

Water in a soil is also always subject to gravitational potential gradients which direct water downwards. The combination of these two potential gradients - moisture tension and gravitational - determine the location and movement of water in the soil. However water would initially collect in the lower part of a void because of gravity so that dispersion of soil particles is more likely in the lower part of a void. The possible removal of dispersed particles along with water drawn from the void would also be concentrated in the area surrounding the lower portions of a void. The result of this would be voids enlarging because of the dispersion of particles from the void walls and removal of these particles into the surrounding soil. This enlargement would be concentrated in the lower regions of a void and if continued would lead: to a large vertical void if a layer resistant to dispersion or a layer of low hydraulic conductivity did not occur; or to a downslope tunnel if such a layer was present.

If such processes do occur the initial development of a void into an elongate tunnel would probably be a slow process taking repeated wetting and drying over perhaps a number of years. Tunnels have only been observed to develop quickly where there has been a concentrated supply of water such as that which occurred when contour furrows were built. On areas at Wither Hills which have been treated to remove tunnels some redevelopment has usually occurred at a slow rate.

It has also been noted that tunnels in other areas of New

Zealand have developed in soils which are saturated or close to saturated throughout the year. In this case removal of soil particles by water movement due to repeated wetting and drying would be impossible and water movement would occur solely in response to gravitationally induced hydraulic gradients. The soil at Wither Hills was in a saturated condition during August 1986. It is probable that these conditions would hold for a few weeks or possibly months during most winters. It is possible that tunnels could develop in this "dry" area during these wet periods, due to the same processes by which tunnels may have developed in wetter areas such as parts of Northland.

As mentioned above these ideas are entirely speculative. The most debateable point is whether dispersed particles could be carried along with water as the water is drawn out of a void. If it can this explanation of tunnel formation seems plausible.

If particles are carried out of a void along with liquid water they may be deposited at some stage. Deposition would occur if the water vaporised (which is probable in a dry soil), or if the clay particles flocculate because of changing electrostatic conditions in the soil water. Such deposition could lead to particular areas becoming denser (or compacted) because of pores being blocked with redeposited material. If such redeposition occurred downwards because of water containing dispersed material being subject to gravitational potential gradients, a partial explanation for the occurrence and development of fragipans is also made. However this possibility is even more speculative than that given above for tunnel origins. Nevertheless nothing is lost in presenting these speculations here even though they are not the direct thrust of this thesis.

CHAPTER 12 SUMMARY AND CONCLUSIONS

Tunnel-related erosion has been recognised as a significant erosion form in New Zealand since the 1930's. A considerable body of research has subsequently been devoted to investigating various aspects such as, tunnel formation, gully development, control by mechanical means, control by vegetative and grazing manipulation, and estimating the hydrological effect of tunnels.

This research has resulted in a better but by no means complete understanding of the causes, effects, and controls of tunnel-related erosion. In a pragmatic sense it does not really matter if understanding is incomplete, if the negative effects of tunnel-related erosion can be reduced to an acceptable level. Techniques for controlling tunnel-related erosion by destroying both tunnels and gullies, then restricting their redevelopment by careful grazing management have evolved. This study has provided some understanding of the effects of such catchment control works. The soil moisture experiment (outlined in Chapter 7) carried out at both Wither Hills and Tuapaka illustrated that the traditional reasons given, for the effectiveness of controlled grazing, i.e. restricting surface drying and crack development, are probably incorrect. Following from this conclusion there are two possibilities:

i) the apparent success of grazing management is due to other effects of the pasture, such as maintaining good root development or increased levels of soil organic matter;

ii) the apparent success of grazing management is due to other unrelated factors, such as the accompanying mechanical treatment, or favourable climatic conditions, or the passing of insufficient time for tunnels to redevelop into a problem.

While not being the prime objective of this study the effects of grazing intensity on root development, and of fluctuating climate were both briefly investigated, with inconclusive results (see Chapters 9 and 10 respectively). However it is the authors opinion based on observations of crack development in sparsely vegetated soil, and on the manner of tunnel subsidence rather than collapse in a humid climate conducive to vegetative growth, that appropriate grazing management reduces the problems of tunnel-related erosion by assisting in the maintenance of root health and strength. Maintaining root quality could effectively reduce the incidence of cracking, the rate of tunnel development, and the rate of gully formation from tunnel roof destruction.

The grazing techniques which have been designed to maintain pasture quality also maintain root quality. However in the Blenheim area with its dry summer climate some damage to pasture health is inevitable. While damage to root health may result from excessive summer grazing, greater harm to root health can probably occur as a result of overgrazing in the first period of growth following winter dormancy. This period of growth uses reserves of nutrients held in roots. These reserves are only replaced if leaf and shoot growth continue and photosynthesis occurs. If defoliation occurs before root reserves have been replaced, the pasture then has no further reserves to stimulate growth and both root and foliage health are retarded (see Chapter 5a). The level of root reserves that are available for the initial burst of spring growth may itself be affected by defoliation late in the previous growing season. Davidson (1978) noted that defoliation in late autumn suppressed pasture growth throughout the ensuing growing season even when defoliation in the following summer was light. The same problems may occur as a result of defoliation at any stage of the growing season as root reserves are depleted when regrowth occurs. However the most lasting and damaging effect on root and pasture condition results from defoliation in late autumn or early spring. It is for this reason that it is imperative to have alternative food supplies available for these two periods to ensure that pasture condition is not detrimentally affected. A certain amount of defoliation can be tolerated before any negative effects on root development are noticeable. The greatest sustainable stock carrying capacity is obtainable by not grazing past a point which reduces pasture health. This level of defoliation is more easily managed with cattle grazing than with sheep because it is more difficult for cattle to graze excessively than sheep.

Lenient grazing also almost certainly results in increased levels of soil organic matter. As shown in chapter 4 increases in organic matter reduce the susceptibility of a soil to both dispersion and cracking, as well as improving soil structure. All these effects have probably had some part in reducing the reoccurrence of erosion since cattle grazing was introduced.

Following from the results of this study is the recommendation that there be no change in the policy of predominantly cattle grazing in the dryland areas affected by tunnel-related erosion. This conclusion is based on reasons different to those which have been given in the past favouring cattle grazing, which now appear to be incorrect. This recommendation is of course qualified by economic considerations. If cattle grazing becomes uneconomic while sheep grazing was not, then strictly controlled sheep grazing would be acceptable. However complacency must be avoided. There is no guarantee that tunnel-gullies will not redevelop with time and/or inappropriate management. The current management of susceptible properties is probably only reducing the chances of tunnel redevelopment, not removing the chances, and as such remedial action will probably be a necessary ongoing activity.

The final recommendation is the usual urging for further research. However further research directed primarily at tunnel-related erosion is not seen as being as valuable as

The final recommendation is the usual urging for further research. However further research directed primarily at tunnel-related erosion is not seen as being as valuable as research into other more widespread and severe erosion forms. The research that is recommended is into the effects of New Zealands most widespread group of soil conservation plants - the pasture species. Adequate pasture health has an influence on most of the erosion types that affect pastoral grassland yet insufficient research has been directed at investigating such influences. Davidson (1978) described root systems as the "forgotten component of pastures". As it is the root systems of pastures which hold New Zealands most valuable soil in place, it is surprising that we have little knowledge of the appropriate management to fully optimise root and pasture condition. A study into the effects on different types of pasture under different grazing intensities by the various grazing animals; measuring pasture production, root growth, soil moisture levels, nutrient levels, and properties relating to soil structure and stability; would be of great value in ensuring that land management came to be based on rational and sustainable principles.

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