SELECTED SOIL PHYSICAL PROPERTIES AND THEIR AFFECTS ON CEREAL YIELDS IN THE MANAWATU-RANGITIKEI REGION, NEW ZEALAND

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ABSTRACT

The Manawatu-Kairanga-Rangitikei region is now a major cropping district in New Zealand. Expansion and intensification has led to a need for more specific information on soil physical properties and how these properties interact with crop yield and soil management.

Soil physical properties largely determine the rooting depth and available water storage capacity of a soil-crop system. Compacted subsoils (1.5-1.7 Mg/m^3), low saturated hydraulic conductivity (0-10 mm/hr), and poor aeration (0-5% large pores) were the probable causes restricting root depth in the six high terrace soils (Kiwitea mottled, Marton, Tokomaru silt loams) investigated. The two river plain soils (Kairanga silt loams) gave results which indicated a more suitable rooting environment than the high terrace soils.

Restricted rooting depth led to low (65-80mm) total available water contents (TAWC) for the high terrace soils and higher, but more variable, TAWC (80-116mm) for the Kairanga soils.

A simple soil water balance model allowed soil water storage and climate to be integrated to estimate periods of moisture stress. In the year of this study (1985/86) there was a range in moisture stress days (0-27 days) dependant on soil type. However, there was no correlation between the computed number of moisture stress days and crop yield. This was due to an unusual wet spring-summer growth

season. Thus other factors, probably related directly and indirectly to poor drainage and aeration, affected yield more than moisture stress. Extended to different climatic seasons, the model predicted that 25-64 moisture stress days would occur in a drier season, depending on soil type. This is predicted to cause a 40% and 20% reduction in yield due to moisture stress for the high terrace soils and a Kairanga soil respectively.

ACKNOWLEDGEMENTS

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CHAPTER 1

CHAPTER 1

INTRODUCTION AND OBJECTIVES

1.1 Introduction

The Manawatu-Kairanga-Rangitikei region has recently become a major cropping district in New Zealand. Arable farming has increased from 9000 to 15000 hectares between 1973 and 1983, making it the second largest cropping district after the Canterbury region (Agric. Stat., 1974, 1984). The expansion in cropping is due mainly to the locality of the region. Transportation has become a major cost when considering the economic viability of a product. The region is close to the main population centres and is centrally located for ease of product distribution. There is an extensive road network servicing the lower North Island, and the main railway lines and state highways pass through this region.

The expansion in arable farming has exposed a need for more specific information related to factors that affect crop yield in the region. At present a substantial part of our knowledge, relating to arable land use in New Zealand, comes from research done in the main cropping areas of the South Island (Canterbury, Otago and Southland). Less research has been done in the Manawatu - Rangitikei region where conditions, particularly soil type and climate differ from those in the South Island.

Many factors affect potential crop yields (Fig. 1.1). It is

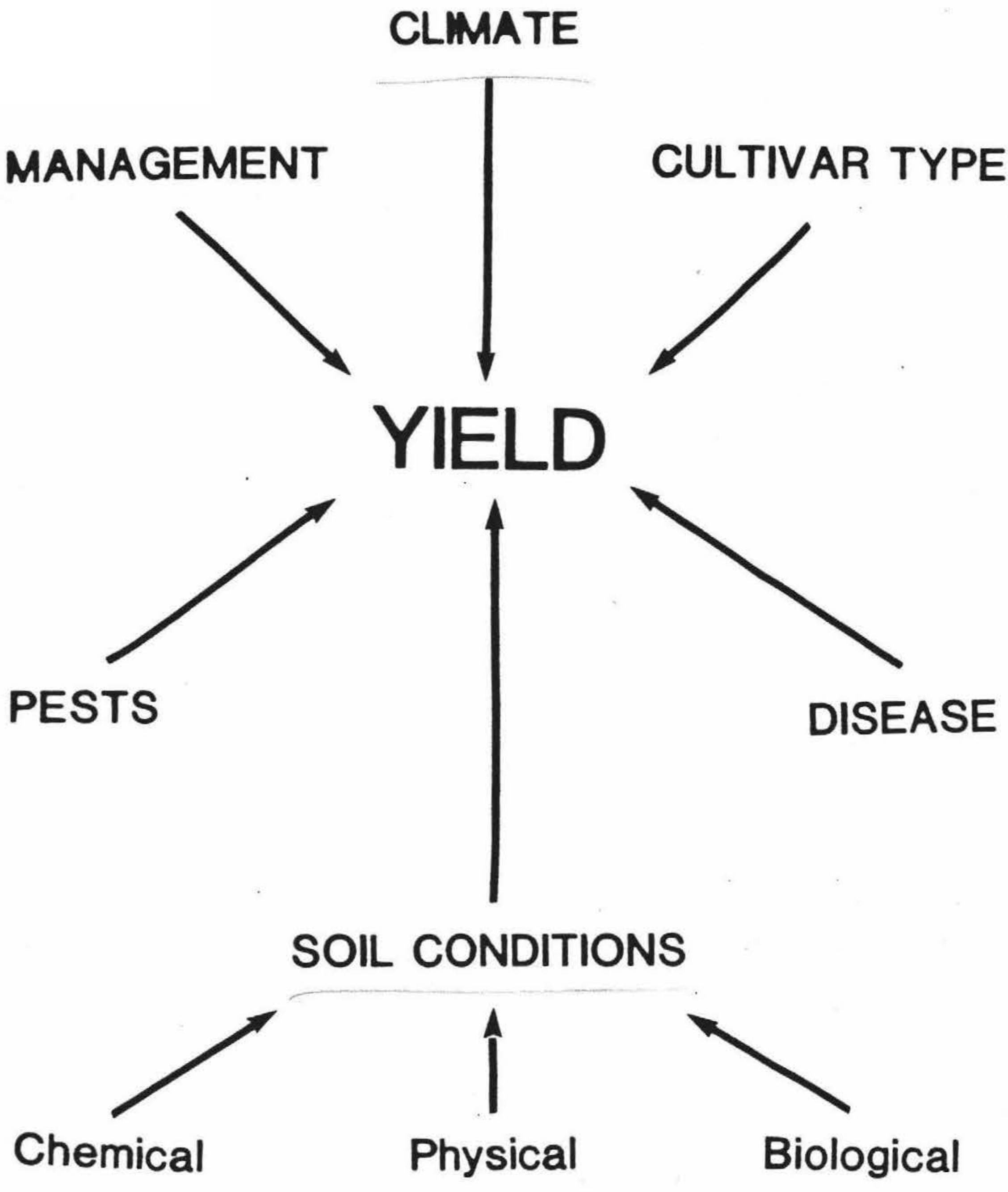


Figure 1.1 Factors affecting potential crop yield.

generally agreed that climate, disease, pests, cultivar type, and the soil conditions are all involved in determining final yield. Climate and soil type are the major causes of yield variations between seasons and sites. This study concentrates on the significance of soil conditions, particularly the soil physical aspects and the interaction of various climatic seasons on different soil types. To enable soil properties to be compared between sites, the effect of the soil properties on barley yield will-be studied. In the Manawatu - Kairanga - Rangitikei region barley was grown on 66% of the total area used to grow grain, peas and maize in 1984 (Agric. Stat., 1985).

Soil information for this region is found in three N.Z. Soil Bureau Reports; Soils of Manawatu County, (Cowie and Rijkse, 1977); Soils and Agriculture of Kairanga County, (Cowie, 1978); Soils of Rangitikei County, (Campbell, 1979). These reports contain detailed soil maps, soil descriptions, and a general land use classification based on soil limitations. There is no published information on soil physical properties of this region that have specifically been interpreted and related to arable land use.

This project is a study of soil types and their physical properties that are used for cropping in this region. It is anticipated that the major limitations and benefits to barley cropping and arable land use management will be identified for further research.

1.2 Objectives

The study has three main objectives:

(1) To provide information on basic soil physical properties relevant to cropping.

(2) To demonstrate that different soil types have differing physical properties that potentially affect crop yield.

(3) To show how various soil types may respond to seasonal variations in climate.

To provide this information, the study focuses on:

a) the major cropping soils in the Manawatu - Kairanga - Rangitikei region,

b) characterising the soil environment,

c) comparing and contrasting soil physical properties within and between soil types,

d) developing a soil water balance model to investigate the potential moisture deficits between sites and between different seasons,

e) identifing major soil limitations to arable land use.

CHAPTER 2

CHAPTER 2

SITE SELECTION

2.1 Introduction

Crop yield depends on a number of different factors; disease, weather, pests, cultivar, management and soil conditions (Fig. 1.1). To investigate the influence that soil type has on crop yield, especially the impact that soil physical properties have on the fertility of the soil, the soil physical properties should be the only varying factor. In a field situation this is very difficult to arrange, especially when a range of different soil types are to be compared. Therefore the strategy in selecting sites was to minimize the variation of the above factors except for soil type and their soil physical properties. The following sections briefly discuss these factors and their influence in determining sites selected in this study.

2.2 Barley

Barley is grown as a food for stock or for malting. Most barley is grown as stock food, but with the opening by the Canterbury Malting Company of a factory in 1980 at Marton, the demand for malting has increased.

Barley has an ability to mature rapidly and take advantage of a very short, but favourable season before drought conditions set in. Preferred weather conditions are cool temperatures during the initial growing period, warmth and moisture during tillering, and adequate soil moisture at flowering if high yields are to be achieved (Claridge, 1972). Cool summer temperatures have been shown statistically to give better yields (Jones, 1979). Excessive moisture during ripening will result in uneven maturity and drought will cause premature ripening, both reducing grain quality.

Deep free draining soils able to retain adequate soil moisture throughout the critical growth and development phases can be depended upon to give fairly consistent and satisfactory yields of good quality grain, but yield and quality will vary from season to season depending on the climate (Claridge, 1972). The free drainage allows early cultivation and sowing while a deep soil encourages the proliferation of roots seeking water and nutrients for the plant.

2.3 Site Selection

Topography governs the distribution of crop land, as cultivating, spray and harvesting machinery are restricted to working on slopes less than 12°. Topography in the Manawatu-Rangitikei region is not a constraint, most of the region is flat with a few undulating hills and terrace scarps.

The type of crop that can be grown in a region is determined by climate, specifically temperature and rainfall. Temperature regulates the physiological processes which control the rate of crop development and growth (Gallagher, 1983). While the amount of rainfall and its distribution are important for determining management patterns and crop performance.

The climate of the region is mild and subhumid. Annual rainfall ranges from 920mm at Kairanga to 1030mm at Marton. Rainfall is on average fairly evenly spread throughout the year, with a slight summer minimum. The prevailing wind is west to north-west. Mean annual temperature is approximately 12°C. A summary of climatic data for the spring and summer period, from three meterological stations (N.Z. Met. Ser., 1981) is given in Table 2.1. The climatic regime is similar across the region, but it is recognised that there will be variations in microclimate, especially in rainfall. The climate of the region is suited to growing barley. The interaction between climate and soil properties will be discussed further in Chapter 5 where a soil water balance is used.

To allow soil type and properties to be compared between sites, a dependent variable is needed. This variable could be crop grain yield, ear No.-m^{-2}., or plant dry matter weight. In this study crop yield is used because accurate yield measurements could be obtained and the objective of farmers is to achieve high yields to get the best return on their investment.

Table 2.1 Summary of mean rainfall and mean temperature data for the spring and summer months at the Marton, Ohakea, and Kairanga meterological stations (From N.Z. Met. Serv., 1980).

	Month					
	Sept	Oct	Nov	Dec	Jan	Feb
Marton (1947-66)						
Rainfall (mm)	62	99	85	96	85	74
Temperature (°C)	9.8	11.6	13.2	15.1	16.3	16.9
Ohakea (1947-80)						
Rainfall (mm)	69	86	68	84	68	60
Temperature (°C)	11.0	12.6	14.3	16.2	17.5	17.8
Kairanga (1970-80)						
Rainfall (mm)	95	87	62	70	62	41
Temperature (°C)	10.9	12.4	14.0	15.8	17.5	17.6

Yields can vary depending on the type of cultivar. The variety of barley grown on all sites used to provide yield data was 'Fleet', a grain feed variety. Yield data came from two sources;

(1) Massey University, Department of Agronomy trials, where responses to nitrogen fertilizer were being studied.

(2) Ammo-phos competition plots, a competition run by East Coast Fertilizer Company for grain growers.

The variation in assessment of maximum yields was not expected to differ greatly between the two sources.

Examination of available trial sites indicated that it was not possible to select sites with similar management and paddock history. The farmers entering the Ammo Phos competition and those used for the Agronomy trials are top grain growers in the region. Therefore it would be expected that they have optimised their management programme on their site to reach the best yield. This includes crop rotation, sowing date, timing of fertiliser and spray application, and harvesting grain at optimum quality. An important aspect of their programme is the control of disease and pests, which can have a significant impact on yield. It is assumed that variations in management techniques between sites had minimal effects on the crop yield.

2.4 Site - Location, History, and Yield

Eight sites were finally chosen for this project, two sites on each of four different soil types. Their location is shown in Figure 2.1. All sites are within either Rangitikei County, Manawatu County, or Kairanga County, whose soils have been mapped by Campbell (1979), Cowie and Rijkse (1977), and Cowie (1978) respectively.

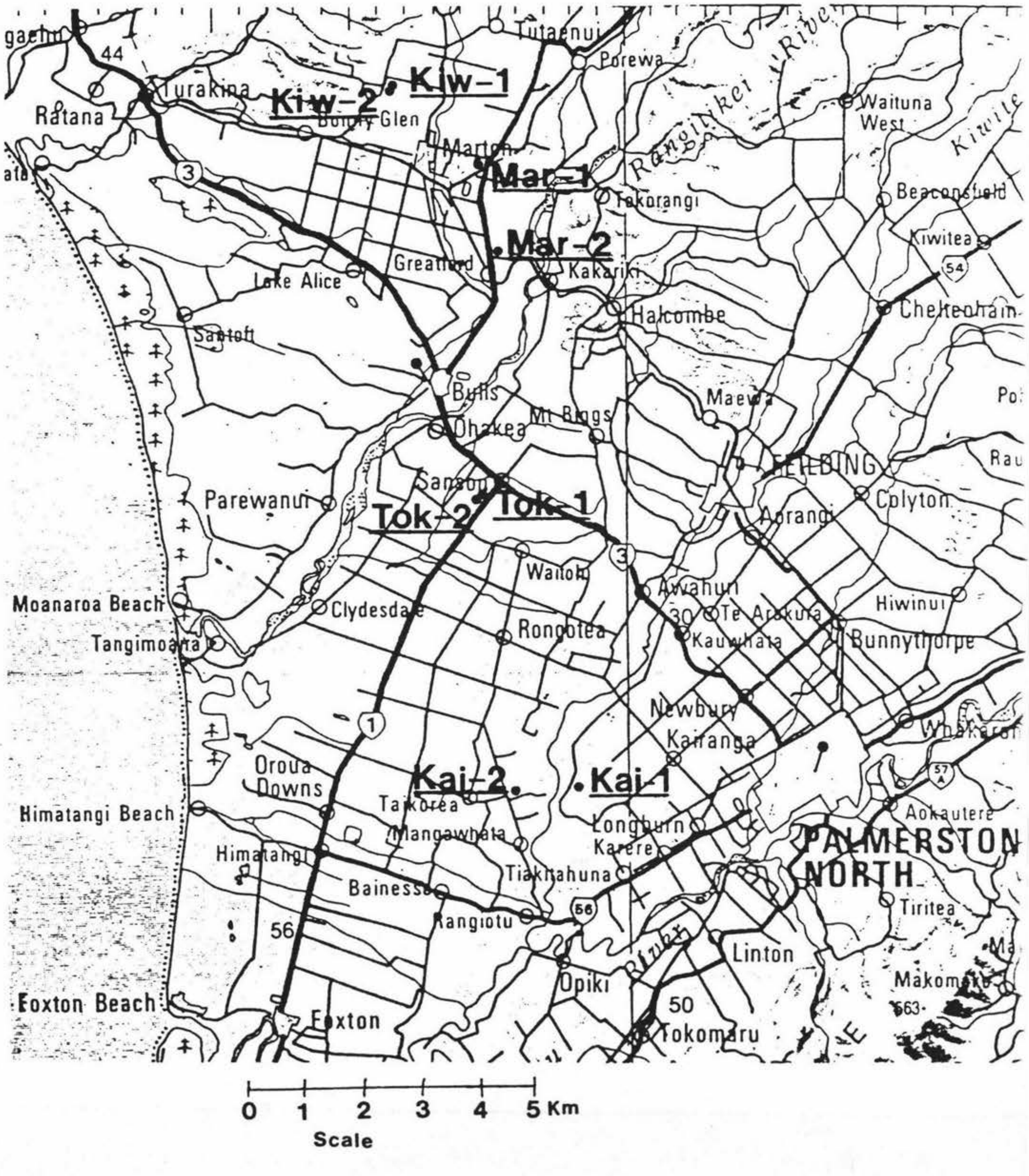


Figure 2.1 Map showing the location of the eight sites.

The four different soil types are Kiwitea mottled silt loam, Marton silt loam, Tokomaru silt loam, and the Kairanga silt loam. Kiwitea 1, Kiwitea-2, and Kairanga-2 soils were from Ammo-Phos competition sites. The other five sites were from Department of Agronomy trial plots.

Table 2.2 Sowing and harvesting dates, number of years out of grass, and yield data for the eight soils.

Soil Type and Site Number	Sowing Date (Oct. 1985)	Harvest Date (Feb. 1986)	Number of Years out of grass	Yield tons/ha
Kiwitea-1	29	7	6	5.6
Kiwitea-2	29	7	6	5.6
Marton-1	2	2	3	5.8
Marton-2	15	4	4	4.2
Tokomaru-1	1	9	10	4.8
Tokomaru-2	1	9	10	5.1
Kairanga-1	10	3	10+	5.0
Kairanga-2	10	7	2	3.5

Details of the paddock history and management for this season are given (Table 2.2) along with the barley yields for 1985/86 season. All sites were sown during October and harvested within a week during early February. The number of years out of grass range from 2 to 10+ years.

Barley yield for the region in 1985/86 season was down by 30 percent on average, due to poor summer weather growing conditions and disease problems (Hampton and Milner, 1986). These eight sites had yields (Table 2.2) above the average of 3.5 tons/ha and some were among the highest in the region.

2.5 Soil Conditions

Factors affecting crop yield, except for the soil conditions were discussed briefly in the previous sections. As far as practicable the variations in all factors except soil type and consequent soil properties were minimized. Some variation eg. management differences, (such as seed-bed preparations, number of years out of grass, or sowing dates) will be indirectly reflected in the soil physical condition, and accounted for when studying the soil physical properties.

Soil conditions depend in an interactive way on soil chemical and physical fertility and biological properties. Biological properties will not be discussed explicitly in this study. A discussion on the soil chemical fertility is included in the following section. The soil physical fertility, which is likely to be the most important parameter distinguishing differences between soil types, will be the focus of the following chapters.

2.5.1 Soil Chemical Fertility

The soil chemical fertility refers to the nutrient status of the soil. There is little doubt that an adequate soil nutrient status is needed to achieve high yields. Cereal crops deplete the soil of nutrients. In the past these crops were rotated with a long period in grazed grass-legume pastures to improve the soil structure and soil nutrient status, particularly nitrogen. However, farmers are now cropping continuously for longer periods and in some cases eliminate permanent pasture altogether from the rotation. To overcome the problem of nutrient depletion by continuous cropping, plant nutrients need to be added. An important part of the management programme of the farmer is maintaining the soil nutrient status at an adequate level for growing crops by applying fertiliser.

There is little information for the Manawatu-Rangitikei region quantifying the effects of nutrient availability on crop yields. Trials in other regions, particularly the South Island have shown the importance of some fertiliser elements. Nitrogen has a substantial effect on cereal crop yields and economic returns. Responses to phosphorus can also occur, but responses to potassium, sulphur and magnesium have not been recorded in New Zealand (Stephen, 1982).

Nitrogen responses depend on the soil nitrogen status and soil moisture during the period of most active growth ie. tillering and grain filling (Stephen, 1982). Soil nitrogen status is decreased by successive cultivation and heavy rain (Ludecke and Tham, 1971). Soil moisture stress will cause poor nitrogen responses and even depressions if stress occurs during tillering. Excessive nitrogen reduces barley quality for malting. For 'Fleet' barley, a grain feed variety, nitrogen content in the grain is not important, but excessive nitrogen will cause extensive lodging (Stephen, 1982) and loss of productivity.

Lime applied at sowing has not produced yield responses possibly because of its relatively slow reaction. It is recommended that barley should be sown on soils with a pH between 5.5 and 6.5 (Claridge, 1972).

The fertiliser programme is determined by the crop requirements; the soil nutrient status, and objective of the farmer ie. to maintain current fertility status. Soil test results (Table 2.3) for the sites, provide information on the soil nutrient status before sowing. This information is useful for calculating fertiliser requirements, provided soil tests are done regularly. The fertiliser applied by the farmer for the season is shown in terms of kg/ha of nitrogen, phosphorus, and potassium (Table 2.4).

Soil nitrogen status and pH are the two most limiting soil chemical properties (Stephen, 1982). The soil test results (Table 2.3) indicate that all sites were within the optimum pH range at the time of sowing. The weather for the season was dry in spring with high summer rainfall. The Department of Agronomy trials indicate that there were no responses to nitrogen fertiliser application above the rates of the farmer for these weather conditions (Withers pers comm., 1986). It can be concluded that for the 1985/86 season, soil chemical fertility on all sites was not likely to be a major variable affecting yield between sites.

Table 2.3 Soil test results (for the top 15cm), showing nutrient status of soils before sowing.

Site	pH	Available N (ug/g)	Ca	K (ppm)	P	Mg
Kiwitea-1	6.2	31	11	5	34	28
Kiwitea-2	6.2	31	11	5	34	28
Marton-1	5.8	31	5	2	30	21
Marton-2	5.5	16	3	3	19	22
Tokomaru-1	6.0	19	5	3	21	22
Tokomaru-2	6.0	19	5	3	21	22
Kairanga-1	6.0	31	5	4	12	19
Kairanga-2	5.7					

Table 2.4 Fertiliser applied by the farmer for the 1985/86 season.

Site	Fertiliser (Kg/ha)		
	N	P	K
Kiwitea-1	25	9	9
Kiwitea-2	25	9	9
Marton-1	27	30	0
Marton-2	25	7	14
Tokomaru-1	15	13	13
Tokomaru-2	15	13	13
Kairanga-1	23	19	19
Kairanga-2	20	11	0

CHAPTER 3

CHAPTER 3

SOIL PHYSICAL FERTILITY

3.1 Introduction

The soil acts as a medium in which water, air, nutrients, and energy are transmitted to seed and plants; thus, soil properties that describe storage and transmisson of these entities are of prime importance. Because plant roots provide contact with the soil, a soil environment and profile conducive to root growth and proliferation are desirable to maximise plant production. The soil provides an environment for seed germination, emergence, and root development. If these physiological processes are restricted crop growth and ultimately potential yield may be reduced. Soil physical fertility refers to this environment which is described by soil physical properties (Fig. 3.1). Soil physical properties directly related to these physiological processes are generally agreed to be soil temperature, strength, aeration, and moisture (Eavis, 1972; Wingate-Hill, 1978; Scott-Russell, 1982; Prihar, 1982; Gales, 1983). Water movement and structure stability are other soil physical properties considered important for this study. The restraint that these physical properties place on root development is of primary concern, as this controls the volume of soil the roots explore to extract nutrients and water.

Ideal soil conditions for plant growth are not necessarily those which lead to maximum proliferation of roots. They are those which permit the shoot system to photosynthesize and develop at the maximum

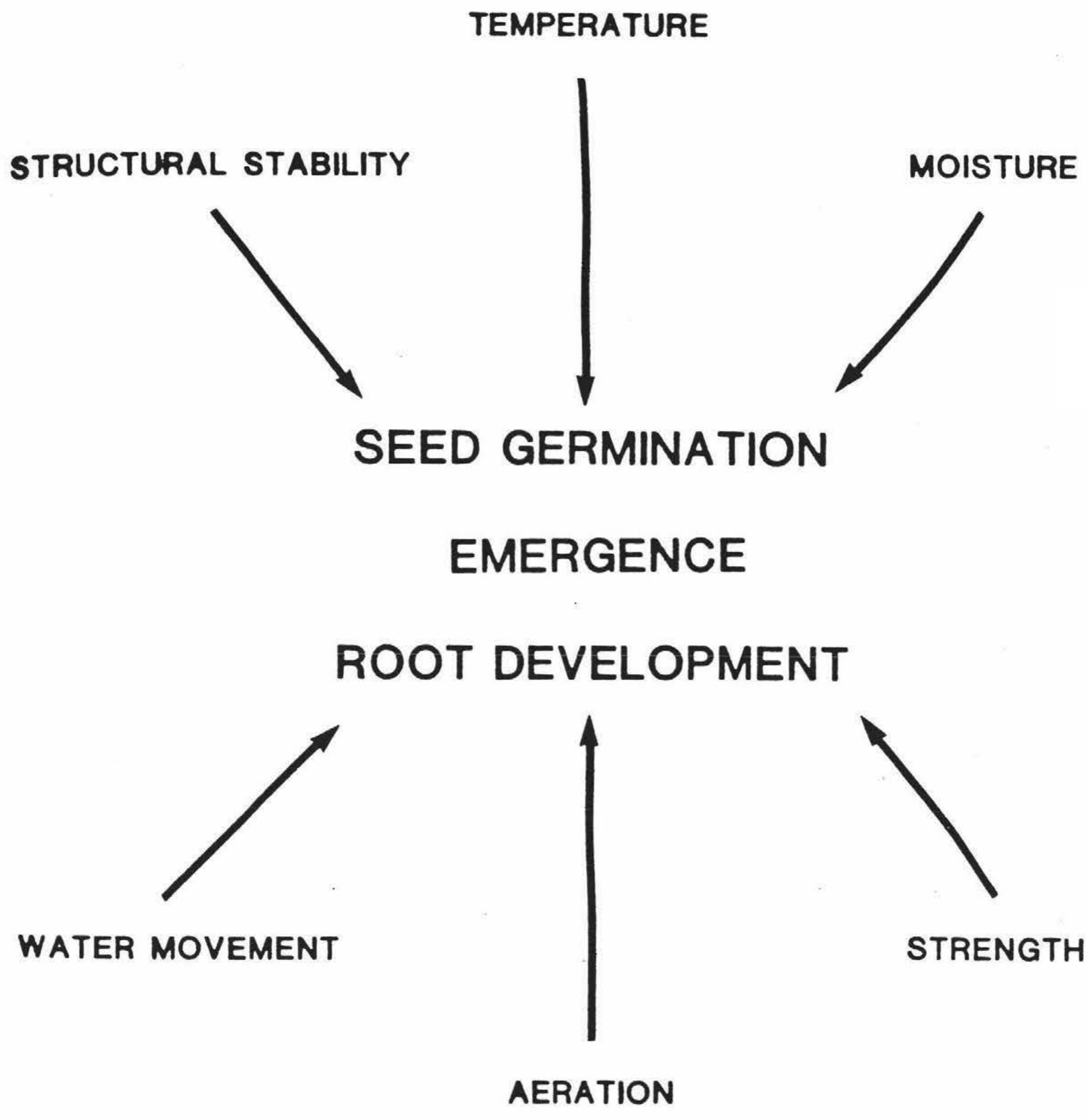


Figure 3.1 Important soil physical properties related to some plant physiological processes.

rate which the aerial environment and genetic factors allow (Scott-Russell, 1982). If the root medium is at a favourable temperature, well aerated and constantly supplied with adequate water and nutrients, other conditions being favourable, very restricted root systems can support considerable shoot growth. Therefore unfavourable soil conditions, especially physical ones which restrict the performance of roots, are a common reason why crop yields are below their potential maximum.

The effect of each soil physical property (Fig. 3.1) on crop yield is well documented. Most published work deals with the effects of each factor singly, correlating it with root growth and yields. It should be noted that although factors are considered singly, they are in fact very closely interrelated. To describe this environment a detailed profile description was made and followed by measurements on the soil packing, porosity, water holding capacity, and water movement. This chapter contains profile descriptions of the eight sites, plus the soil analysis methods and results. Sites were described and sampled immediately after harvesting in February 1986, as access to the trial areas was restricted until then. Following this, is a review of each soil physical property and a discussion on its importance to each of the eight sites. No attempt has been made to correlate yield with these properties because of the difficulty in controlling the interrelationship between factors.

3.2 Methods

3.2.1 Profile Descriptions

Methods of description are those outlined by Taylor and Pohlen (1979), except for horizon designation and terms for soil consistence. Horizon designations follow FAO - UNESCO. methods (FAO - UNESCO, 1974). Soil consistence terms are those of Soil Survey Staff (1981).

3.2.2 Dry Bulk Density

Dry bulk density measurements were made using aluminium coring cylinders, 50mm in diameter and 50mm in length (Fig. 3.2). Four replicate samples were taken at each sampling depth. The sampled soil was shaved off at the ends to equal the core volume, oven dried at 105°C for 24 hours and then weighed. Dry bulk density (ρ_B) was calculated as the oven-dry mass of soil (M_S) divided by the sample volume (V_T).

$$\rho_B = M_S / V_T \qquad (3.1)$$

Figure 3.2 Plate showing large, medium, and small cores used for sampling the soil to measure saturated hydraulic conductivity, bulk density, and soil water retention respectively.

3.2.3 Particle Density

Air dried, <2mm soil fraction was used for the analysis. The gravimetric water content of the air dried sample was calculated so that the oven dried mass of soil added to the pyconmeter bottle was known. Soil and water in the pyconmeter bottle was vacuated for 1 hour, and then the bottle topped up with water to a known volume. The volume of soil (V_s) was calculated by the difference in mass between;

$$V_s = (\text{bot.} + \text{wat.}) - [(\text{bot.} + \text{wat.} + \text{soil}) - (\text{air dried soil mass})]. \quad (3.2)$$

Particle density (ρ_s) is the mass of soil (M_s) over the volume of soil (V_s).

$$\rho_s = M_s / V_s \tag{3.3}$$

3.2.4 Saturated Hydraulic Conductivity

The method used to measure saturated hydraulic conductivity is the same as that used by McAuliffe (1985). Four undisturbed soil samples were obtained at each sampling depth, using aluminium cores, 75mm diameter and 180mm length (Fig. 3.2). The core was pressed into the soil about 50-70mm. The top surface of the soil had been picked back with a knife and the core was removed by tearing the sample away from the underlying soil. This avoids surface smearing.

The cores were placed on a wire mesh grid. Water was ponded on the core surface, ensuring the surface was protected against direct water impact. Once a steady flow rate was reached, measurement of saturated hydraulic would commence. It is desirable to maintain a constant ponded depth of water and in most cases this was possible. The flow rate was calculated from the time taken for a known volume of water to flow through the core. Darcy's law was then used to calculate saturated hydraulic conductivity (K_s) from the measured flow rate.

$$K_s = (Q / A) [L / (L + H)] \tag{3.4}$$

where Q is the flow rate (m^3 sec^{-1})

A is the area of the core surface (m^2)

L is the length of soil (m)

H is the height of ponded water (m).

3.2.5 Water Retention Characteristics

Haines and pressure plate apparatus were used to determine the water retentivity of the soil at specific pressure potentials.

Haines apparatus was used to find the gravimetric water content at -0.05 bar (and -0.1 bar for Kairanga-1 site) pressure potentials. At these high pressure potentials, structural properties of the soil have a marked impact on the water retention characteristics. Therefore "undisturbed" cores 50mm in diameter and 20mm in length were used (Fig. 3.2). Duplicate cores at each sampling depth were saturated in Haines' apparatus, brought to equilibrium at 50cm suction (-0.05 bars), then the samples were weighed, oven dried at 105°C and reweighed 24 hours later. The gravimetric water content (ω) was calculated as the mass of water in the soil (M_w) divided by the oven dried mass of soil (M_s).

$$\omega = M_w \;/\; M_s \qquad (3.5)$$

Duplicate gravimetric water content measurements were made at -1 and -15 bars using the pressure plate apparatus. Small aggregates (ie. disturbed samples) were used. At these pressure potentials the influence of soil structure is negligible, texture and organic matter content have a stronger influence on the water held. The samples were saturated, pressure applied for about seven days until equilibriation occurred, then weighed, oven dried, and reweighed. Gravimetric water content was then calculated.

At each pressure potential the soil volumetric water content (θ) retained is calculated as;

$$\theta = \omega \rho_B / \rho_W \tag{3.6}$$

where ρ_B and ρ_W are dry bulk density and water density respectively.

3.2.6 Total Carbon

A Leco Automatic Analyzer was used to measure total carbon. Calcium carbonate and a soil sample with a known total carbon content were used as standards. Triplicate soil samples of the <2mm air dried soil fraction were analysed for each topsoil.

3.2.7 Root Mass

Root mass measurements were made on the four soil core samples collected at each depth for saturated hydraulic conductivity measurements. Once the saturated hydraulic conductivity measurements had been determined, the samples were soaked separately and then soil particles removed by washing the roots. The roots were dried at 60°C for 24 hours and weighed. To maximise the number of roots sampled, cores were taken directly under the crop rows.

3.3 Results

3.3.1 Soil Profile Descriptions

A brief profile description, an outline of the parent material and physiographic position is included in this section. The soils have been correlated and named after the appropriate soil type described in New Zealand Soil Bureau Publications. For a detailed profile description and location of each site see Appendix A.

3.3.1.1 Kiwitea mottled silt loam

The Kiwitea mottled silt loam is an intergrade between the Yellow-brown Earth and Yellow-brown Loam soils (Campbell, 1979). This soil is found on dissected old high terraces, and has developed in quartzo-feldspathic loess, with some volcanic ash. The soil is moderately well drained, with a friable, silt loam topsoil, and a mottled, compacted, clayey subsoil horizon (Fig. 3.3 and Fig. 3.4).

3.3.1.2 Marton silt loam

The Marton silt loam is a Yellow-Grey Earth (Campbell,1979). It is formed in thin deposits of fine textured loess occurring on the flat to rolling tops of the dissected high terraces. The loess is of dominantly quartzo-feldspathic composition, with some volcanic ash (Aokautere Ash). The soil is imperfectly to poorly drained. The topsoil is a dark greyish brown silt loam, with moderately developed nut structure and light grey AB horizon with iron-manganese concretions. The B horizon is a light grey clay with many brown mottles, concretions and strongly developed blocky structure. Clay coatings are strongly developed in the B horizon. Below this horizon, horizontal and vertical grey veining is found (Fig. 3.5 and Fig. 3.6).

3.3.1.3 Tokomaru silt loam

The Tokomaru silt loam is a Yellow-Grey Earth soil (Cowie, 1978). It is formed in thick deposits of silty textured loess on the high terraces. The Tokomaru soil is generally found on flatter, less dissected surfaces than the Marton soil. The Aokautere Ash is found in this soil, but at greater depths than the Marton (≈2m). The Tokomaru soil is imperfectly to poorly drained. It has a dark greyish brown silt loam A horizon on an olive grey, firm, silty clay loam B horizon with abundant yellowish brown mottles and moderate development of clay coatings. Beginning about 70cm is a well developed fragipan with vertical grey veining (Fig. 3.7 and Fig. 3.8).

3.3.1.4 Kairanga silt loam

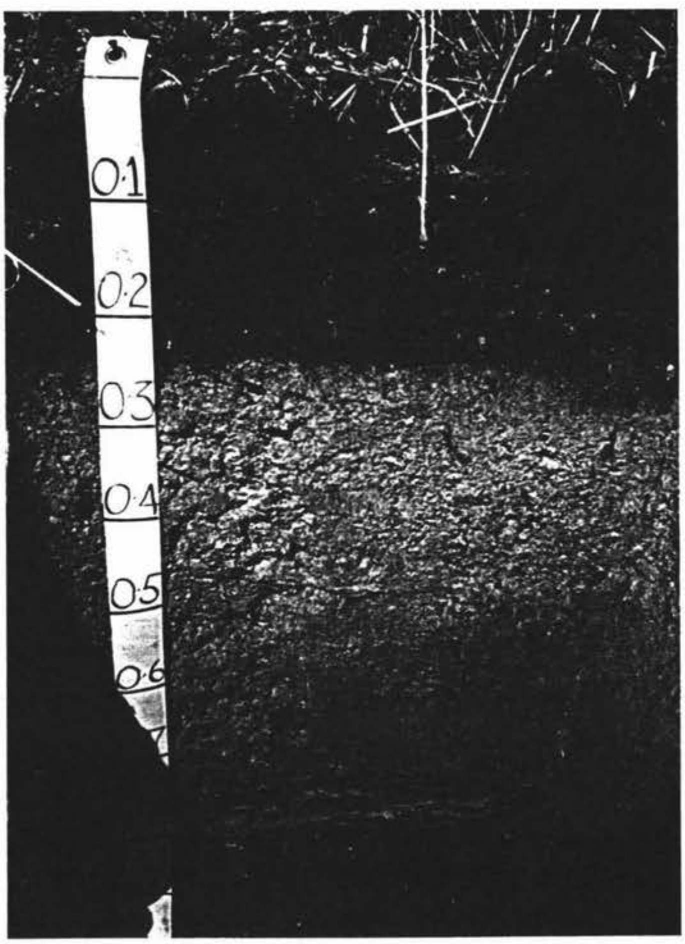
The Kairanga silt loam is a Gley-Recent soil (Cowie, 1978). It is developed in recently deposited quartzo-feldspathic river alluvium. It is found on the backslopes of levees on the low terrace where the drainage is poor and flooding is infrequent. It has a distinct silt loam A horizon overlying a grey B horizon of variable texture with few to many brown mottles (Fig. 3.9 and 3.10).

Kivitea mottled silt loam (Kiw-1) Figure 3.3

Ap	0-17cm	Dark grey; silt loam; weakly developed nut structure; very friable.
AB	17-20cm	Yellowish brown and grey; silty clay loam; weakly developed nut structure; friable.
Bv	20-34cm	Yellowish brown; silty clay loam; weakly developed blocky structure; friable.
Bg	34-130cm	Yellowish brown; clay; abundant light yellowish brown mottles; massive structure; firm; black, brittle concretions below 85cm.
Cg	130-135^{+}cm	Grey; silty clay; massive structure; firm.

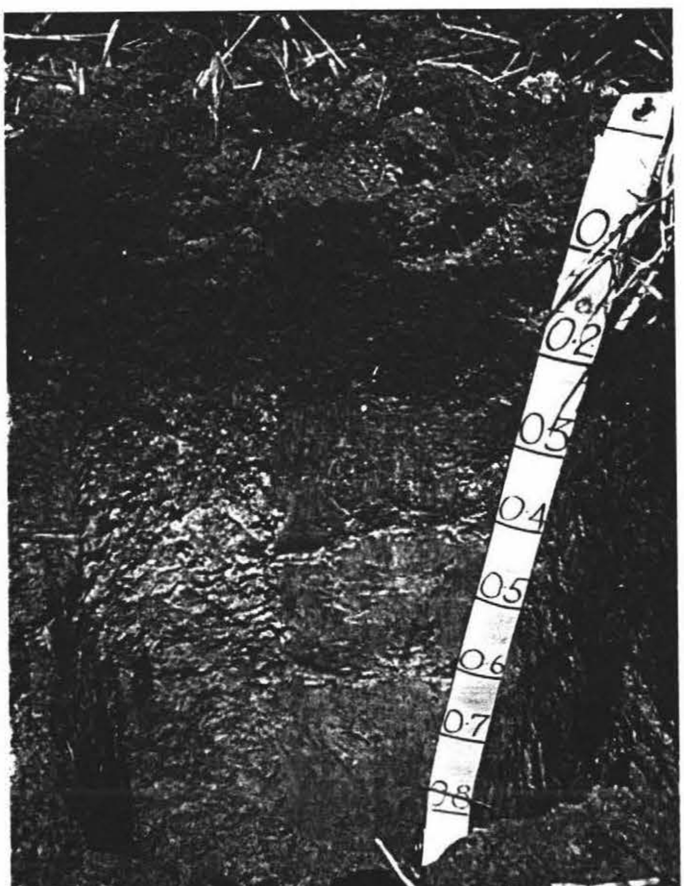
Kivitea mottled silt loam (Kiw-2) Figure 3.4

Ap	0-23cm	Very dark brown; silt loam; weakly developed nut and fragment structure; friable.
ABc	23-26cm	Light brownish grey and very dark brown; silt loam; weakly developed blocky structure; firm; hard, black concretions.
Bgc	26-42cm	Light brownish grey; gritty silt loam; weakly developed nut and fragment structure; firm; hard, black concretions.
Bg	42-73cm	Pinkish grey; silty clay loam; many light brownish grey mottles; massive structure; firm; concretions.
C	73-83^{+}cm	Strongly weathered brittle sandstone.



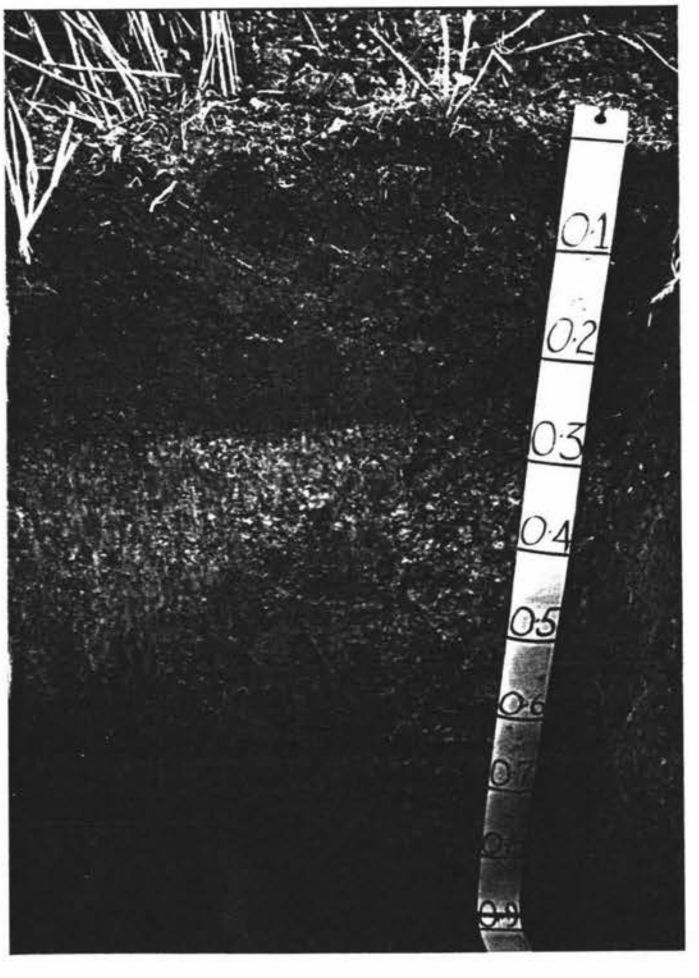
Marton silt loam (Mar-1) Figure 3.5

Ap	0-22cm	Very dark greyish brown; silt loam; moderately developed nut and fragment structure; friable.
ABg	22-25cm	Colours mixture of above and below; silty clay; few organic dark brown mottles; moderately developed blocky structure; firm; few black concretions.
Bg1	25-57cm	Strong brown; Clay; profuse light grey mottles; strongly developed block structure; common black organic coatings and concretions.
2C	57-62cm	Light grey; silty clay; abundant strong brown mottles; massive structure; very firm; (Aokautere Ash).
Bg2	62-90cm	Light grey; clay; abundant strong brown mottles; massive structure; very firm; common black organic and/or Fe/Mn coatings.
uABg	90-110$^+$cm	Yellowish brown; clay; profuse grey mottles; massive structure; very firm; common, black concretions.



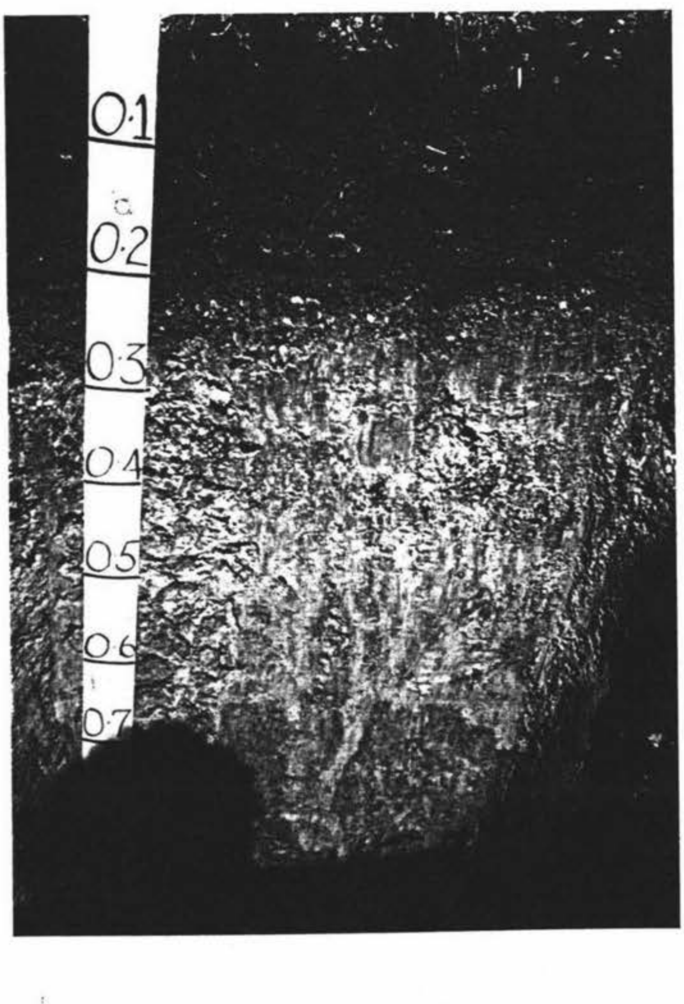
Marton silt loam (Mar-2) Figure 3.6

Ap	0-24cm	very dark greyish brown; silt loam; moderately developed nut and fragment structure; friable.
ABg	24-27cm	Yellowish brown, very dark greyish brown, and grey; silty clay loam; weakly developed blocky structure; friable.
Bg1	27-52cm	Light brownish grey; silty clay; abundant yellowish brown mottles; massive structure; firm; hard, very dark brown concretions.
Bg2	52-110cm	light brownish grey; silty clay; abundant yellow brown mottles; massive structure; firm.
Cg	110-120^{+}cm	same as above but a clay loam texture.



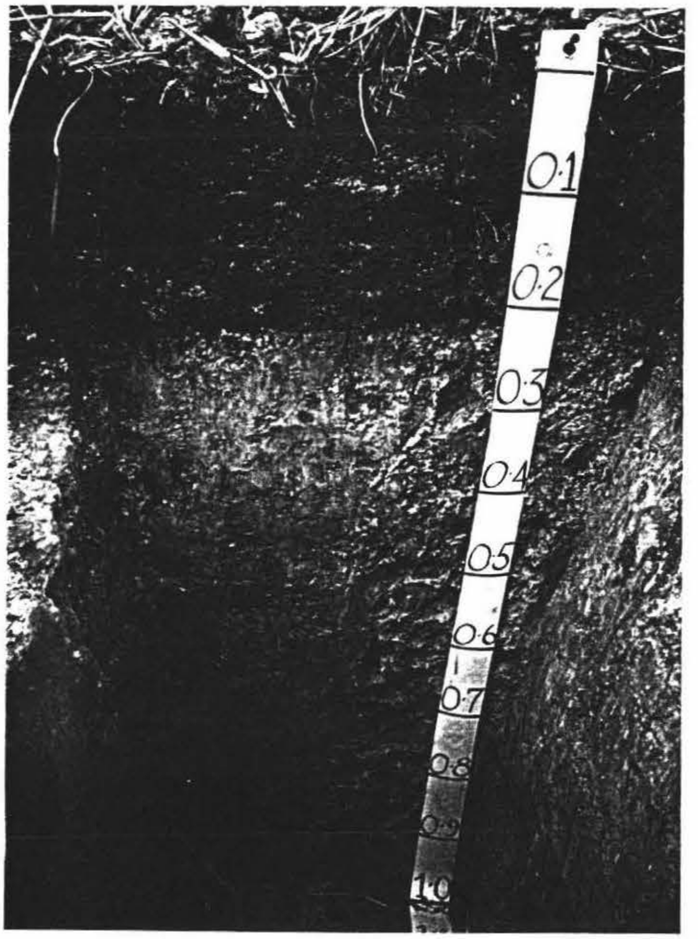
Tokomaru silt loam (Tok-1) Figure 3.7

Ap	0-20cm	Very dark greyish brown; silt loam; weakly developed blocky structure; friable.
ABgc	20-26cm	Light brownish grey and very dark greyish brown; silt loam; abundant brownish yellow mottles; weakly developed blocky structure; friable; hard concretions.
Bg	26-53cm	Light olive grey; silty clay; grey humus coatings down cracks; abundant brownish yellow mottles; massive structure; firm.
Btg	53-73cm	Light olive grey; silty clay; grey hūmus coatings down channels; profuse brownish yellow mottles; massive structure; firm.
Cxg	73-100^{+}cm	Light olive grey; silty clay loam; grey humus coatings down cracks between prisms; brownish yellow prism colour; weakly developed prismatic structure; firm.



Tokomaru silt loam (Tok-2) Figure 3.8

Ap	0-20cm	Very dark greyish brown; silt loam; weakly developed block structure; friable.
ABgc	20-27cm	Very dark greyish brown and grey; gravelly silty clay loam; abundant yellowish brown mottles; massive structure; friable; brittle, black concretions.
Bg	27-48cm	Grey; silty clay; profuse yellowish brown mottles; massive structure; firm; hard, black concretions.
Btg	48-68cm	Light olive grey; clay; grey material washed down vertical cracks; abundant yellowish brown mottles; massive structure; firm.
Cxg	68-94^{+}cm	Greyish brown prism colour; silty clay loam; greyish brown material down cracks; abundant yellowish brown mottles; massive structure; firm.

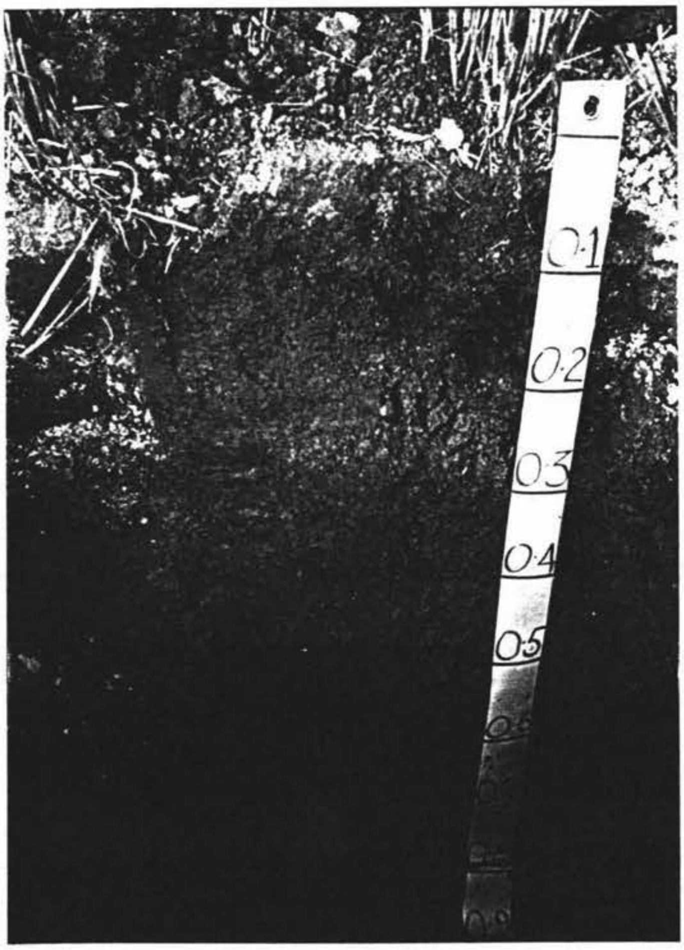


Kairanga silt loam (Kai-1) Figure 3.9

Ap	0-21cm	Brown; loam; moderately developed blocky structure; very friable.
Bgc	21-31cm	Grey; loam; abundant strong brown mottles; massive structure; very friable; very dark brown soft concretions.
Bg	31-77cm	Strong greyish brown; fine sandy loam; abundant dark yellowish brown mottles; massive structure; friable.
Cg	77-110^{+}cm	Grey; fine sandy loam; abundant dark yellowish brown mottles; massive; firm; alternating layers of sandy loam and fine sandy loam.

<u>Kairanga silt loam</u> (Kai-2) Figure 3.10

Ap	0-20cm	Dark greyish brown; silt loam; moderately developed fragment structure; friable.
ABg	20-28cm	Greyish brown and dark greyish brown; silt loam; abundant yellowish brown mottles; weakly developed blocky structure; firm; pronounced mixing and tounging of topsoil into subsoil.
Bgr	28-65cm	Greyish brown; silty clay; abundant yellowish brown mottles; massive structure; firm.
Brg	65-100^{+}cm	Greyish brown; silty clay; abundant yellowish brown mottles; massive; firm.



3.3.2 Dry Bulk Density

Dry bulk density gives a measure of the soil packing.

The average dry bulk density is plotted as a function of depth for the eight profiles in Fig. 3.11. Each soil pair for the Kiwitea, and Tokomaru silt loams follows a similar profile form for most of the soil depth. The Marton soil pair differs in the subsoil where a lower bulk density (1.27 Mg-m^3) occurs in Marton-1 due to the Aokautere Ash. The Kairanga-2 bulk density is distinctly lighter than Kairanga-1 throughout the profile. For all soils there is a marked bulk density increase between topsoil and subsoil horizons. This is particularly noticeable in the Tokomaru soils which have a very high subsoil bulk density (1.7 Mg-m^{-3}).

To facilitate comparisons within and between soil types, average bulk density at selected positions in the soil profiles are graphed along with the 5% and 1% least significant differences (Fig. 3.12). The Kairanga-1 soil has a higher bulk density at all profile positions than Kairanga-2, this difference is highly significant ($P<0.01$). For the other three soils there is no significant difference in the topsoil and upper subsoil depth (30cm) within each soil type pair. At the lower subsoil depth (70cm) the mean difference between the Kiwitea pair of soils is highly significant ($P<0.01$), as is the Marton pair, and the Tokomaru subsoils are significant ($P<0.05$).

The Marton and Tokomaru topsoil bulk densities are similar, but the Tokomaru subsoil is significantly ($P<0.01$) more compact. Kiwitea

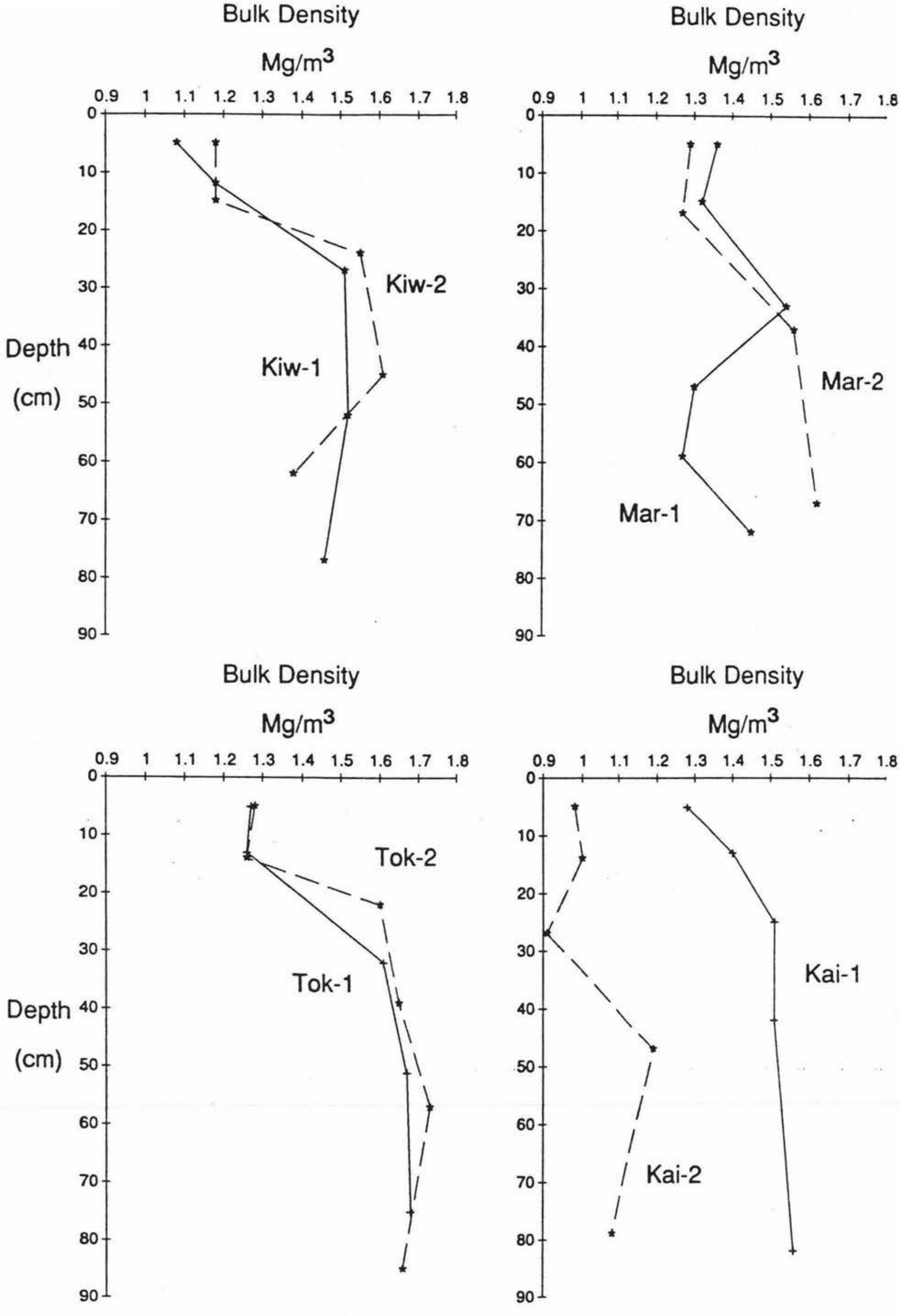


Figure 3.11 Average bulk density plotted against depth for the eight profiles. Points indicate approximate sampling position.

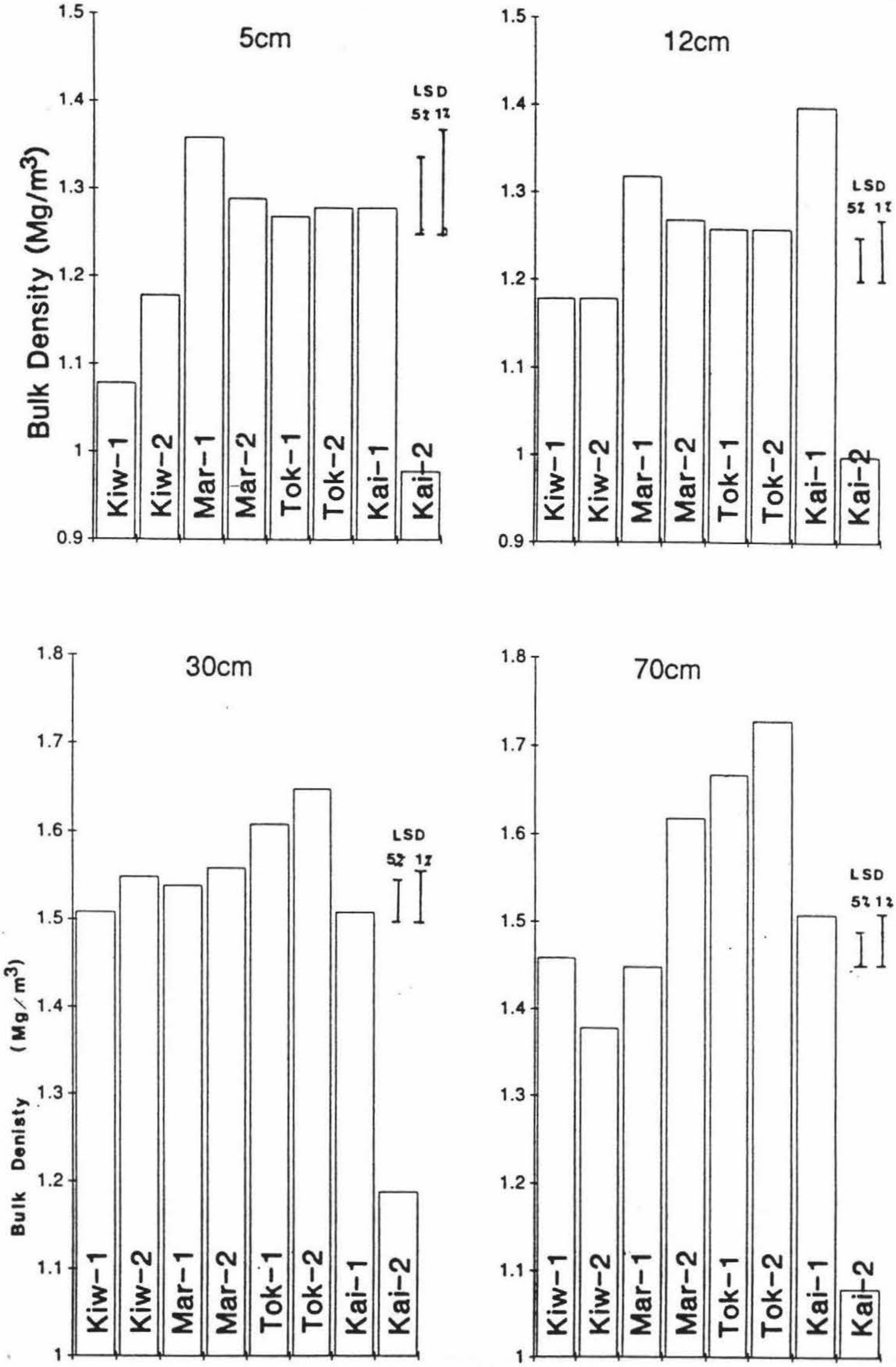


Figure 3.12 Bar graphs showing the corresponding horizon bulk density at selected depths in the soil profiles. Least significant difference at the 1% and 5% levels.

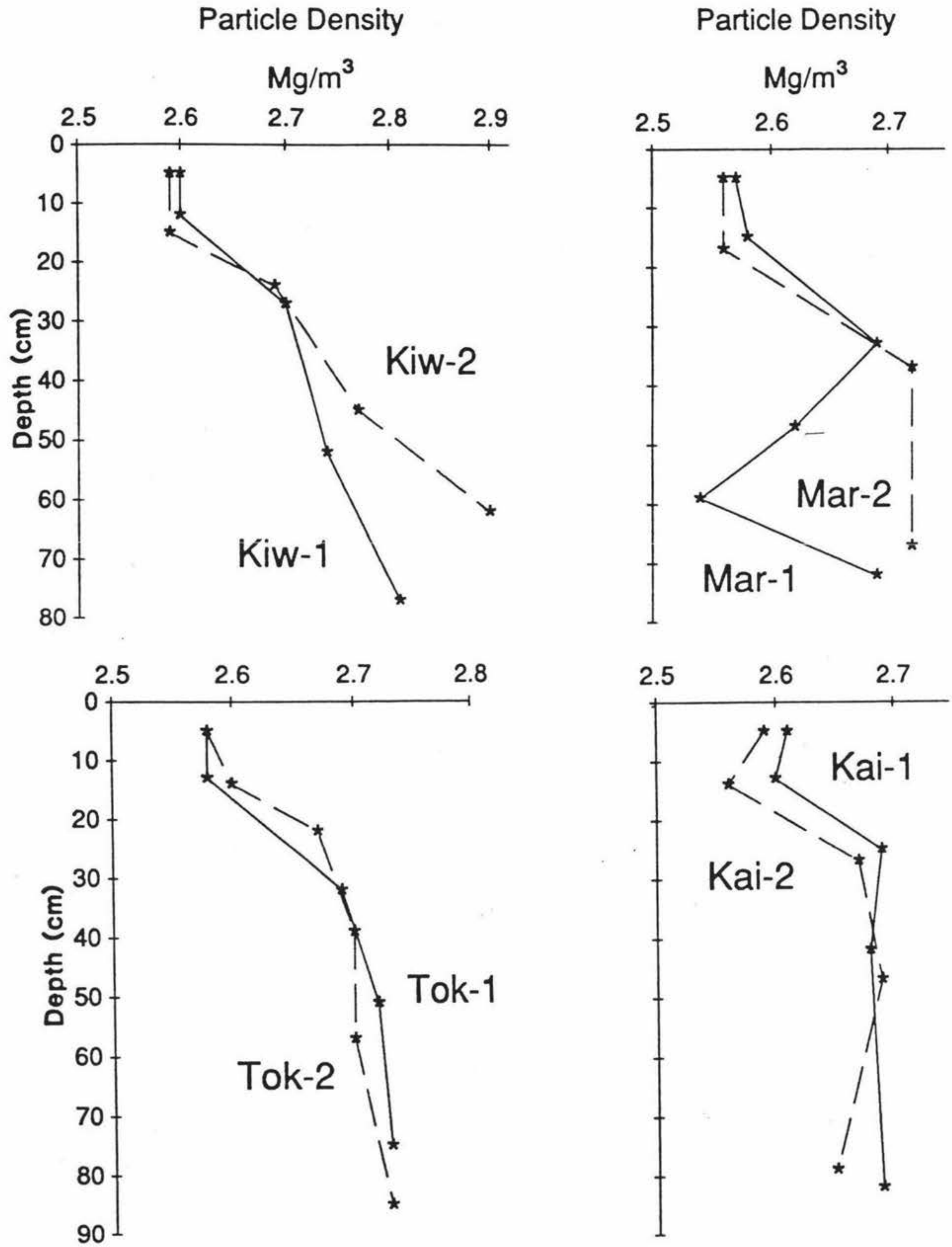
soils have a significantly ($P<0.01$) lower topsoil bulk density than the Marton and Tokomaru soils, and their subsoils are also less dense at depth. The Kairanga-2 soil bulk density is low compared to all the other profiles, and the difference is highly significant ($P<0.01$).

3.3.3 Particle Density

Particle density is a measure of the density of the soil particles. It was measured so that using dry bulk density data, total porosity could be determined. The profile forms of particle density (Fig. 3.13) are similar for all soils. Lower values are recorded in the topsoil due to the higher organic matter content, and in the Marton-1 2C horizon (57-62cm) due to the Aokautere Ash.

3.3.4 Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (K_s) is a measure of the soil permeability. It is the rate that water will flow through an area of saturated soil. The core method was used to provide an assessment of the relative permeability between horizons. The method does give artifically high K_s values, especially in horizons where continuous macropores are present. Although this does indicate unimpeded vertical flow at that depth (McAuliffe, 1985).



<u>Figure 3.13</u> Particle density plotted against depth. Points indicate approximate sampling position.

The range of saturated hydraulic conductivity values for each sampled depth are presented in Fig. 3.14. The permeability of the topsoil is 1 and 2 orders of magnitude greater than in the subsoil, for all soils. All profiles have a subsoil horizon where permeability is impeding to vertical drainage. For the two Kairanga soils this horizon has a slow-moderate permeability, and for the other soils a very slow permeability (Griffiths, 1985; Table 14).

3.3.5 Water Retention Characteristics

Soil water retention is a measure of the water held within the soil matrix by adsorption at surfaces of particles and by capillarity in the pore spaces. This property has is important in determining the soil water storage. The effect of pore spaces on water retention allows the retentivity curves to be interpreted to give the soil pore size distribution. The lower the matric potential the smaller the pore diameter that water will be drained from. The profiles for water held at matric pressure potentials of -0.05, -1, and -15bar, and the total soil porosity are shown in Figures 3.15a and 3.15b. Total porosity is calculated from the bulk density and particle density data. The standard deviation bars calculated from the bulk density data are shown on the total porosity profiles.

The area between the total porosity and -0.05bar profiles show the large pore spaces, ie. those greater than 0.06mm diameter. The volume of these pores is small (<10%) in all the soils, except for Kairanga

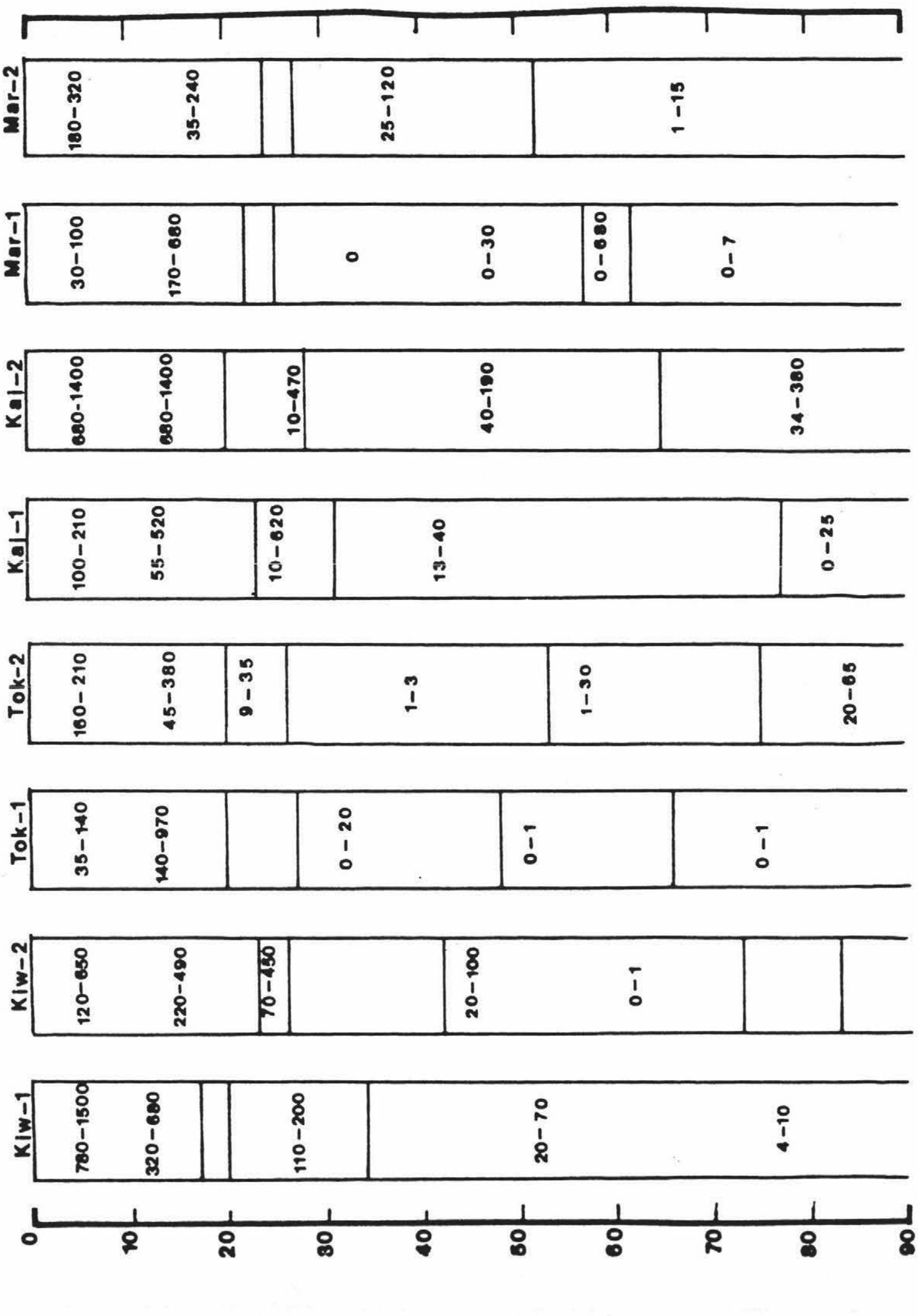


Figure 3.14 The range of saturated hydraulic conductivity (Ks) values at sampled depths for each site (values are in mm/hr).

and Kiwitea topsoils. The volume is particularly small in the subsoils, especially for the Marton and Tokomaru soils.

The water held in the Kiwitea soils increases towards the base of the profile. This corresponds to a decrease in bulk density and increase in particle density near the subsoil/weathered sandstone contact.

The Marton soils differ only in the effect that the Aokautere Ash (57-62cm) has on the lower subsoil of the Marton-1 site. At this depth bulk density is lower than in the Marton-2 site, affecting the pore size distribution.

There is no obvious differences between the two Tokomaru soils.

The Kairanga-1 soil retains little water at the low (-15 and -1 bar) matric potentials compared to all other sites. This difference is due mainly to the influence of soil texture. The Kairanga-1 site has a sandy-loam subsoil whereas all other sites are silty clay loam to clay. An extra water retentivity profile at -0.1 bars is included for this soil, as the differences in water retentivity is greater for this soil than any others. The Kairanga-2 soil water retentivity profiles are at relatively high water contents compared to all other sites. The ABg horizon (20-28cm) is prominent, presumably because of a high organic matter content. Kairanga soils in the vicinity contained buried organic horizons at this level.

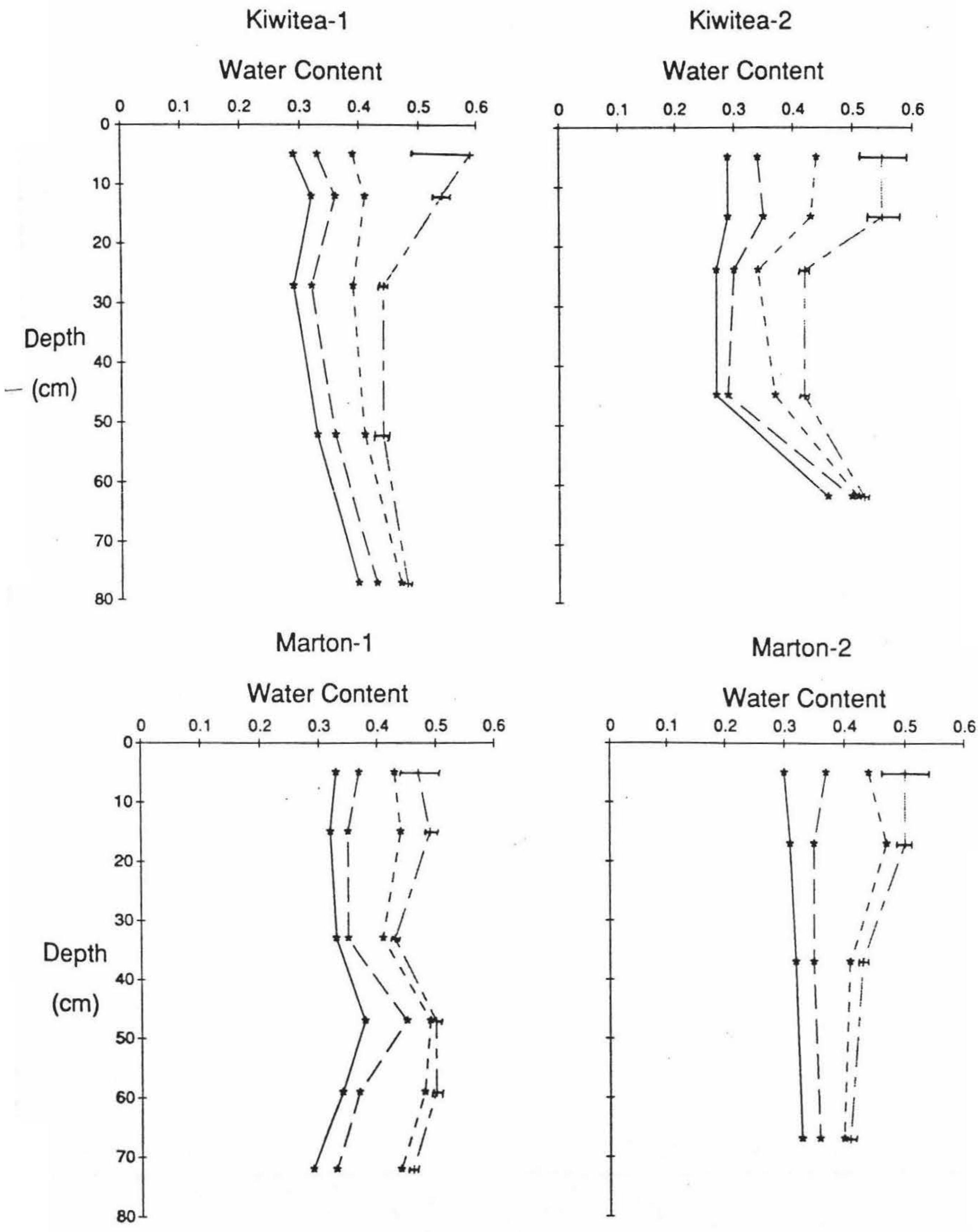
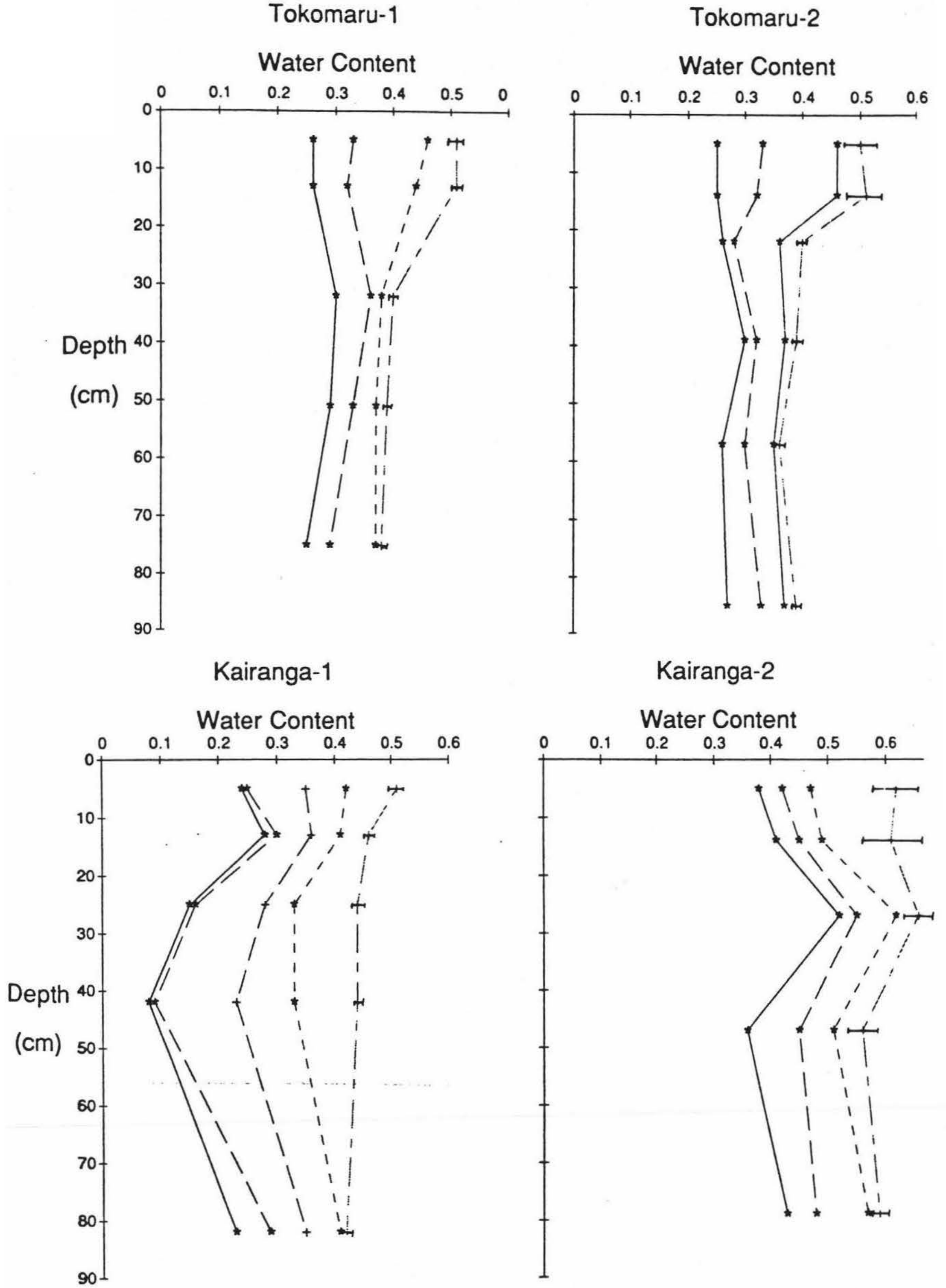


Figure 3.15a Soil water retentivity profiles (Volumetric Water Content versus Depth) for -15 bars (*—*), -1 bar (*—*), -0.05 bar (*--*), and total porosity (*-·*), measured for the Kiwitea and Marton soils. Standard deviation bars shown on total porosity points.



<u>Figure 3.15b</u> Soil water retentivity profiles (Volumetric Water Content versus Depth) for -15 bars (*—*), -1 bar (*— *), -0.1 bar (*--*), -0.05 bar (*—*), and total porosity (* *), measured for the Tokomaru and Kairanga soils. Standard deviation bars shown on total porosity points.

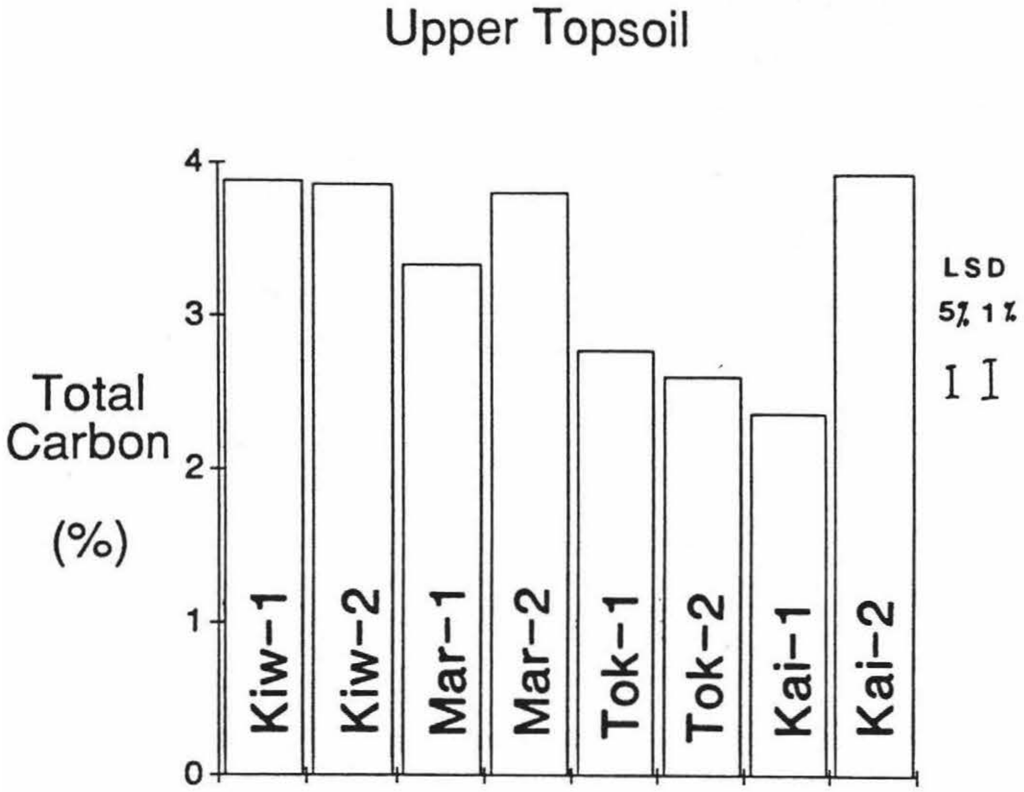
3.3.6 Total Carbon

Total carbon is used as a measure of the organic matter in the soil, since organic matter is 1.72 * %O.C.. Standards indicated that recovery of carbon was about 96%. The topsoil values for each site are shown in Fig. 3.16.

In the upper topsoil the Kiwitea soil pair has similar values, as does the Tokomaru pair of soils. The difference in the lower topsoil values within these two soil pairs are just significant ($P<0.05$). This similarity between the two soils within each pair was expected as each soil pair was sampled within the same paddock where management conditions would have been the same.

Within each of the Marton and Kairanga soil pairs, the differences are highly significant ($P<0.01$) at both depths. Kairanga-1 topsoil has lower values than Kairanga-2. This would probably be due to the number of years of continuous cropping, 10 years and 2 years respectively.

The lowest carbon values are recorded in Kairanga and both Tokomaru soils. These soils had been continually cropped for the longest period (10 years) of the eight soils.



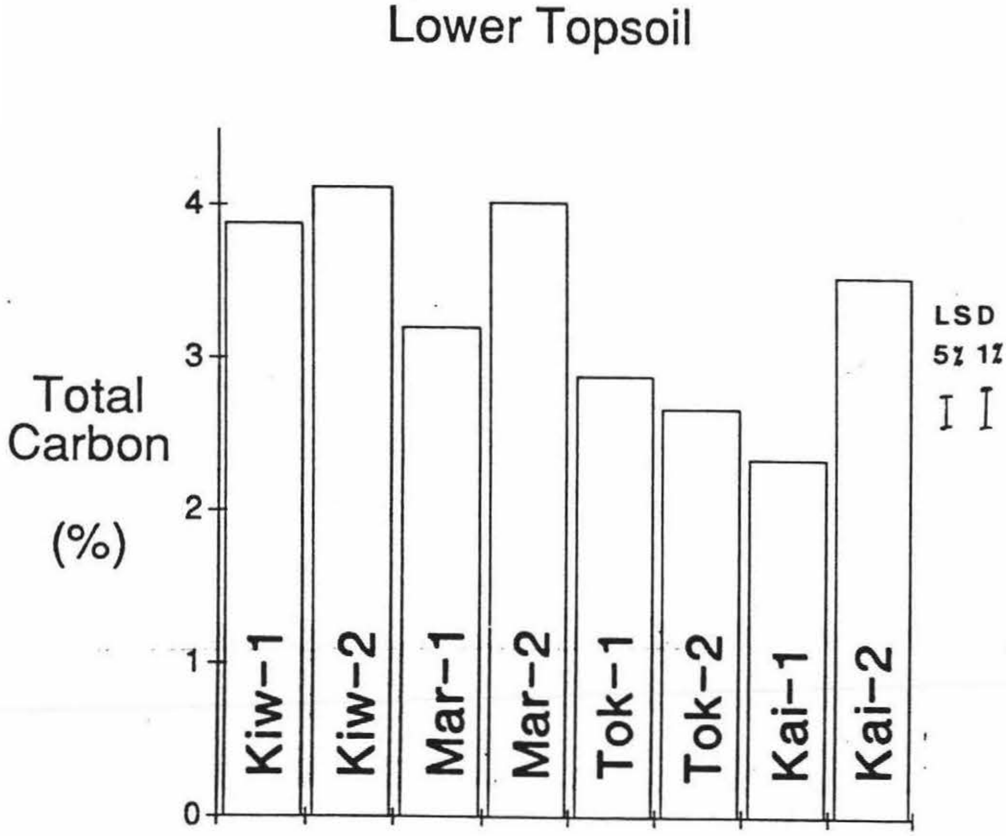


Figure 3.16 Total carbon percentage for the two topsoil sample depths. Least significant difference at 1% and 5% levels.

3.3.7 Root Mass

Root mass measurements were made to indicate the root distribution down the profile. The root mass for the topsoil horizons are low compared to other barley root measurements (Day et al, 1981). The low values for root mass would probably be due to the poor recovery of roots from cores rather than a low root density at these sites. Great difficulty was encountered in washing the soil particles away from the roots, especially for the clayey horizons. The trend otherwise is similar to other root mass measurements, with root mass decreasing quickly with depth (Fig. 3.17).

Each pair of soils has a similar profile form, except the Kairanga soil pair, which differs significantly ($P<0.01$) in the topsoil.

All the sites follow a similar profile form, with most of the roots occurring in the top 20-30cm. At this depth the transitional AB horizon occurs, and the root mass decreases rapidly to the low values in the subsoil. The low root mass recorded in the subsoil is supported by field profile observations (Appendix A). In the compacted subsoils the roots were few and fine, and more often observed in fissures rather than penetrating the soil peds.

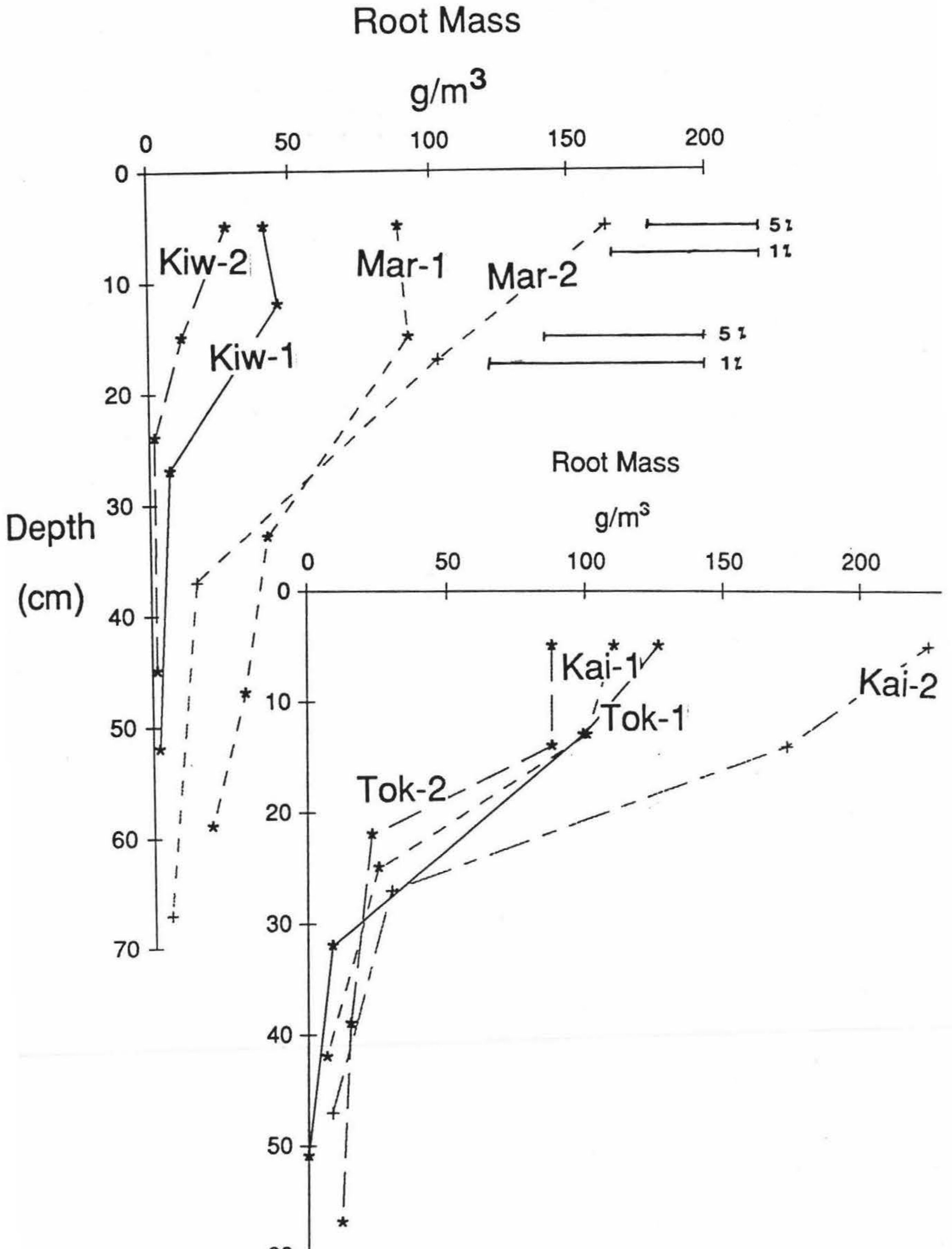


Figure 3.17 Root weight ($g\text{-}m^{-3}$) distribution measured down the profile for the eight soils. Least significant difference at the 1% and 5% levels.

3.3.8 Summary of Results

The results can be summarised as follows:

i) There is little difference between soils within each pair of the Kiwitea, and Tokomaru soils. The Marton soils differ slightly because of the presence of Aokautere Ash in Marton-1. The similarity within each soil type is visually observed in the field and supported by the soil physical property data presented. The pair of Kairanga soils differ significantly.

ii) The Kairanga soils, although mapped as the same soil type (Cowie, 1978) have distinctly different subsoils. The Kairanga-1 subsoil has alternating layers of massive, friable, sandy loam and fine sandy loam texture, whereas Kairanga-2 is a firm, silty clay. The Kairanga-1 soil has a higher bulk density, retains little water at the low matric potentials, leading to a large difference in water retention between total porosity and the low matric pressure potential, than Kairanga-2 site.

iii) The Kiwitea soils have slightly better drainage, a more strongly developed topsoil structure, a higher carbon content and a more porous topsoil (>10% large pores) than the Tokomaru and Marton soils.

iv) The Tokomaru and Marton soils are similar except that the Tokomaru has a higher bulk density (1.7 $Mg\text{-}m^{-3}$), a well developed fragipan and greater depth to the Aokautere Ash. The Marton soil has a heavier textured subsoil with greater development of clay coatings and more well developed block structure.

v) Visually there is little difference between three of the soil types, ie. between the Kiwitea, Marton and Tokomaru soils. They have a friable, silt loam topsoil on a mottled clay loam - silty clay loam, firm subsoil. Most of the soil physical properties are not markedly different between these soil types. Subsoil bulk densities are high (1.5-1.7 $Mg\text{-}m^{-3}$). Saturated hydraulic conductivity indicates vertical water flow in these subsoils is restricted (20 mm/hr). Soil water retention characteristics follow similar trends, and indicate that the percentage of macropores in the subsoil is small (<5%).

vi) The Kairanga-1 and Kairanga-2 profiles are significantly different from the other soil types. Both subsoils are more permeable, Kairanga-1 has a wider water retention range and Kairanga-2 has a significantly lower bulk density throughout the profile (maximum of 1.2 $Mg\text{-}m^{-3}$) than all other soils.

vii) At the base of the topsoil a layer of concretions and mottles was observed in all sites. This zone corresponds to just below the plough depth, where there is a marked increase in bulk density and the saturated hydraulic conductivity decrease by 1 or 2 orders of magnitude. Below this depth (20-30 cm) the mass of roots becomes very small. Very few roots reach the maximum observed rooting depth at about 70cm for each soil.

3.4 Review of Soil Physical Properties and Discussion of Results

3.4.1 Soil Temperature

Hagan (1952) extensively reviews the effect of temperature on specific aspects of crop growth and root physiology. An increase in temperature within certain limits will speed up cell division, root elongation and root metabolic functions. If soil temperature deviates from the "optimal" range, crop growth and potential yield will be restricted.

The temperature of a soil volume is dependent on the radiation balance at the soil surface, soil heat flux, and soil water flux. The soil derives its heat almost entirely from the sun and loses much of it by radiation back into the sky. The heat may be transferred into the soil as sensible heat by conduction, or as latent heat by radiation. Conduction is the principal method (Kirkham and Powers, 1972).

Most detailed soil temperature study is based on plant growth trials where temperature is kept constant. In the field, soil temperatures are characterised by a diurnal temperature wave. The alternating soil temperatures have a quite different affect on crop growth than constant soil temperatures. Therefore an average of the diurnal temperature, does not result in an averaged behaviour (Walker, 1970) based on constant temperature trials. However, until more is known about the effects of diurnal temperatures on plant performance, averaged daily temperature is treated as having the same effect as a constant temperature.

Seed germination, emergence and early plant growth of crops are closely related to temperature. A temperature at optimum will encourage a rapid germination rate. At a temperature slightly lower than optimum of about 8 to 15° C (Wingate-Hill, 1978) a more complete germination and stronger plants develop. The rate of root elongation increases with temperature to an optimum and then falls rapidly as temperature rises further. Optimum root elongation occurs at about 20°C (Russell, 1973), though roots can grow actively at lower temperatures.

Apart from the effects on germination and root elongation, soil temperature significantly affects certain functions of roots that are important for crop growth. Such functions are the absorption rate of water and nutrients by roots and the root respiration rate, these increase with temperature. Also the occurrence and severity of some soil and seed borne diseases that seriously impair plant growth are related to soil temperature.

Direct measurements were not made for soil temperature at the sites. Average monthly data from nearby meterological stations were used (Table 3.1). These stations occur at either end of the region. The variation in soil temperature across the region is not great,

Table 3.1 Monthly long-term soil temperature averages and monthly soil temperature averages for the 1985-86 season. Soil temperature data is for 10cm and 30cm depth, at Marton and Kairanga Meterological Stations (N.Z. Met. Serv., 1981).

		Average Soil Temperature (°C)						
		Aug	Sept	Oct	Nov	Dec	Jan	Feb
Marton								
1947-66	at 10cm depth	6.8	9.1	11.9	14.4	16.8	17.9	17.7
1985-86	at 10cm depth	6.7	9.3	12.0	14.6	17.5	19.6	18.5
Kairanga								
1970-80	at 10cm depth	7.2	9.6	12.3	14.5	16.9	18.4	17.7
1970-80	at 30cm depth	9.4	11.4	13.4	15.7	18.1	19.7	19.6
1985-86	at 10cm depth	6.8	9.8	12.5	14.8	18.6	20.2	18.3
1985-86	at 30cm depth	9.4	11.7	14.0	16.7	20.2	22.0	20.9

as shown by the long-term average temperature at 10cm depth (N.Z. Meterological Service, 1981). Although the stations are not necessarily on the same soil type, at similar moisture conditions and similar leaf area cover, the small variation in soil temperature between stations and sites would be of little consequence to crop growth.

Monthly soil temperatures for the 1985-86 season at the Kairanga and Marton stations are above the summary averages. At a depth of 10 cm the average soil temperature for sowing in October is about 12°C. This temperature for the critical periods of seed germination and emergence is very close to optimum. For root growth during November and December the soil temperature is not at the optimum (20°C), but it would not be a major limiting factor to crop productivity.

3.4.2 Soil Strength

Soil strength can reduce potential crop yields by mechanically impeding seedling emergence and preventing root elongation. Mechanical impedance is a function of the soil bulk density, porosity, moisture content, and the thickness of soil covering the seed. Some of the ways that it can hinder plant growth are;

(1) A soil crust preventing emergence,
(2) A soil layer too hard for root penetration,
(3) A soil layer allowing root penetration when wet but not dry,
(4) Roots may grow between but not penetrate peds, to obtain water and nutrients.

Mechanical impedance of roots and emerging seedlings arise when the soil pores are small, and the cohesive properties of the soil matrix resist deformation by the growing plant roots. For roots to extend through the soil, continuous pores bigger than the diameter of the root-tip (>0.02mm diameter) are desirable, as roots are unable to decrease their diameter to penetrate narrow pores (Wiersum, 1957). The volume of pores greater than this diameter in the soils of this study are almost negligible (See Fig. 3.15a and 3.15b on soil water retention; pores that drain to -0.05 bars matric potential are >0.06mm diameter. The difference between the -0.05 bar and total porosity curves shows a small percentage of these pores, and the proportion of pores >0.2mm diameter would be even smaller). Where such pores do not exist, roots must penetrate by pushing aside the soil particles.

The mechanical resistance offered by soil particles to deformation and the pressure exerted by the roots will control the rate of root growth. Bulk density provides quantitative information on the packing of the soil and its resistance to root penetration. It should be noted that bulk density integrates a measurement over the whole soil volume, substantially larger than the size of a plant root. Small, flexible plant roots can penetrate soil layers through cracks, worm holes, root channels and other voids that may not substantially affect the bulk density. Despite these difficulties, many experiments have shown that crop yields decrease as bulk density increases and the strength of soil layers increases (Nash and Baligar, 1974).

An increase in bulk density leads to a decrease in pore volume, pore size distribution shifts towards a larger proportion of small pores, and pore space continuity is often decreased (Wingate-Hill, 1978). Roots will rarely enter a coarse textured soil if it has bulk density exceeding 1.7 to 1.8 $Mg\text{-}m^{-3}$, or a fine textured soil if it exceeds 1.5 to 1.6 $Mg\text{-}m^{3}$ (Russell, 1973).

The topsoil bulk density results for all the soil sites are low enough for root penetration (Fig. 3.11). However, the Kiwitea, Marton, and Tokomaru subsoils are fine textured and have bulk densities greater than 1.5 $Mg\text{-}m^{-3}$, hindering root penetration. — Profile inspection indicates that few roots extend into the subsoil. Features such as shrinkage cracks, and old root and worm channels provide some access into these compacted subsoils. This was particularly noticeable in the Tokomaru silt loam and the Marton silt loam soils (Appendix A). Although roots do penetrate subsoil horizons of these soils, little root penetration of the peds occur, therefore water and nutrients within such peds remain relatively unavailable to the crop. The Kairanga-1 coarse textured subsoil and Kairanga-2 fine textured subsoil are below the root impeding bulk densities of 1.7 and 1.5 $Mg\text{-}m^{-3}$ respectively.

Barley has a short growing season, therefore an extensive root system does not develop. Most roots of barley were found in the top 30cm and to a maximum depth of about 70cm for the soil in this study (Fig. 3.17). They would not be expected to penetrate much deeper even in a drier season because of the impeding soil strength in all soils, except for the Kairanga ones. Deep roots give a non-uniform root distribution as they follow the lines of least resistance down cracks between structural units, this characteristic was also observed by Scotter et al, (1979a) for grass roots on a Tokomaru silt loam. The deep roots are few but are important for providing the plant with water during drought.

3.4.3 Water Movement

The movement of water through the soil will influence how well drained the soil is. The quicker a soil drains the less likely it is that excess water will cause anaerobic conditions and management problems.

Pore size distribution is one of the most important factors influencing rates of water movement. It imposes direct effects on hydraulic conductivity by controlling the resistances that counter-act the gravitational and suctional forces that draw water into the soil. These resistances to flow depend on the width, continuity, shape, and tortuosity of conducting channels which are in turn a function of the size of soil pores and their configuration. The rate of flow through a pore is porportional to the fourth power of the pore radius. Therefore fine pores transmit water at a much slower rate than do coarse pores (>0.06mm diameter). The number of coarse pores (usually fissures, root and worm channels) in the soil is the most important factor controlling water movement.

The sites were sampled at the end of the summer season. Hence, hydraulic conductivity would be expected to be artificially higher than spring values, due to root and worm activity and structural cracking induced by drying over the summer season. For a Tokomaru silt loam, Scotter et al (1979a) indicated that the difference between seasons could be one or two orders of magnitude.

The moderate to very rapid saturated hydraulic conductivity in the topsoil for all sites indicates that water can move readily through this horizon (Fig. 3.14). But the negligible saturated hydraulic conductivity in the subsoil horizons indicates water movement is impeded there. This has implications for water storage and root development. The subsoil horizon will tend to perch water up in the profile, increasing the soil water holding capacity and encouraging anaerobic conditions to develop. The slow flow indicates that there are very few or no macropores, this corresponds with the high bulk densities where root penetration is restricted. The Kairanga subsoils are slightly more permeable than the other three soil types.

Lateral flow of water through the porous topsoil would not be an important way of removing excess water because of the gentle slopes. Subsoil drainage in all sites is poor, therefore in a wet season when the quick removal of water is critical, these soils will have problems if adequate artifical drainage is not available. A wet soil can delay seed-bed preparation, restrict rooting because of insufficient aeration, encourage disease, and hinder the harvesting of a crop at an optimum stage. The problem of poor water movement was noticeable this year on the Tokomaru site (Fig. 3.18). A few days after heavy rain, water had not drained from the topsoil when harvesting commenced. Traction for the harvester was very poor (eventually dual wheels had to be fitted) and the soil was severly compacted (Fig. 3.19). Compaction

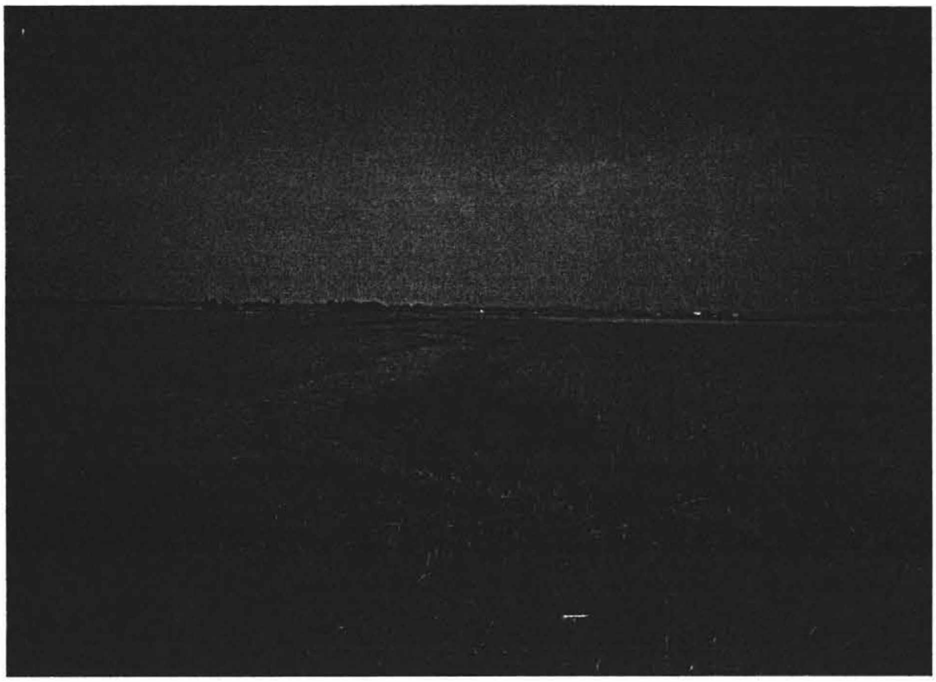


Figure 3.18 Plate showing water ponded on the soil surface of a Tokomaru silt loam five days after the previous rainfall. This caused trafficability problems hindering harvesting.

Figure 3.19 Plate showing compacted soil surface by a harvesting machine wheel. A cylinder 5cm high shown for scale.

of the soil in this way will have detrimental effects on soil structure and may affect crop yields in the future.

3.4.4 Soil Aeration

Soil aeration is essential for providing oxygen to plant roots for respiration and preventing anaerobic conditions developing where toxic substances will accumulate. Poor aeration will hinder the functions of plant roots reducing crop development and yield.

Cannell (1979) outlines the complex responses of soils and plants to waterlogging. Saturation of the soil with water is not the limitation, since plants grow well in solution culture, it is the anaerobic conditions that develop. The rate of oxygen consumption increases with soil temperature and depends on the stage of plant development. Anaerobic conditions develop in soil when roots and soil organisms use oxygen faster than it can enter the soil by diffusion. Interconnected air-filled porosity is the physical property which has the greatest influence on gas exchange with the atmosphere, as oxygen diffuses ten thousand times more rapidly in the gas phase than in solution (Scott-Russell, 1982). If gaseous exchange with the atmosphere is restricted by a saturated soil, surface sealing, or by small pores, oxygen reserves will be consumed rapidly. The lack of oxygen will hamper seed germination, emergence and root development and gases toxic to roots (carbon dioxide and ethylene) will accumulate. Furthermore, anaerobic conditions are believed to favour several soil-borne pathogens that can affect yield, but relatively little is known on this subject (Cannell, 1979).

Greenwood (1975) has reviewed the use and limitations of means available for assessing aeration. These include measuring the composition of soil air, air-filled porosity, diffusion coefficienty and oxygen diffusion rates. Criteria are difficult to establish because of differences in oxygen level inside and outside large aggregates, the effect of the duration of anaerobic conditions, and the varying activities of plant and micro-organisms in different seasons and different soils. As well, the air-filled porosity influenced by changes in both dry bulk density and moisture content is a highly transient property, which will vary considerably during the growing season. Although none of the methods provides a critical means for assessing aeration in relation to plant growth, Greenwood considers that soils with air-filled porosity (Ea) > 10% are likely to be adequately aerated, and that an Ea < 5% in the soil is likely to effect plant growth.

The soils have artifically drainage and the large pores (pores > 0.06mm diameter) should readily drain, drying the soil to a moisture content equivalent to that at -0.05 bars pressure potential. To calculate Ea the difference between total porosity and water filled pore spaces at -0.05 bars shall be used:

$$E_a = T_p - \theta_{-0.05} \qquad (3.7)$$

This information can be interpreted from the water retention characteristic curves, the results are shown in Figures 3.20a and 3.20b. These results are considered to be the minimum soil aeration porosities, obviously soil aeration will improve as the soil dries further.

Soil saturation just after germination but before the shoot has emerged (without the possibility of some oxygen transfer from the air to the roots via the shoot) can greatly diminish the number of surviving seedlings, as well as delay the emergence of those that do survive (Cannell, 1983). The topsoil aeration of the Kiwitea-1, Kiwitea-2, and Kairanga-2 soils are above the 10% level, Kairanga-1 is also close. The two Yellow-Grey Earth soils are near to the critical 5% level (Fig. 3.20a and Fig. 3.20b). Although topsoil aeration is marginal for these soils, it is difficult to make any firm conclusion as to the aeration at the critical time of seed germination since the soil was sampled after harvesting. On an arable field the volume of macropores decreases as bulk density increases from seedbed to harvest (Russell, 1973). Part of the increase is due to natural causes such as the slaking of clods on wetting, filling up coarse pores and partly due to the passage of cultivation, spray, and harvesting machinery. Also, the seed is placed close to the soil surface where evaporative drying and drainage rapidly create water free pores in this layer.

There are few macropores in the subsoil of the Tokomaru and Marton soils (Fig. 3.20a and Fig. 3.20b). The core technique used to measure porosity did not sample across the fissures between the large prismatic structural units, which were observed in the field profile descriptions. These fissures would increase slightly the subsoil

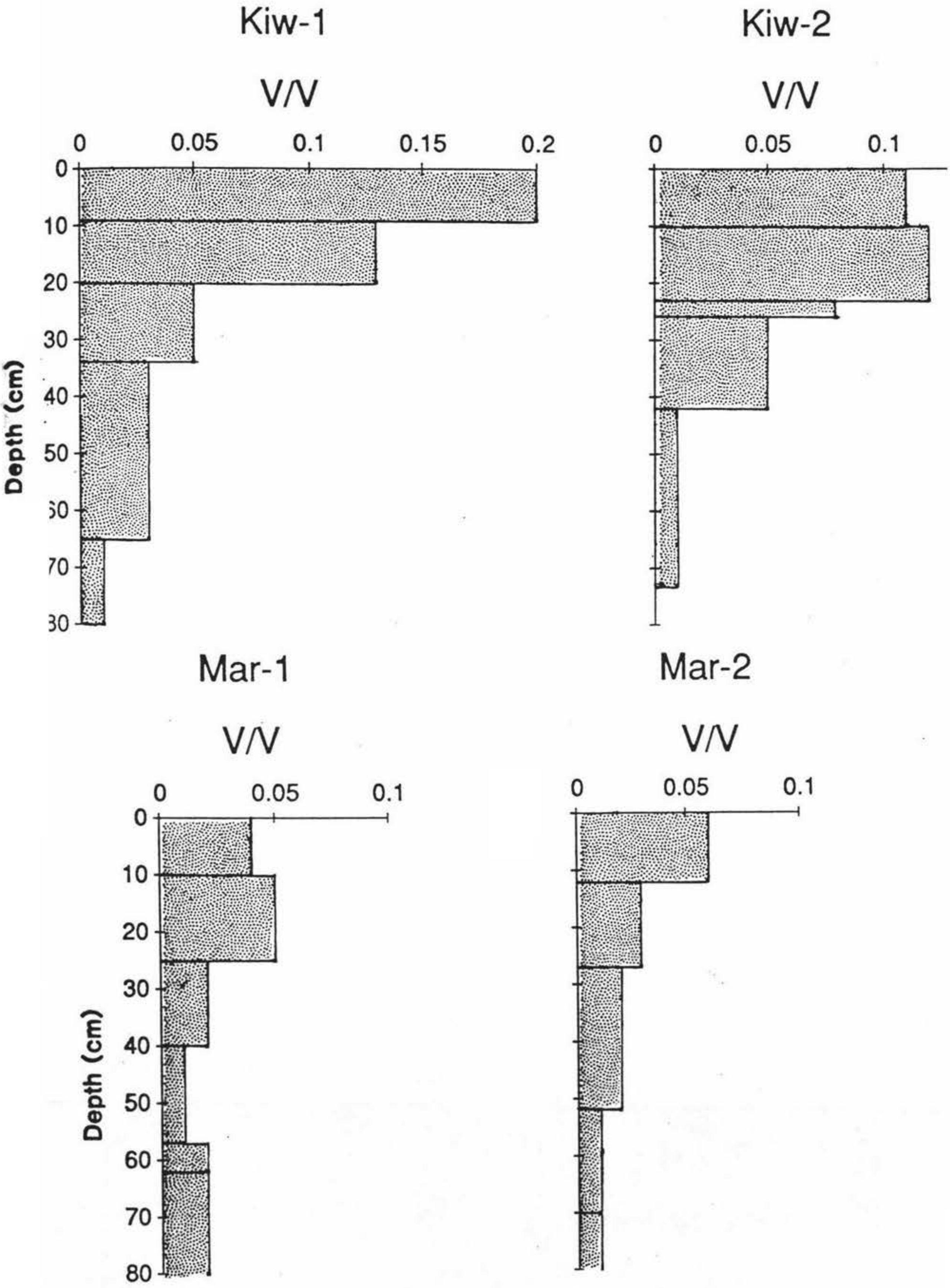


Figure 3.20a Large pore spaces (>0.06mm) important for soil drainage and soil aeration, for the Kiwitea and Marton sites. Data interpreted from soil water retention characteristics.

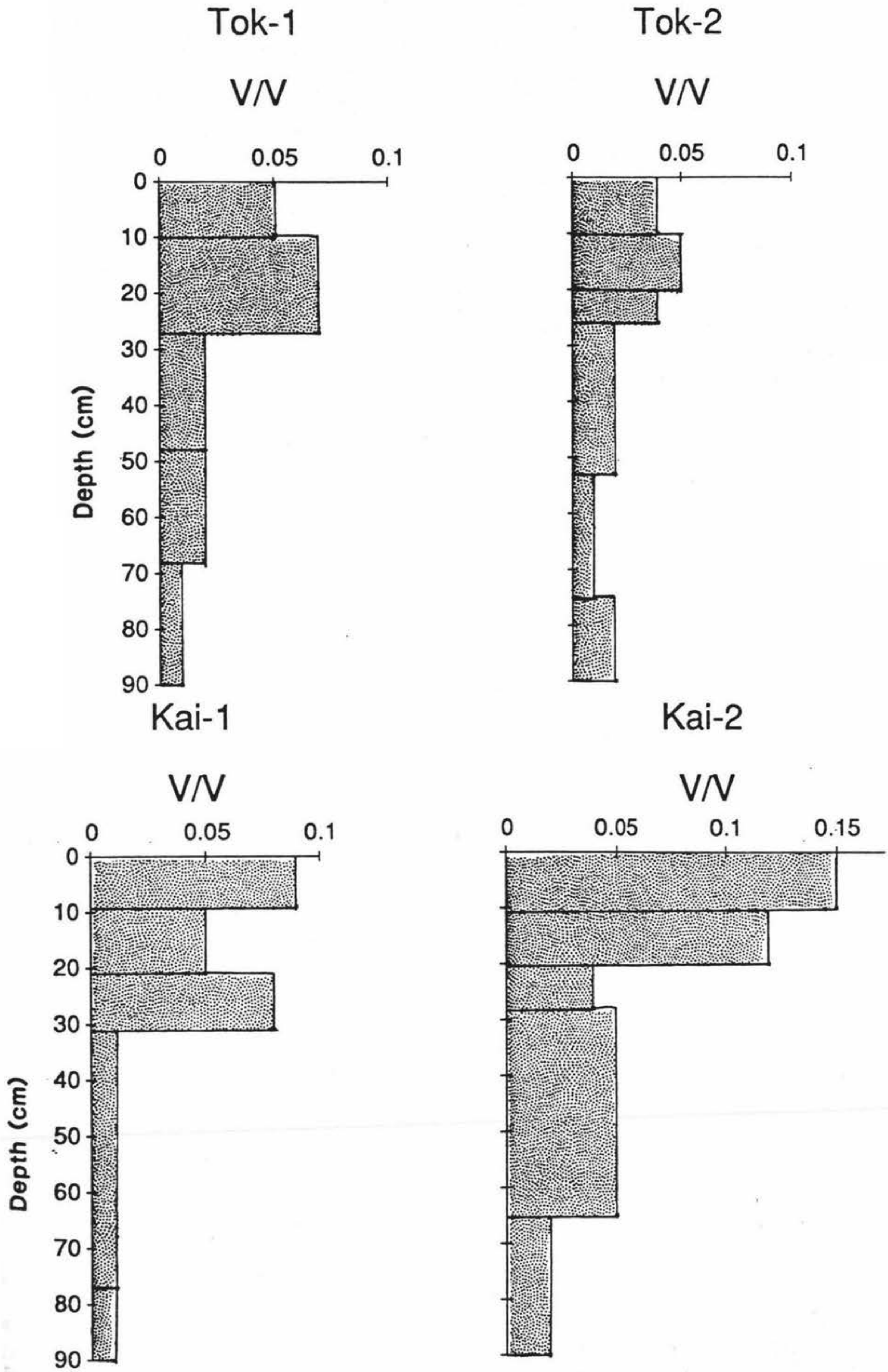


Figure 3.20b Large pore spaces (>0.06mm) important for soil drainage and soil aeration, for the Tokomaru and Kairanga sites. Data interpreted from soil water retention characteristics.

macroporosity. The Kiwitea and Kairanga subsoils had a few more macropores, with Kairanga-1 subsoil being the only one above the 10% level due to its coarser texture. Abundant low chroma colours are characteristic of all these horizons, indicating that the soil is subject to periodic anaerobic conditions.

An added consideration to poor soil aeration in the Kairanga soils is the presence of a groundwater table, which fluctuates throughout the profile during the year. At the wettest parts of the season it can be near the soil surface, saturating the soil profile.

An important factor that has not yet been considered with aeration is the continuity of air filled pores from the soil surface through the topsoil, into the subsoil. Earthworm channels are a major source of continuous macropores improving the soil aeration. Where ploughing destroys this continuity into the subsoil (Douglas et al, 1980), downward water movement will be impeded, water will perch at this boundary preventing aeration of the subsoil. At the base of plough depth, anoxic zones identified by mottling and concretions were observed in the soil profiles. This probably indicates a lack of pore continuity and was particularly obvious in the Kiwitea, Marton, and Tokomaru soils.

Although it is difficult to make any firm conclusions about the topsoil macroporosity because of it changing with the season, it would be expected that the Kiwitea and Kairanga topsoils would not suffer aeration problems in most years, whereas the Marton and Tokomaru topsoils could. All these soils have severe subsoil aeration problems as indicated by the sharp contrast between the proportion of macropores in the topsoil and subsoil, the anoxic zones at the plough depth and the substantial subsoil low chroma colours, preventing any major root elongation.

3.4.5 Soil Moisture

Soil moisture limits crop growth by reducing root growth (as soil moisture decreases, mechanical impedance increases (Eavis, 1972)), and by stressing the plant when water is restricted.

The soil holds water in two ways. In interstices or pores or capillaries between solid particles, and by adsorption on the solid surfaces of the clay particles and organic matter. An ideal soil should have an extensive group of pores small enough to resist gravitational drainage yet large enough to release significant quantities of water to plant roots without forcing the water in the root zone to fall to low matric potentials.

Plant roots absorb water from the soil because they are able to reach a lower potential than the soil. As water is removed from the soil adjacent to the roots, the lowered potential will cause water to move towards the roots by capillarity. This water movement is significant for a few millimeters but over greater distances is not adequate to meet the plants needs. Consequently roots grow towards water, rather than water moving towards roots over larger distances.

As the soil dries, roots will penetrate deeper and deeper ahead of the drying front until a horizon which resists root penetration is met. The rate that roots can take up water from the soil depends on the length of absorbing roots in the soil, the volume of soil they permeate, and the rate that water moves from the soil to the root. The subsoil root distribution at all sites is non-uniform and is confined to channels which least resist root penetration. The confinement of roots accentuates the plants liability to drought. Water must migrate several centimetres laterally from centres of blocks to roots. This is a slow process. Furthermore, soil strength often increases with decreasing soil water content or potential.

There is a dilemma in determining an optimal soil moisture level, as a high water content is not conducive to soil aeration. But a dry surface soil will jeopardise crop nutrition, since maximum soil fertility is in the topsoil and an adequate supply of water is needed to transport nutrients to the plant.

Water is essential for crop growth. In general the greatest utilization of soil and fertiliser nutrients will be achieved if water content is maintained as high as possible without causing aeration or management problems. In Chapter 4 the ability of the soils to retain water is discussed. A lack of moisture is often regarded as a more significant factor than excess water for limiting plant growth and development. The impact of moisture stress on crop yield is discussed in detail in Chapter 5.

3.4.6 Structure Stability

Soil structural stability has an indirect effect on plant growth. It is important because it influences the other properties discussed in the previous sections which directly influence growth.

The stability of soil aggregates can be stressed externally by mechanical action of raindrops or by cultivation, or internally by wetting a dry soil. An unstable aggregate can slake and disperse. Dispersed silt and clay then move into pores and clogs them. The permeability to air and water declines leading to a loss of crop yield through reduced water infiltration, poor aeration and to a loss of water by runoff. Furthermore, dispersed soil and nutrients are easily carried away in the runoff water.

Soil stability depends on clay content, the type of clay, the kind of ions associated with the clay, iron and aluminium oxides, the microbial population and organic matter content. Various methods are used to assess relative structural stability. Most involve applying a slaking and/or dispersion index (Emerson, 1977; McQueen, 1981), or an indirect assessment using an aggregate property such as organic matter.

Organic matter management is important key to continued nutrition of a crop, as problems arising from soil physical fertility are often related to the organic matter content. Structural stability increases greatly with organic matter content (Russell, 1973). The role of organic matter in stability ranges, from entanglement by fungal hyphae and roots to binding by the decomposition products of roots, micro-organisms and soil animals.

There is however no 'magic number' that can be stated as the percentage of organic matter that soils need to contain. It is related to other factors such as soil texture and type of clay. The organic carbon measurements made are relevant only to the soils in this study, as structural stability is dependent on site management and cropping history.

The Tokomaru and Kairanga-1 soils have a low organic matter content and were observed to be unstable. These soils are also the longest cropped sites. The other soils have a medium organic carbon content, with the Kiwitea soils having the strongest development of aggregate structure and stability. The soil structure of Marton and Kairanga-2 would be expected to deteriorate to similar levels of stability as the Tokomaru and Kairanga-1 soils respectively with continued cultivation.

3.5 Conclusions

1) The soil physical properties and profile descriptions indicate that the four soil types can be divided into two distinct groups;
   i) The river plain soils (Kairanga) developed in alluvium.
   ii) The high terrace soils (Kiwitea, Marton, and Tokomaru) developed in loess.

2) The soil provides an environment firstly for seed germination, emergence and then for root development. At these trial sites topsoil temperature, mechanical impedance, aeration and moisture would, in most years all be near optimum, to encourage both germination and emergence. The only property which may hinder emergence is topsoil structural stability in the Tokomaru, Kairanga and possibly Marton soils.

3) The barley root system at all sites was shallow, roots were rarely observed below 30cm. When they were below 30cm it was usually down fissures, worm channels and old root channels. The high subsoil bulk density mechanically impeding the roots, combined with the poor soil aeration are the probable causes of roots not extending into the subsoil. It would be expected that the Marton and Tokomaru soils have less of a chance to develop an extensive rooting system than does the Kiwitea and Kairanga soils which have lower bulk densities and a slightly higher proportion of macropores for aeration.

CHAPTER 4

CHAPTER 4

SOIL WATER STORAGE

4.1 Introduction

Soil water stored and available to plants is dependent on soil physical properties (Fig. 4.1). The previous chapter has shown that soil physical properties determine the plant rooting distribution and depth; the soil water retention characteristics; and the hydraulic conductivity which, controls water redistribution and the rate of water movement to the plant roots. Soil storage integrates the soil physical properties of a profile which can then be used to assess the impact on crop productivity.

Care must be taken when defining the values for the upper and lower limits for calculating soil water storage (Hillel, 1980; Reid et al, 1984; and Scotter, 1977). These are the limits where soil water surplus occurs and where the the plant wilts permanently, respectively. Problems arise especially when laboratory measured water contents at certain pressure potentials are used. Soil water storage is generally not a fixed quantity or a static property but a dynamic process, where soil water is flowing into and out of the soil volume. To be realistic, water content measurements for the limits should be made in the field, by gravimetric sampling or using a neutron probe at the time when the soil is considered to be at the appropriate limit.

Reid et al, (1984) showed that profile laboratory estimates of

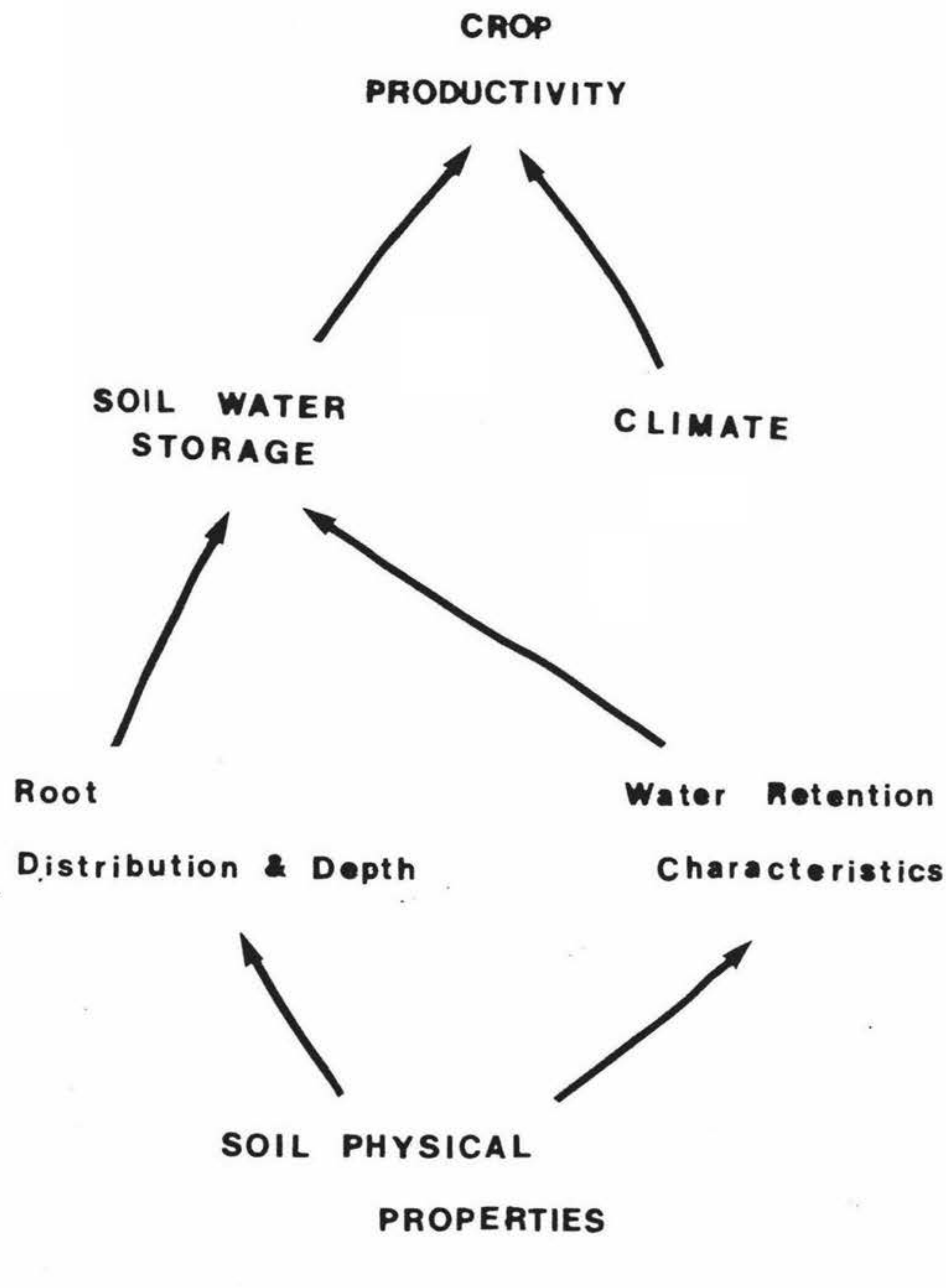


Figure 4.1 The figure shows how soil physical properties determine available water storage. Soil water storage combined with climate may affect crop productivity.

upper and lower limits at intervals down the profile agreed poorly with field observations. However, final estimates of the overall stored water were similar because of compensatory inaccuracies in the laboratory estimates. The limitations of the laboratory method used to calculate available water capacity in this study should be appreciated, as it is an integral part of the water balance model used in Chapter 5. The following sections contain a brief discussion on these limitations. Once the upper limit, lower limit, and stress point are evaluated, two measures of soil water storage can be calculated to describe the water available to plants; readily available water capacity (RAWC) and total available water capacity (TAWC).

4.2 Soil Water Limits

4.2.1 Upper Limit

The upper limit of available water is often referred to as 'field capacity'. It can be defined as "the amount of water held in soil after excess water has drained away and the rate of downward movement has materially decreased", (Veihmeyer and Hendrickson, 1949).

Various laboratory pressure potentials have been used to characterise field capacity. Generally a value somewhere between -0.05 to -0.33 bars is used. There may be a discrepancy between laboratory estimates and field estimates, as laboratory methods measure the water retention of a soil sampled at specific point down the profile. Whereas the real upper limit depends on other properties of the whole soil profile which affect the drainage and redistribution of water after the soil has been wet above this point. Such properties are the presence of a water table, an impermeable layer, layers with different hydraulic conductivities or layers with different antecedent water contents (Scotter, 1977). For example, in a layered soil with either a silt loam topsoil over a sandy subsoil or a silt loam topsoil over a clay loam subsoil, a water table will perch in the upper horizon above the boundary (Hillel, 1980; Clothier, 1977).

Textural change (from silt loam to silty clay loam, clay loam or clay) occurs at all sites (except Kairanga-1) and combined with relatively low saturated hydraulic conductivity in the subsoil will impede downward drainage, holding water up in the soil profile. For this reason a high pressure potential of -0.05 bars was chosen as the upper limit. This matric potential corresponds with field capacity measurements made on a drained Tokomaru silt loam (Scotter, 1979a; Gradwell, 1974). The Kairanga-1 soil had a sandy loam subsoil, leading to different drainage and soil water retention characteristics compared with the other sites. Therefore a pressure potential of -0.10 bars was used to represent the upper limit for this soil.

4.2.2 Stress Point

Stress point (SP) is a measure of the soil water content where plants will begin to suffer water stress. Up to this point the rate of soil water movement to the plant roots is able to meet the crop demands. As the soil dries, the rate of water movement decreases due to the rapid drop in capillary conductivity of the soil. Below this level the roots extract progressively less and less water to meet plant moisture demands.

Stress point varies between plant species depending on the ability of plant roots to draw water from the soil. It is measured in the field by sampling when the first signs of crop water stress occur. There is no information indicating what soil moisture pressure potential barley roots will start to experience stress. It could be anywhere between the upper and lower limit potentials. Commonly a pressure potential of -1 bar is used to represent this point in the laboratory.

4.2.3 Lower Limit

The lower limit of available water corresponds to the permanent wilting point of the crop. Water held below this limit is either too tightly held for plants to extract it, or moves so slowly to the roots that wilting cannot be prevented.

There is poor agreement between field and laboratory estimates of the lower limit water content (Reid et al, 1984; Ritchie, 1981a). This difference is important as laboratory methods are often used, since in New Zealand the chances of a season being dry enough to allow the soil to dry to this level are rare. A pressure of -15 bars has been shown to approximate the lower limit for most crops. The pressure potential of -15 bars tends to give an over-estimate of the surface layer water content and an under estimate of the deeper horizons field lower limit (Reid et al, 1984; Ritchie, 1981b). Over-estimation of wilting point of the surface layer may be due to soil evaporation drying the soil more than plant roots. Laboratory estimates, unlike field estimates of the lower limit, do not allow for the pattern of root distribution. Low root density in the subsoil is probably the reason that the water content at -15 bars is rarely reached in the field for most pasture and grain crops. To overcome this poor agreement some workers split the profile into a topsoil and subsoil component, then use different pressure potentials, -15 to -20 bars for the topsoil and -2 to -5 bars for the subsoil. A unique pressure potential for the lower limit does not exist but it appears that the contribution of an overestimate and underestimate tend to cancel each other out so that -15 bars is a reasonable approximation (Reid et al, 1984), and shall be used in this study.

4.2.4 Rooting Depth

Rooting depth and distribution determine the volume of soil from which the crop is able to extract water. An adequate root system is essential to meet the evaporative demand of the atmosphere and the requirements of a growing crop for nutrients. The size of the soil reservoir is therefore strongly influenced by the ability of the root zone to enlarge.

The ease of water uptake from a given soil horizon increases with rooting density in that region. Most roots are found in the upper topsoil horizon, hence most water uptake occurs from there. The density of roots in lower horizons decreases rapidly with depth. Therefore water extraction from depth occurs slowly, but it is vital to the plants survival when all available water has been extracted from surface soil horizons. In some soils, upward movement of water into the root zone from deeper horizons has a similar effect to increasing the rooting depth, as it increases the amount of available water for the plants to extract.

The effective rooting depth of the crop increases from planting until maturity. This change in rooting depth should strictly be accounted for in estimating soil water storage with time. Provided sufficient water is available for germination and establishment, spring planted cereal crops will have reasonably developed rooting systems by the time water stress occurs in the surface soil horizon. Therefore the rooting depth used in this study will be the maximum one.

The rapid drop in root density with depth, makes it difficult to define a precise rooting depth for the water holding capacity calculation. Deep root penetration is primarily influenced by soil physical properties (soil mechanical impedance, moisture, aeration, and temperature, as discussed in Chapter 3), as well as the influence of the chemical environment and the effects of disease. It is assumed that upward movement of water from lower horizons to the roots is negligible because of low saturated hydraulic conductivity in the subsoil of these sites. Therefore the potential rooting depth is the depth to which the roots penetrate, and was determined using soil profile observations and interpreting the change in soil physical properties and their influence.

4.3 Available Water Capacity

4.3.1 Readily Available Water Capacity

Readily available water capacity (RAWC) measures the amount of water available to plants before either transpiration or crop growth becomes affected by water stress. It is the amount of soil water held in the effective root zone (R) between a drained upper limit (UL) and a critical water storage limit (Stress point, SP). Calculated as;

$$RAWC = \int_0^R (\theta_{UL} - \theta_{SP})\, dR$$

4.3.2 Total Available Water Capacity

Total available water capacity (TAWC) is the total amount of water available to the plant. It is the total water stored in the effective root zone (R) between a drained upper limit (UL) and a lower limit (LL). Calculated as;

$$TAWC = \int_0^R (\theta_{UL} - \theta_{LL})\, dR$$

4.4 Results

For this study, detailed long term assessment of crop and field soil water conditions was not possible. Therefore laboratory measurements on the samples collected immediately after harvesting were used to give water content values for the various limits, ie. using -0.05, -1, and -15 bars to represent UL, SP, and LL respectively.

The water content at each pressure potential limit can be determined from soil water retention characteristics (Fig. 3.15a and 3.15b). Integration of these curves to the maximum rooting depth will give the total and readily available water capacities (Table 4.1). A breakdown of the water content by horizon is shown in Appendix B.

TAWC is between 60 and 85mm for all sites except for Kairanga-1 (116mm). The ratio of RAWC to TAWC shows that the sites (except for both Kairanga soils) have 60% of the TAWC readily available to plants.

Table 4.1 Readily available and total available water capacities, determined from the integration of the water retention characteristic curves to the maximum rooting depth.

	RAWC (mm)	TAWC (mm)	Rooting Depth (cm)	RAWC/TAWC
Kiwitea-1	38	61	70	0.6
Kiwitea-2	40	68	73	0.6
Marton-1	50	78	70	0.6
Marton-2	49	76	70	0.6
Tokomaru-1	44	75	68	0.6
Tokomaru-2	55	85	73	0.6
Kairanga-1	107	117	77	0.9
Kairanga-2	37	81	65	0.5

In contrast for the Kairanga-1 soil the ratio is very high (90%) and the Kairanga-2 soil low (50%).

4.5 Discussion

The concept of defining absolute water storage limits and available water capacities has been criticized by many soil physicists (Hillel 1980; Baver, Gardner and Gardner, 1972; and Reid et al, 1984). However, the values are recognised as having a useful purpose when comparing the ability of different soils to retain plant available water. Field estimates of the various limits are desirable for calculating available water. However, laboratory measurements can give a good approximation, but the limitations on accuracy should be appreciated.

Rooting depth had a significant effect on the soil water storage (Table 4.1). Within the soil type pairs the deeper rooting sites have a higher RAWC and TAWC. The available water storages calculated are lower than results of Gradwell (1974) and Scotter et al (1979a) for the Tokomaru silt loam. This is partly due to the shallow rooting depths observed and used. Most available water storage data are quoted for permanent pasture rooting depths of up to 1m depth. If this were the case and the rooting depth was extended for these sites to a metre (ie. plus about 300mm) approximately 30mm would be added to the water capacity figures. The 1985/86 season was particularly wet, but the unfavourable subsoil physical properties would in a drier season hinder deeper root elongation at all sites, except both Kairanga ones. Therefore the data shown here is considered realistic for most seasons.

The readily available water is of most interest, as this is the water available to the plant before it is moisture stressed. The

Kairanga-1 site has a surprisingly large proportion of water readily available (Table 4.1). This will have a significant impact on the ability of the crop to withstand dry conditions, although once the soil reaches stress point it will rapidly exhaust all the available soil water. The low proportion of RAWC/TAWC for the Kairanga-2 soil means it will more readily go into stress, and the soil will reach the lower limit at a slower rate. The high terrace soils have a similar, but lower proportion of RAWC/TAWC. This is possibly characteristic of these older more developed soils with a uniform loess parent material, compared to the variability in texture, horizons and structure of the recent, Kairanga soils of alluvial origin.

The water storage values show the maximum amount of water that the soil can store and make available to the plants. If the inputs and outputs of the water balance do not differ greatly, crop growth may not be limited. However, it is likely that the output of water exceeds the input for certain periods. Here, crops on soils with a higher soil water reserve will be more able to withstand drought conditions. The fluctuation of soil water storage will be discussed using a soil water balance in the following chapter.

CHAPTER 5

CHAPTER 5

SOIL WATER BALANCE

5.1 Introduction

Seasonal lack of water is a major factor limiting crop and pasture production, and the primary cause of year to year variability (Kerr et al, 1986; Ritchie, 1980; and Gales, 1983). Excessive moisture, that may occur in soils with poor drainage can also have a significant influence on final yield.

The moisture available to a crop over the growing season is largely determined by the ability of the soil to store available water, and the climate (Fig. 4.1). These factors can be combined in a soil water balance model to show the fluctuations in soil moisture over a season. The effects of water deficit and surplus on yield can be assessed in terms of size, onset and duration. The soil water balance model provides information to allow this assessment to be made, enabling soil moisture storage between sites and with other years to be related to crop yields.

Models provide an analytical mechanism for studying a system. Their complexity can vary greatly. Two recent soil water balance models are the General Soil Water Balance Computer Programme - SWAT (Giltrap, 1986), and the Crop Environment Resource Synthesis - CERES (Jones et al, 1984; Godwin et al, 1984). Both models have common inputs of soil, climate, management, and crop data. They take account of multiple soil layers, and varying root depth. The SWAT model has a predictive purpose for crop management aspects, such as the number of spring field work days, planting dates, harvesting dates, and the means for assessing irrigation strategies. The CERES model is a model proposed for the international transfer of agrotechnology by means of crop modelling. This model is more complex. It has a soil water balance as the main forcing function, but includes a nitrogen submodel and simulates crop phenological development, growth, and yield. It was developed to predict the likely yield to assess the economic viability of planting a crop in a particular area.

The model developed for this study only considers the soil water system in a simple way. Therefore only the most important aspects will be incorporated, ie. the input and output of water, and the soil water storage. The model is simple and its use is restricted to crops well supplied with nutrients, and free from disease. It is possible in some cases that limiting nutrients and/or disease are factors that may weaken the ability of the model to predict the affects of water stress on yield.

To investigate the influence of moisture stress on crops the model developed can be used to predict the effect of various climatic seasons on the soil water balance. The model can then be extended to enable interpretation of transpiration and moisture stress on yield. Comparing the effects of waterstorage on the degree of moisture stress for years with different climatic seasons, is an important step towards quantifing the influence of water limitation to growth.

In this chapter a soil water balance model will be used to:

1) investigate the variation in soil water storage over the season,
2) quantify the extent of moisture stress for the season,
3) analyse the affect of moisture stress on yield,
4) predict the influence of water limitation to growth for different climatic seasons.

5.1.1 Soil-Plant-Atmosphere

Water is an essential requirement for plant growth. Three components determine water use and crop production; soil, plants and atmosphere. Before an assessment of water limitation on yield can be made, it is necessary to understand how soil water is limiting to plant growth. The following sections outline the relationship between water and crop productivity.

The function of the plant above the ground is to adsorb sunlight and carbon dioxide (CO_2), to form sugars by the process of photosynthesis. Photosynthesis depends on the transfer of gaseous CO_2 through stomata into the plant. This process can only proceed when there is a simultaneous transfer of water vapour through the stomata into the atmosphere. A restricition in the transfer of water vapour will be accompanied by a reduction in adsorption of CO_2 and production of photosynthate.

The water storage of plant tissue is small compared to the volume of water transpired. Water transpired into the atmosphere comes from soil water which is adsorbed by roots and flows through the plant to the leaves. This flow of water from the soil is also a process for supplying the plant with nutrients.

The upper limit of evapotranspiration (ie. evaporation of water from the soil plus transpiration of water by plants) is controlled largely by climate. Penman (1948) showed for an extensive area of short crop at full canopy cover and well watered, that evapotranspiration (ET) was determined by temperature, wind speed, humidity, radiation and soil heat flows. The availability of soil water directly affects the ability of the crop to meet the potential ET. When soil water is limiting, the crop has physiological control of transpiration by stomatal closure or leaf shedding.

5.1.2 Water Stress

Differences in soil water deficit are a major cause of year to year variation in yield. Plant growth responds to water stress in many ways, some of the responses are immediately measurable whereas others do not become apparent for some time.

The first response to water stress is a slowing of the processes of cell division and expansion. With increasing stress, the maximum photosynthesis rate declines because of an increase in the diffusion resistances for CO_2 (Monteith, 1981). Thus wilting and stomatal closure may quickly follow when plants are stressed, while effects on plant structure, number of flowers and finally grain yield will be seen only after some considerable time.

Drought causes leaf expansion in cereal crops to slow with the consequence that the canopy closes more slowly, if ever. Leaves are smaller with severe drought (Lawlor et al, 1981) but whether this is due to unfavourable plant water status or reduced availability of mineral nutrients is unknown (Gallagher et al, 1983). In terms of yield, the slowing of photosynthesis is often less important than the reduction of leaf growth (Lawlor et al, 1981) causing a reduction of the amount of light energy intercepted by the canopy over the growing season (Legg et al, 1979). Total dry matter production and yield are strongly correlated with total light absorption, which depends on the seasonal variation in leaf area index. Therefore many of the effects of water shortage on grain yield appear to be indirect effects through reduction in photosynthate availability (eg. light intercepted).

5.1.3 Water Stress - Nutrient Availability

The relationship between nutrient uptake and drought is complex. Soil water stress will indirectly affect the ability of the plant to receive nutrients. The rate of supply of nutrients is decreased in a dry soil because the mobility of ions, water uptake, and hence mass flow of nutrients is less than in wet soil (Russell, 1973). The locality of available nutrients through the soil profile is important, for example most available phosphate is in the topsoil, and thus in any prolonged drought period when the surface is dry and root activity is at depth to find water, phosphate uptake will be decreased. Therefore a plant can be nutrient stressed before it suffers water stress.

The rate of leaf expansion is sensitive to nitrogen supply. A restricition in the absorption of nitrogen will delay leaf expansion and give rise to a decrease in total light interception, consequently decreasing dry matter production.

5.1.4 Transpiration and Yield

Water stress causes the crop to reduce transpiration. Day et al (1978) showed that barley yields were decreased by drought at any growth stage, though the more serious effects are likely when a shortage occurs after ear initiation. Pre-anthesis water shortage can affect the number of ears and number of grains per ear (Day et al, 1981). The anthesis to maturity phase is not hindered by drought (Gallagher et al, 1983). This assumes that growth is not significantly limited by factors other than water, eg. nutrients or disease.

Because of the link between photosynthesis and transpiration, above ground dry matter production has generally been found to be linearly related to water use (Day et al, 1978). The relationship between grain yield and water use is more variable. Further studies have shown that crop and pasture production is proportional to actual evapotranspiration (ETa) or transpiration (Ta), (Tanner and Sinclair, 1983; Jamieson and Wilson, 1982; Gallagher et al, 1983). Transpiration is a better measure of crop performance, because the water lost by soil evaporation has only indirect physiological consequences (Tanner and Sinclair, 1983). However for irrigation planning total water use is more important, so here ET is probably more valuable.

Tanner and Sinclair (1983) review the use of the various moisture parameters to consider the response of yield to the degree of water stress. The conditions required to achieve maximum yields are the same as for maximum transpiration. It has been shown that to a good first approximation,

$$Ya / Yp = Ta / Tp. \tag{5.1}$$

This states that the ratio of actual (Ya) to potential (Yp) yield equals the ratio of actual (Ta) to maximum weather dependent transpiration (Tp), (Hanks, 1974; Hanks, 1983). These approximations assume that crop development and yield is not significantly affected by factors other than water. This equation shall be used to investigate the possible reduction in yield due to moisture stress.

To allow comparisons between sites and between years of the onset, duration and degree of moisture stress, a simple index shall be used, ie. moisture stress days. A moisture stress day occurs when water storage is below that held at -1 bar pressure potential.

5.2 Water Balance Construction

5.2.1 Introduction

To establish the relationship between yield and water stress, a simple water balance needs to be calculated. The water balance traces the degree and timing of soil water storage to which a crop is exposed, allowing moisture stress to be calculated.

The soil water balance accounts for the changes in soil water storage (W) (Fig. 5.1) caused by incoming water from Rainfall (R), Irrigation (I), and Capillary Rise (C) and water loss by Evapotranspiration (ET), Surface Runoff (RO) and Deep Drainage (D). The soil water storage on day i can be calculated as;

$$W_i = W_{(i-1)} + R_i + I_i + C_i - ET_i - RO_i - D_i \tag{5.2}$$

Each term has units of mm/day. When W > TAWC the surplus rainfall and irrigation is considered to be immediately lost as runoff and/or drainage. W is always greater than or equal to 0, the minimum water storage. None of the study sites are irrigated, therefore irrigation is not a variable and shall be excluded from the calculation. Water balance studies by Scotter (1979b) on the Tokomaru silt loam indicate negligible deep drainage occurs if the soil water storage is less than field capacity. All high terrace sites have a similar slow permeable subsoil, therefore the deep drainage term is omited. There is no groundwater table associated with the high terrace soils for capillary

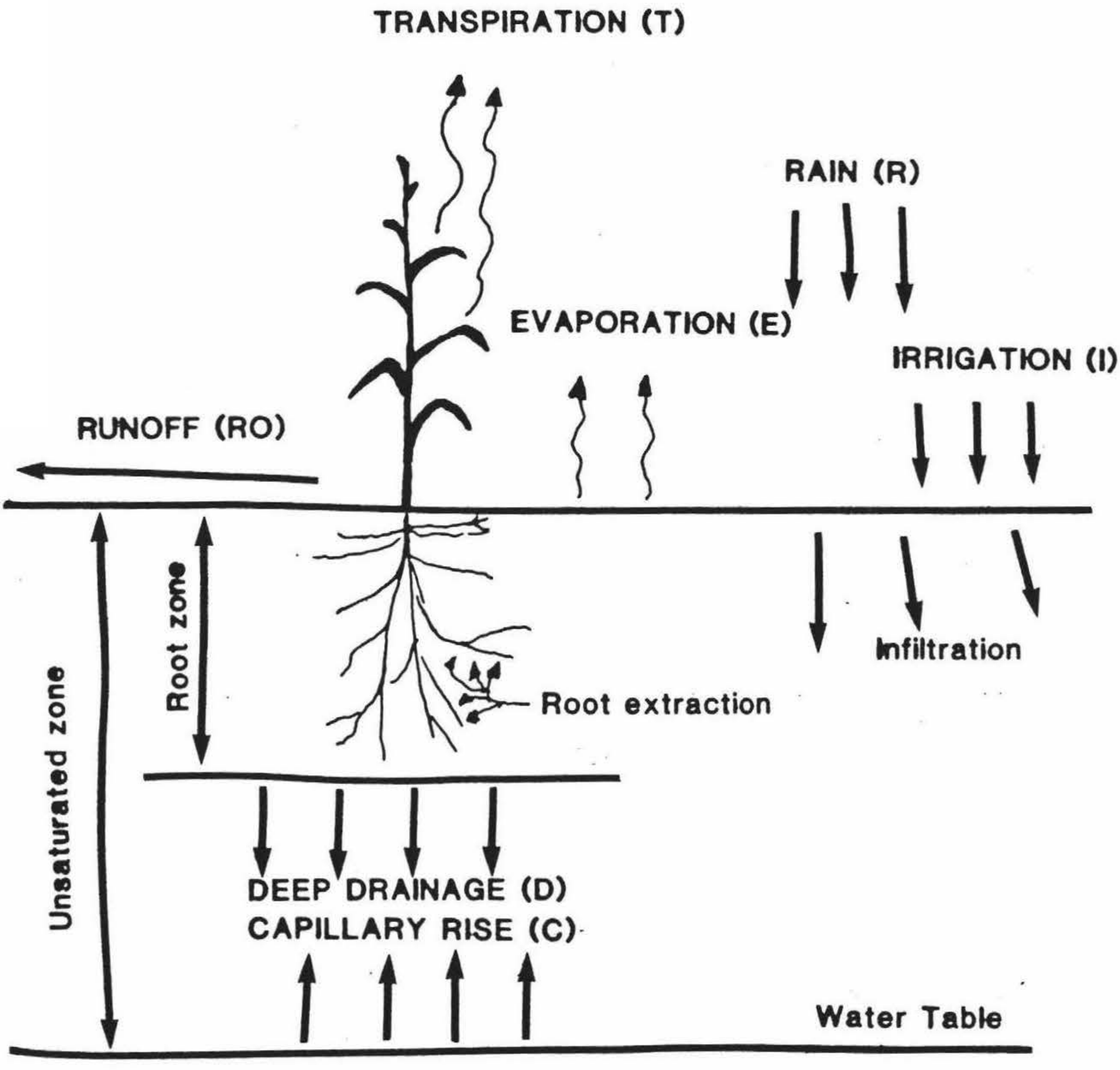


Figure 5.1 Diagram showing components of the soil water balance.

rise to occur from. For the Kairanga soils, the subsoil is more permeable than the high terrace soils and there is a groundwater table, but for simplicity deep drainage and capillary rise is considered to be negligible.

The input values for rainfall and soil water storage (Chapter 4) are straightfoward, the ET input is more complex. ET is computed from meterological data and then reduced for soil moisture stress and crop canopy cover. The method used is outlined in the following section.

5.2.2 Evapotranspiration

Potential evapotranspiration (ETp) represents the upper limit of evapotranspiration that occurs with a well watered, full canopy crop. It is governed by meterological conditions, mainly radiant energy and the saturation deficit of the air. A number of methods can be used for calculating evapotranspiration from meterological data. A review of these methods is discussed by McNaughton et al (1979), and with application for a barley crop by, Jamieson (1982). Two main methods of ETp estimation are described by, Penman (1948) and Priestly and Taylor (1972).

The Penman (1948) equation,

$$ETp = [(s/(s+\gamma))\ (Rn-G)] + [(\gamma/(s+\gamma))\ F(u)\ (e_z^*-e_z)] \tag{5.3}$$

describes potential evapotranspiration (ETp) occurring from an extensive area of short well-watered crop, completely covering the ground. Were s is the rate of change of the saturated vapour pressure with temperature, γ the physcrometric constant is proportional to the specific heat of air and inversely proportional to the latent heat of vaporisation, Rn is net radiation, G is soil heat flow, F(u) is the wind function, and $(e_z^*-e_z)$ is the saturation deficit.

The first term, involving radiation usually dominates the equation, accounting for 60-80% of ETp (Priestly and Taylor, 1972). The second term is smaller and adds little to the improvement of the equation accuracy (Clothier et al, 1982). Priestly and Taylor (1972) considered ETp to be proportional to the dominant first term, simplifing it to,

$$ETp = a[(s/(s+y))(Rn-G)] \tag{5.4}$$

where a is a constant with a mean value of 1.26 ($\pm$5%), and s/(s+y) can be estimated from the mean daily temperature. The net soil heat flow over a day and night is small and can be ignored.

In a humid climate, radiant heat provides most of the energy for transpiration from pasture and field crops. In this situation the success of Priestly and Taylor (1972) methods for estimating ETp has been demonstrated in Manawatu (Clothier et al, 1982), and for barley in Canterbury (Jamieson, 1982).

Priestly and Taylor estimates of ETp shall be used in this study. However, ETp holds only under the conditions for which it is defined ie. full ground cover of an extensive area of short vegetation and no water stress. Both of these conditions are not always met during the growth of barley. Therefore ETp has to be modified to account for these factors, as outlined in the next section.

5.2.2.1 Non-potential Evapotranspiration

In the early stages of growth an annual crop such as barley has little vegetative cover. Evapotranspiration depends primarily on the evaporation of moisture from the exposed soil surface. If the soil surface is dry this will be controlled mainly by hydraulic properties of the soil surface. But if the soil surface is moist evaporation will be close to ETp. As plant cover increases, the evaporation rate becomes more dependent on leaf area and the soil water available to meet the plants' transpiration demands.

For conditions of non potential ET, models are used which account for the degree of water deficit and the proportion of plant cover. A model proposed by Ritchie (1972), has been applied successfully in New Zealand (Jamieson, 1986; Jamieson et al, 1984). It calculates separately the two components of actual evapotranspiration (ETa), that is evaporation (Es) and transpiration (Ta), and then sums them to find ETa, so

$$ETa = Es + Ta \tag{5.5}$$

5.2.2.1.1 Transpiration

ETp gives a good estimate of Ta when there is complete ground cover and soil moisture is non-limiting (Ritchie, 1972). It also gives a good estimate of Ta when ground cover is incomplete provided the estimate is multiplied by the fraction of crop canopy covering the ground.

A crop factor (CF) is related to the fraction of incomplete canopy. To calculate CF the sum of growth degree days (GDD_i) is accumulated. A growth degree day is defined as:

$$GDD = [(Tmax - Tmin) / 2] - \text{base temperature}, \tag{5.6}$$

where the base temperature for barley is 0°C. For barley it is assumed that to reach emergence and then full canopy, it takes 80 and 660 GDD respectively from planting (de Ruiter pers comm., 1986). The number of GDD for a particular day (i) is reduced by a soil moisture factor (SF) described below, as it would be expected that soil moisture will limit the developing plant. Giving

$$GDD = \quad (GDD_i * SF) \tag{5.7}$$

The crop cover (CC) can be calculated from the GDD by

$$CC = (1/580 * GDD) - 0.1379 \tag{5.8}$$

which describes the growth curve (de Ruiter pers com., 1986), when GDD < 80, CC = 0 and increases to 1 when 660 GDD is reached. CF is calculated from canopy cover (Kerr et al, 1986) as;

$$CF = 0.2 + (0.8 * CC). \tag{5.9}$$

so that CF = 0.2 at sowing and increases to 1 when full cover is achieved.

As soil water content decreases the effective resistance to soil water flow increases greatly. This decreased availability results in various degrees of plant stress and leads to a reduction in Ta. The reduction in transpiration can be empirically derived using a linear relation between a soil moisture factor and soil water storage (McAneney and Judd, 1983; McAneney and Kerr, 1985), assuming complete cover at all times (Fig. 5.2). The soil moisture factor (SF) is calculated as;

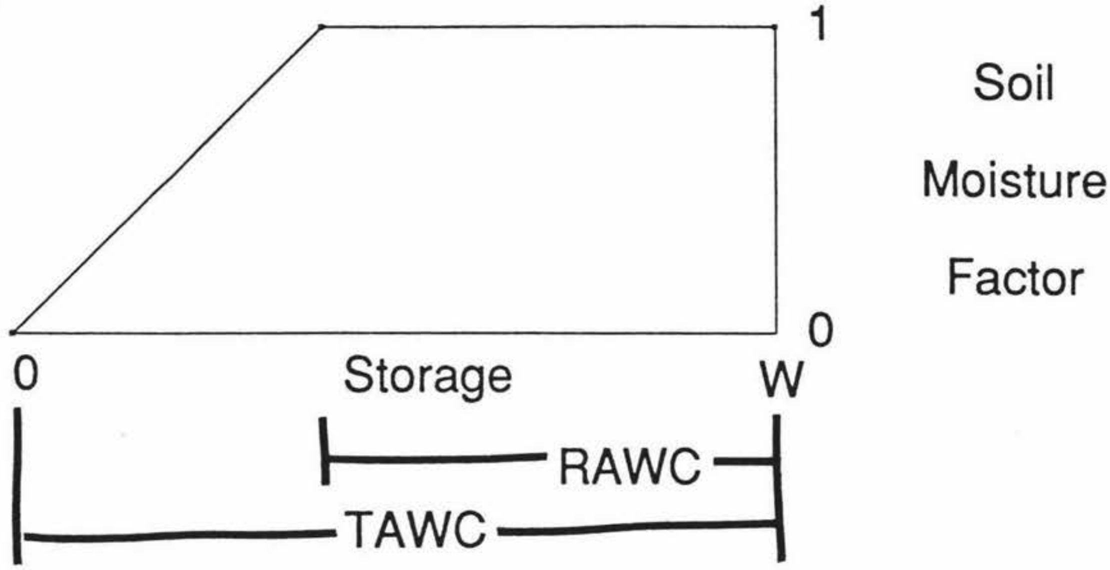


Figure 5.2 Relationship between soil water storage and the soil moisture factor.

(5.10)

$$SF = 1 \qquad \text{when} \quad W \geq (TAWC - RAWC)$$

(5.11)

$$SF = \frac{W}{(TAWC - RAWC)} \qquad \text{when} \ (TAWC-RAWC) > W \geq 0$$

The model for transpiration from a crop is as follows:

(5.12)

$$Ta = ETp * CF * SF.$$

5.2.2.1.2 Soil Evaporation

Evaporation from most bare soils (Es) is treated as having two distinct phases (Philip, 1957);

1. The 'constant rate phase',

2. The 'falling rate phase'.

In the constant rate phase, the soil is sufficiently wet for water to be transported to the surface at a rate approximately equal to the ETp. Evaporation is therefore limited by available energy reaching the soil surface, ie. controlled by the climatic factors and degree of canopy cover.

$$Es = ETp * (1 - CF) \tag{5.13}$$

In the falling rate phase, evaporation is limited by water movement to the surface controlled by the soil hydraulic properties. Water vapour must traverse a thickening layer of dry soils so that the rate of evaporation falls as soil dries. Black et al (1969) established that the amount of water evaporated from a bare soil during a drying phase, is proportional to the square root of the phase duration,

$$Es = C\ (t^{0.5} - (t-1)^{0.5}) * (1 - CF) \tag{5.14}$$

where C is a constant for a particular soil and t is time (the number of days since rainfall exceeded 3mm). The equation was successfully used by Kerr (1984) in the Manawatu, with a C value of 5.53 mm-day$^{-0.5}$ for the Manawatu fine sandy loam soil. The choice of a value for C is not critical because of the rapid decrease in ET with time. For this model C = 5 mm-day$^{-0.5}$ shall be used for simplicity.

The model of Ritchie (1972) assumes that Es is not influenced by transpiration, but moves back and forth along the Es $t^{0.5}$ curve according to the current deficit of Es over precipitation. In practice, Es is taken as the lesser of the results for the two equations, and ceases when W reaches 0.

5.2.3 Running The Model

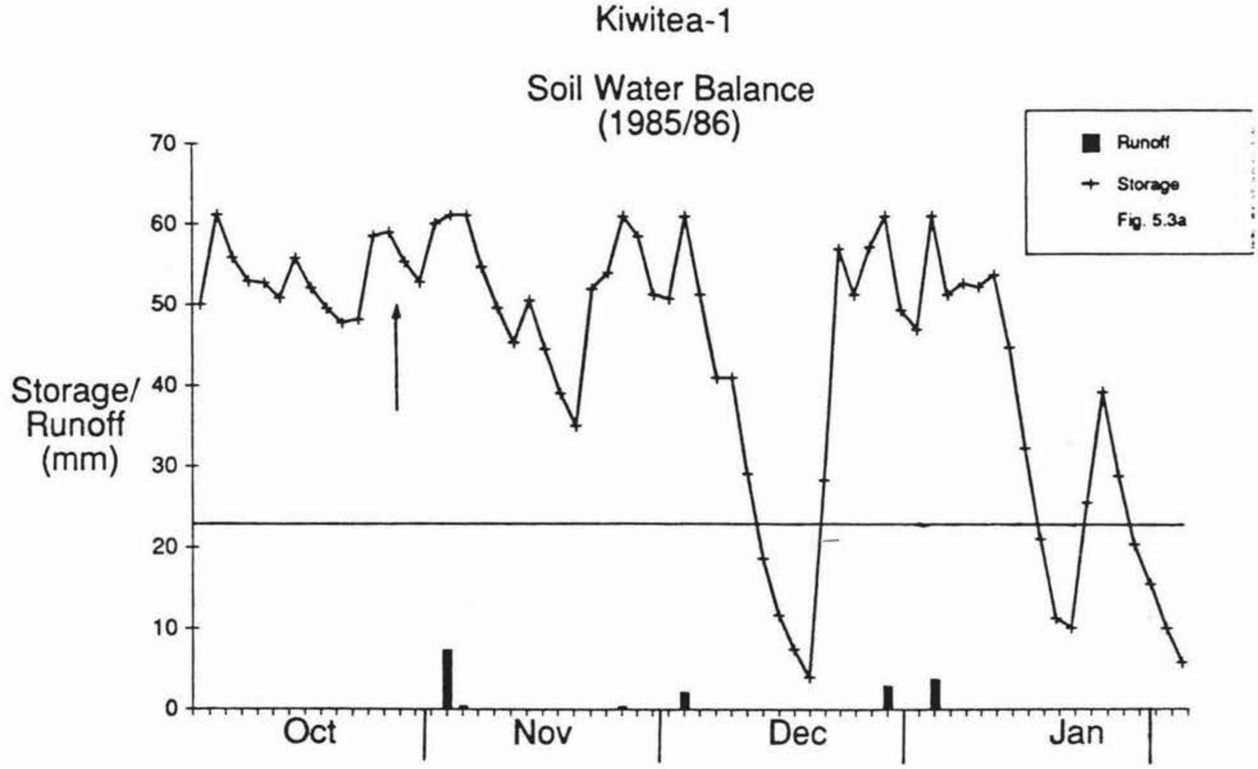
The model was run on a micro-computer using a multiplan spreadsheet programme (Microsoft, 1984). The input data is water storage and daily climatological data for rainfall, maximum and minimum temperature, and solar radiation. The solar radiation data from the Ohakea Meterological Station were used for all sites, as it varies little over the region. Temperatures were measured at Kairanga, Ohakea and Marton Meterological stations. Rainfall data were supplied by the Meterological Stations and rainfall gauges on the farms. The programme was started on the 1st September with water storage equal to TAWC. The model was started at least a month prior to sowing to give the soil water storage values a chance to equilibriate, as heavy rainfalls will tend to reset soil water storage at TAWC as would occur in a field situation. It was assumed that the site was fallow until sowing. From this stage, growth degree days and parameters used to assess moisture stress were accumulated.

5.3 Results - 1985/86 Season

The calculated soil water storage and runoff values for each site are shown in Figs. 5.3a-h. To validate the soil water balance model predictions, actual soil moisture measurements should be made throughout the season. Soil moisture data using a Neutron Probe had been anticipated from another project at some of the sites. Unfortunately data from the Neutron Probe was inconsistent because of the wet season causing difficulties in measuring the wetter end of the profile water contents, and unreliable as problems with the access tubes occurred (De Ruiter pers comm., 1986). Therefore the accuracy of the soil water balance model has not been assessed. A discussion on the reliability of the model will follow later.

The soil water storage curve for each of the sites follows a similar trend, peaking and dipping in unison. This would be expected as the climatic variation (rainfall being the major variable) across the region is not great. The main difference between sites is the amplitude of the curves and this will depend on the total and readily available water contents.

Water storage values indicate the soils are moist to wet



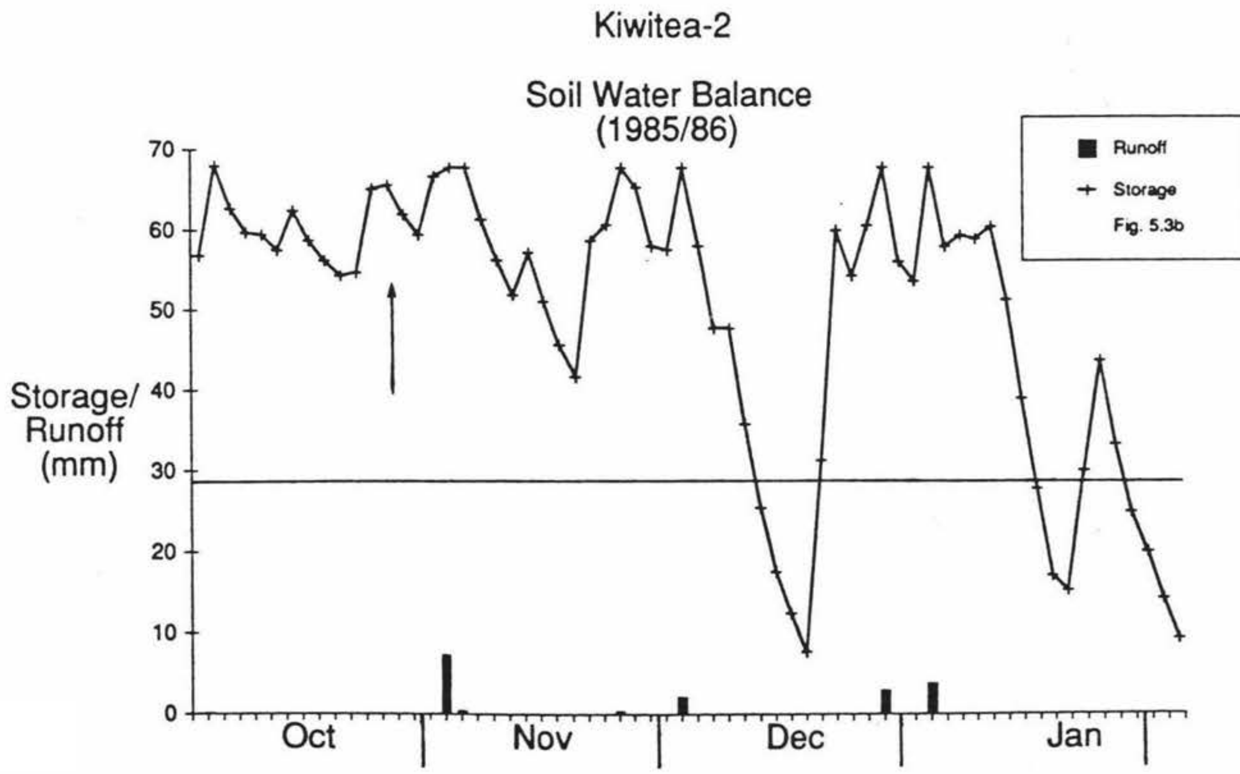
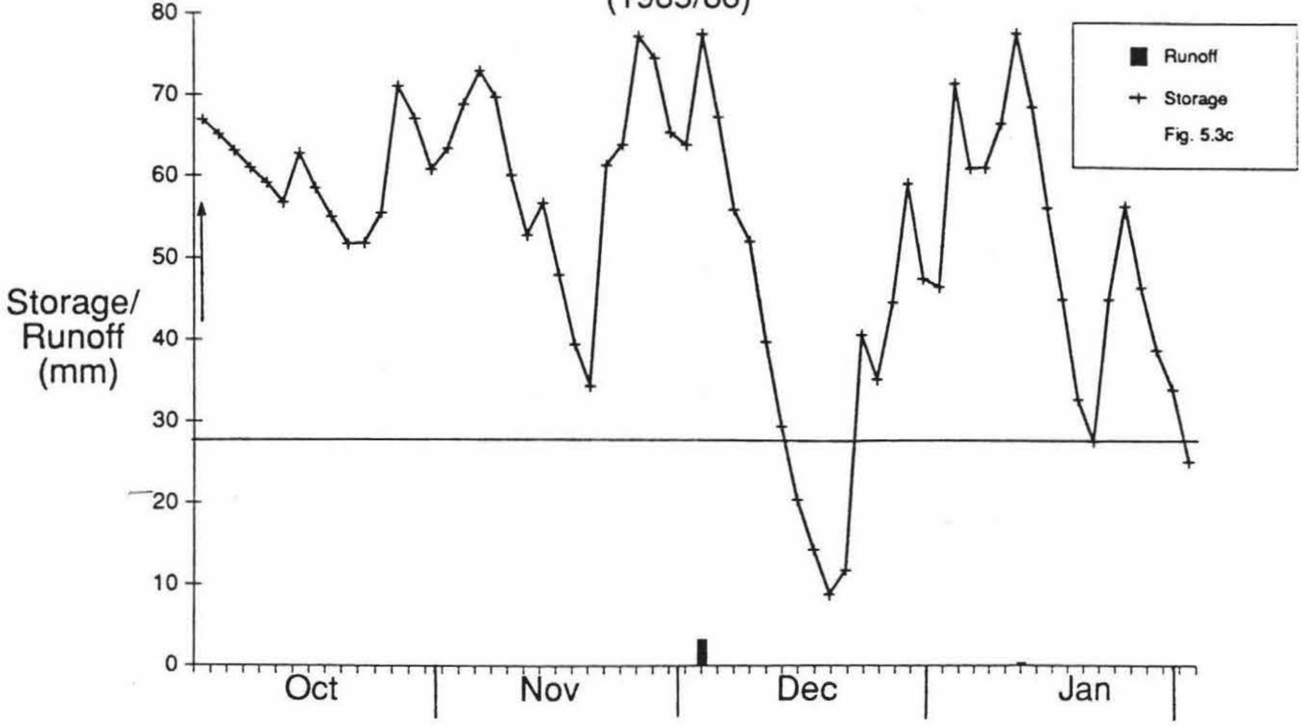


Figure 5.3a-h The soil water balance for each site for the 1985/86 season. Sowing dates are indicated by an arrow and harvest day is the last day. The horizontal line indicates the level below which moisture stress will occur.

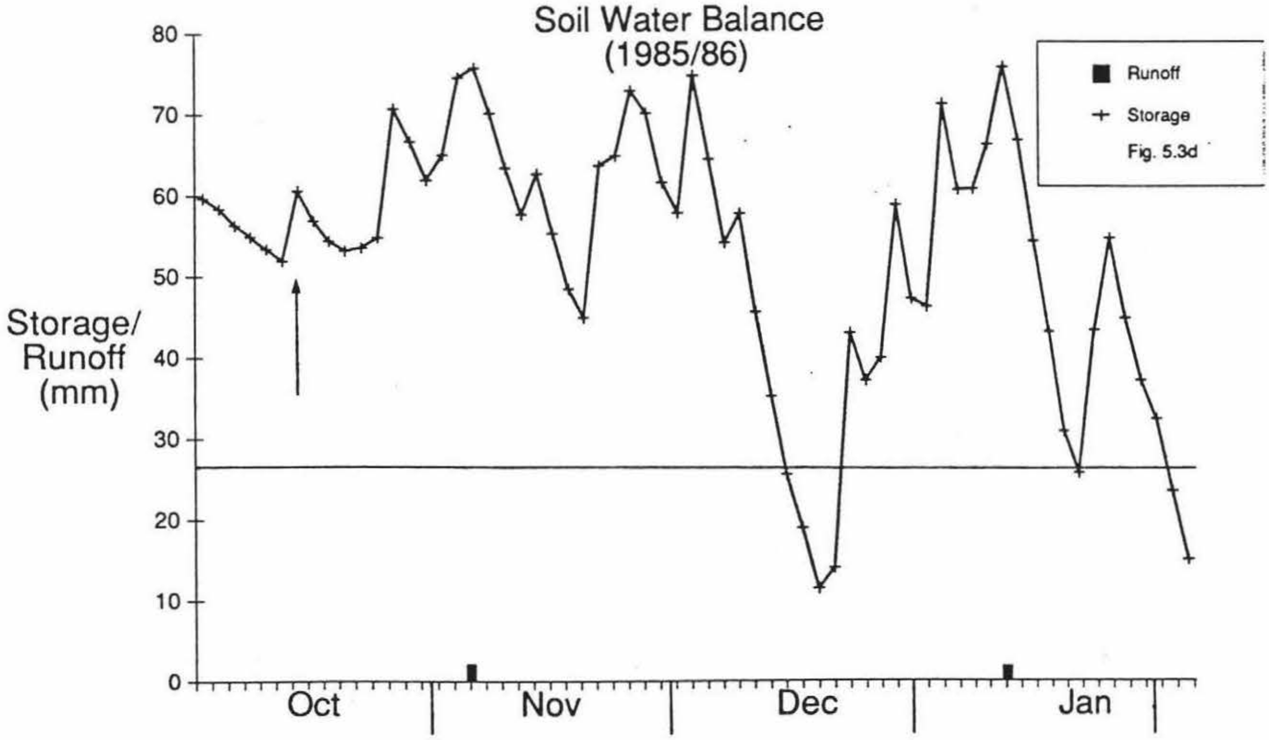
Marton-1

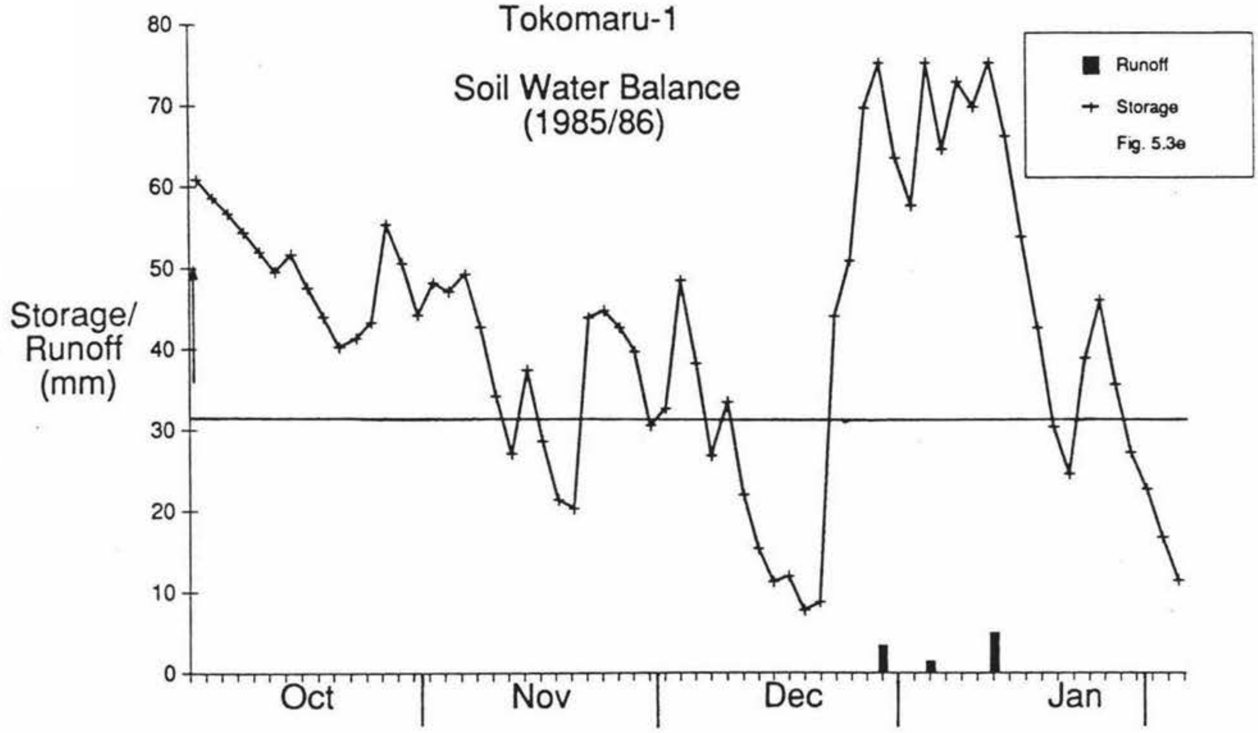
Soil Water Balance
(1985/86)

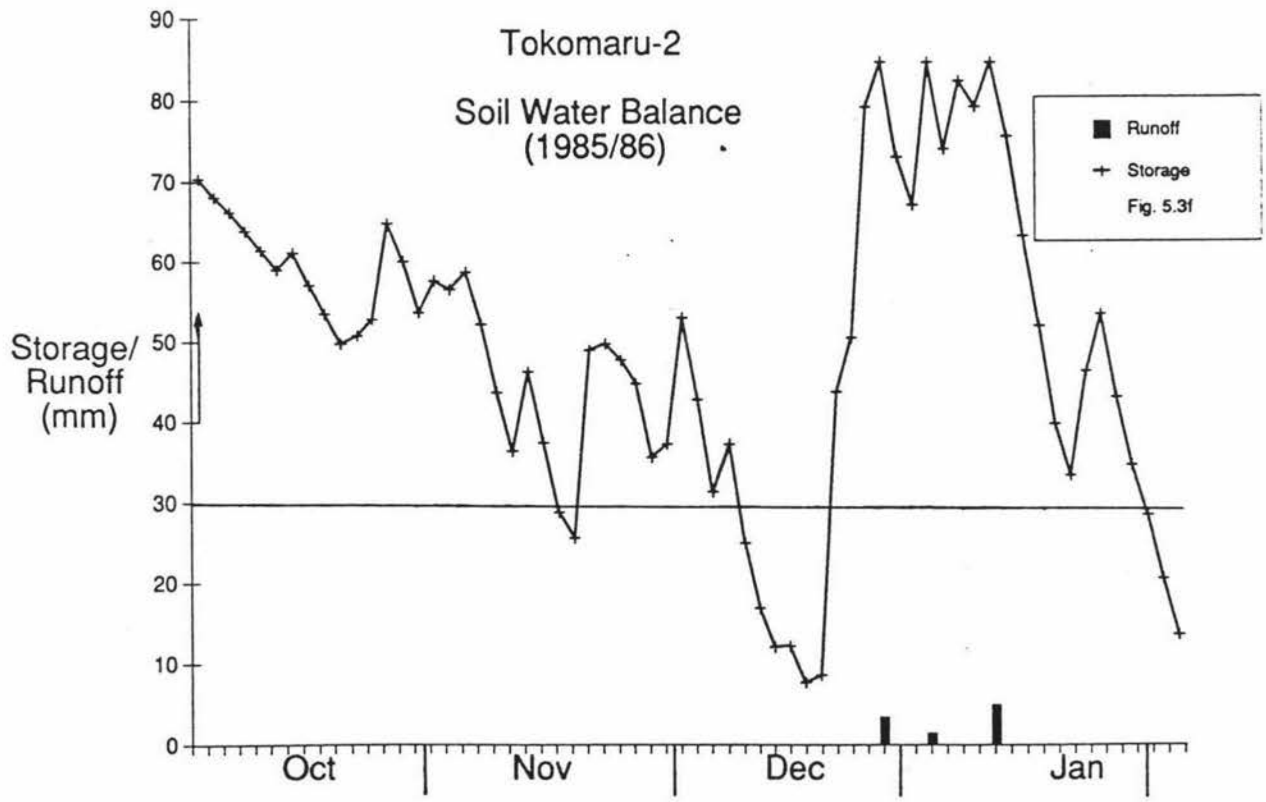


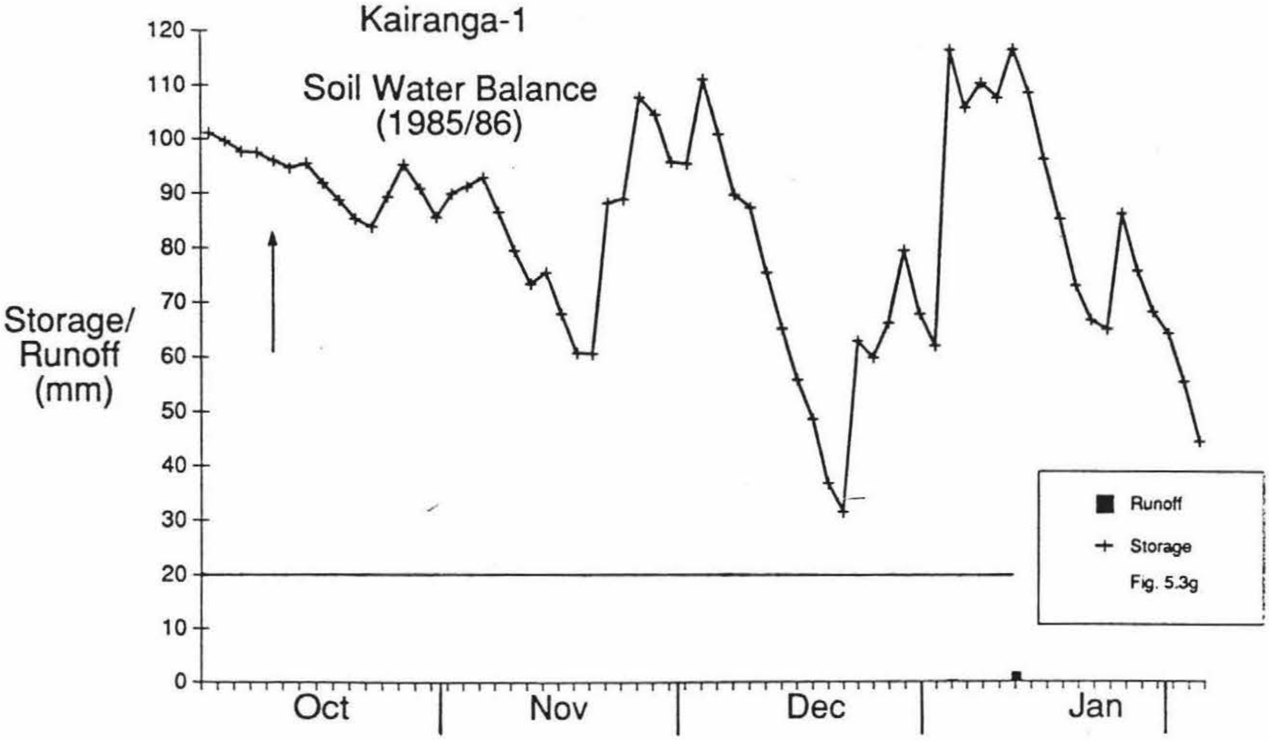
Marton-2

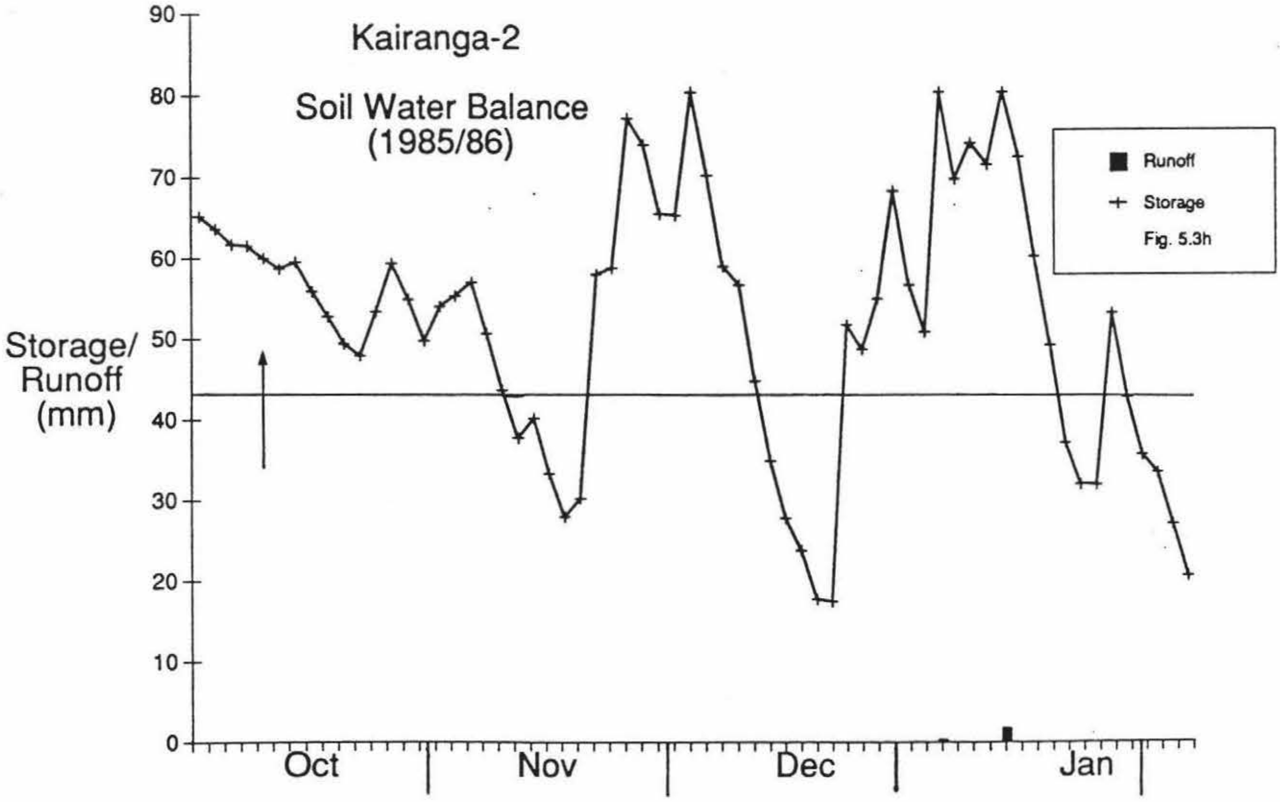
Soil Water Balance
(1985/86)




Tokomaru-1
Soil Water Balance
(1985/86)
Runoff
Storage
Fig. 5.3e
Storage/
Runoff
(mm)
80
70
60
50
40
30
20
10
0
Oct
Nov
Dec
Jan


Tokomaru-2
Soil Water Balance
(1985/86)
Runoff
Storage
Fig. 5.3f
Storage/
Runoff
(mm)
90
80
70
60
50
40
30
20
10
0
Oct
Nov
Dec
Jan


Kairanga-1
Soil Water Balance
(1985/86)
Storage/
Runoff
(mm)
120
110
100
90
80
70
60
50
40
30
20
10
0
Oct
Nov
Dec
Jan
Runoff
Storage
Fig. 5.3g


Kairanga-2
Soil Water Balance
(1985/86)
Storage/
Runoff
(mm)
90
80
70
60
50
40
30
20
10
0
Oct
Nov
Dec
Jan
Runoff
Storage
Fig. 5.3h

throughout most of the season (October to mid January), at all sites. A dry period was experienced in mid December for about a week, and then from mid January onwards.

The heavy rain in late December and early January caused runoff at all sites. Some runoff also occurred earlier in the season on the sites with a lower TAWC (the Kiwitea and Marton soils).

The moisture stress days correspond to the periods where soil water storage is below the horizontal line equal to [TAWC - RAWC]. Moisture stress limits crop growth until the anthesis development stage is reached. After this stage until harvesting, a period of about 14 days, moisture stress is no longer limiting. The decrease in crop canopy during senescence has not been allowed for in the model and moisture stress will enhance grain drying before harvesting (Gallagher et al, 1983). Therefore the number of moisture stress days accumulated until 14 days prior to harvesting is considered a better measure of the moisture stress limiting crop development and final yield.

Moisture stress days have been used to show the distribution of moisture stress through-out the season (Fig. 5.4). The other moisture stress parameter (ratio Ta/Tp) shows a close relationship to the number of moisture stress days. As expected the two Kiwitea soils with similar available water content values behaved identically, as did the Marton soils. There is a small difference between the Tokomaru soils with the higher number of stress days occurring in the soil with lower available water content. The Kairanga soil shows a marked difference. The difference is due to Kairanga-1 having a much higher RAWC than

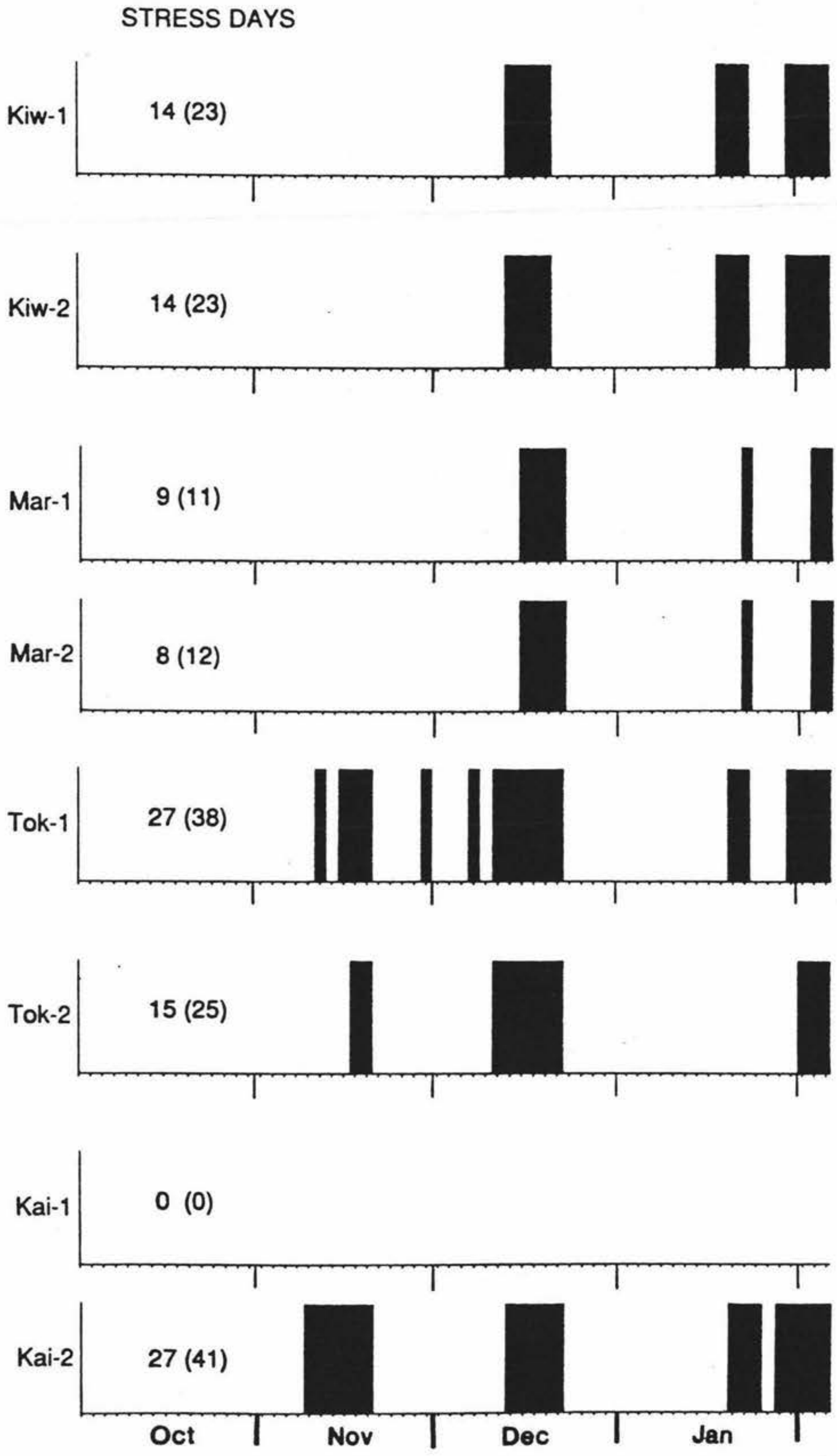


Figure 5.4 Distribution of moisture stress days at each site for the 1985/86 season. Included is the number of moisture stress days until 14 days before harvesting and in brackets the total number of moisture stress days until harvesting.

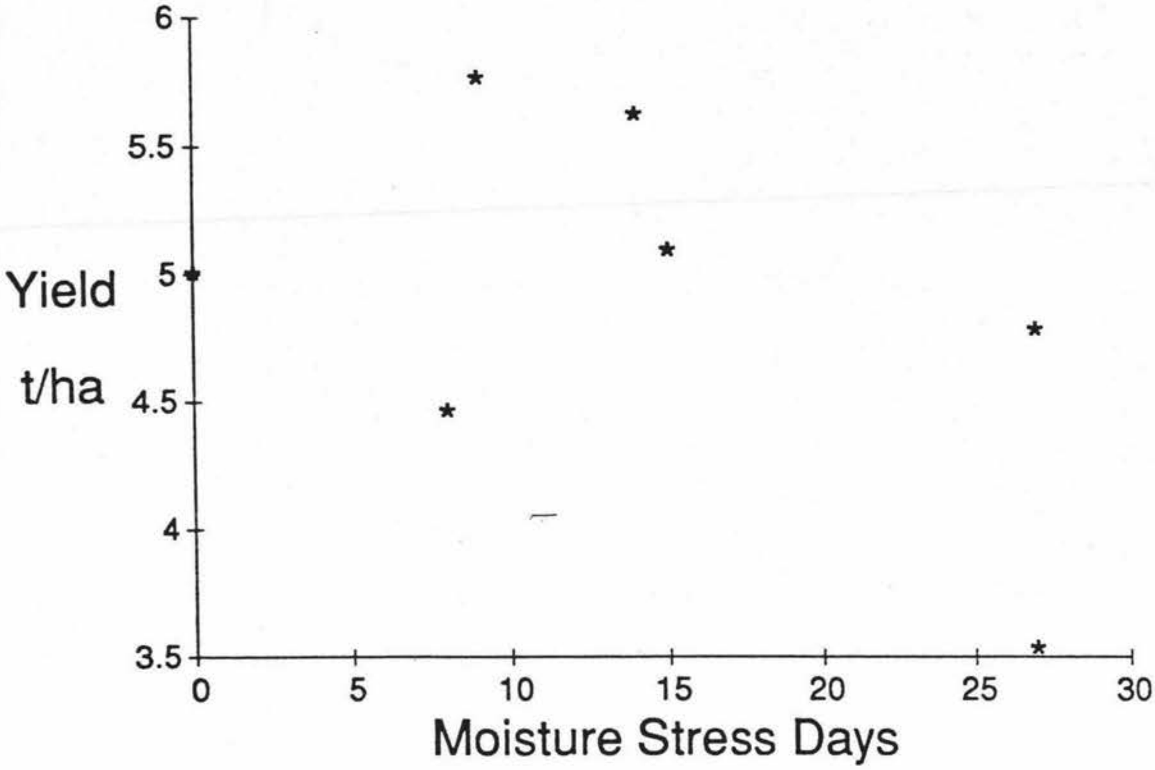
Kairanga-2 and so is more able to survive a dry period, rather than a climatic difference as both sites are located near each other.

Water supply is a major limitation to crop yield. Therefore it was anticipated that there would be a relationship between yield and the parameters used to access moisture stress. The relationship between moisture stress days (Fig. 5.5) and the ratio Ta/Tp (Fig. 5.6) showed no relationship with yield for the 1985/86 season. The high ratio of Ta/Tp (≈ 0.9 for most sites) indicates that soil moisture stress did not greatly reduce transpiration and therefore would not have a major impact on yield reductions.

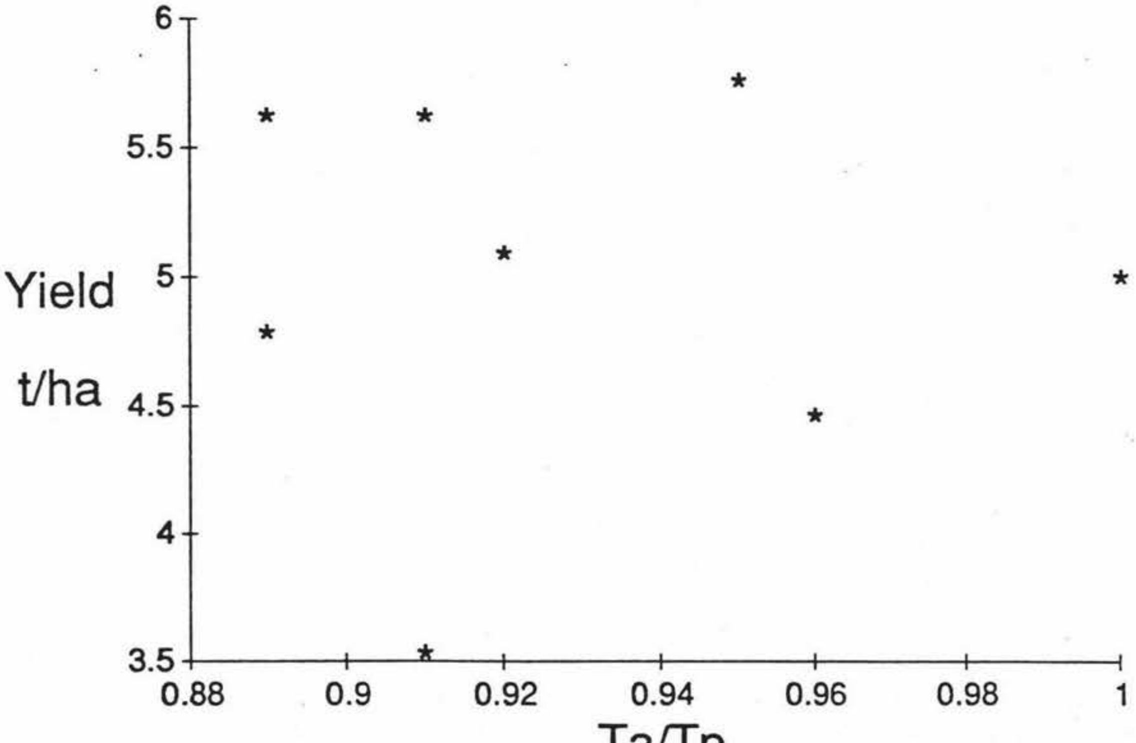
5.4 Discussion - 1985/86 Season

The model developed is simple and restricted to crops well supplied with nutrients and free from disease. Before a discussion on the information provided by the soil water balance can proceed, its accuracy needs to be appraised. The best way to evaluate the soil water balance is to make field moisture measurements at intervals throughout the season to compare with the model predictions. As already mentioned this validation did not eventuate. Therefore an empirical approach shall be used to assess the variability. Sources of inaccuracies in the model are in the method used to calculate water-holding capacities, ET estimates, and rainfall measurements.

Rainfall gauges may have a measurement error of 2 - 9% (Scotter *et*



<u>Figure 5.5</u> Total number of moisture stress days plotted with yield for the 1985/86 season for all sites.



<u>Figure 5.6</u> Ratio of actual transpiration and potential transpiration (Ta/Tp) plotted with yield for the 1985/86 season at all sites.

al, 1979a). The error in estimating Priestly and Taylor ETp from a barley crop was about 9 to 15% for standard daily meterological data (Jamieson, 1982; Kerr, 1984), but will be less for longer periods. A 5% lower rainfall and 10% higher ETp systematic error when applied to the Tokomaru-2 site can lead to an extra 8 moisture stress days over the growing season.

The limitation of the method used to assess available water capacity has been outlined in some detail in Chapter 4. The available water capacity is determined by the rooting depth of the plants and the soil water retention characteristics. To show the possible variation in moisture stress days due to soil water the model was rerun for a few sites, but with water holding capacities adjusted by ± 20%. It was assumed that TAWC and RAWC would change proportionally. The number of moisture stress days significantly decreases as available water storage increases (Table 5.1). The large variability supports the need to carefully define water holding capacities for water balance models.

The soil water balance has an advantage in that errors are not compounded. The model will tend to correct itself as soil water storage approaches either the upper boundary (W=TAWC) or lower boundary (W=0). For this reason and the fact that the model has been put together from proven research in soil water studies, the prediction by the model is likely to be close to actual field conditions.

As expected there is a close relationship between available water holding capacity and the moisture stress parameters.

Table 5.1 Variation in the total number of moisture stress days for 1985/86 season when available water holding capacities are adjusted by ± 20%.

Site	Accumulated Stress Days		
	+20%	0	-20%
Kiwitea-2	10	14	17
Marton-1	7	9	13
Tokomaru-2	10	15	26
Kairanga-1	0	0	1

A soil with a higher water holding capacity has a better ability to prevent moisture stress during dry conditions. This is particularly noticeable with both Tokomaru soils which were modelled under the same climatic conditions from Ohakea meterological data. The Tokomaru-1 soil has a lower water holding capacity and more stress days than Tokomaru-2. Modelled with Kairanga meterological data were the two Kairanga soils which followed the same trend. This illustrates the importance of an adequate root system to explore the soil for meeting the evaporative demands of the atmosphere as well as to provide nutrients.

Previous studies have shown that there is a close relationship between crop yield and moisture stress parameters (Section 5.1.4).

Most of these parameters have a good predictive ability when the crop is suffering more than slight moisture stress. In the 1985/86 season barley yields for this region were down by 30% compared to the long term average, dropping to an average of 3.5 t/ha (Hampton and Milner, 1986). Yields on sites used in this study were higher than the regional average as farmers selected were among the better growers (Section 2.2). However there is still an obvious lack of correlation between crop yield and any of the moisture stress parameters (Fig. 5.5 and Fig 5.6). The lack of correlation is probably due to a number of complicated and interrelated processes.

(1) Rainfall was 30%, 40%, and 60% above normal for November, December and January respectively. The wetter than average season has precluded any significant moisture stress occurring.

(2) It is possible that the surplus water during the season, (indicated by runoff on the soil water balance) may not have been removed quickly enough and remained ponded on the surface as observed at the Tokomaru site (Fig. 3.18). Poor soil aeration (Section 3.4.4) at these sites may have been a contributing factor to yield reduction.

(3) Temperatures for the 1985/86 season were 2°C above average in December and 3°C above in January. Statistical studies have frequently shown that cool summers are associated with large barley yields (Jones, 1979). High temperatures cause grains to be lighter by shortening the period of grain filling (Gales,1983).

(4) The moist soil combined with the warm temperatures encouraged

lush growth in the spring. Later in the season the leafy plants lodged, reducing yield.

(5) From mid November the wet, warm, and humid season provided the right environment for diseases to contribute to yield reductions. Comparisons of disease impact between sites were not made. In the region disease (spot blotch/foot root, and fusarium foot rot/head scab) played an important part in substantially reducing the crop yield in the region (Hampton and Milner, 1986). However, these diseases are possibly a manifestation of the soil physical properties as they are soil and seed borne.

(6) The excess moisture would have leached mobile nutrients (eg. nitrogen) away from the roots, affecting plant growth.

(7) To make better comparisons between sites, it would be useful to have detailed plant physiological data, as moisture stress will effect the final crop yield differently depending on what stage of development it occurs in.

(8) The heavy rainfalls towards the end of the season created traction problems on the poorly drained soils, preventing farmers harvesting the grain when it was at optimum quality.

5.5 Extension

5.5.1 Introduction

The soil water balance model is a useful tool for showing soil water storage fluctuations over a season and for enabling parameters which measure the water supply to crops to be assessed and ultimately related to crop yield. Once the model has been validated, the logical extension is to use it to simulate various outcomes by varying the input factors. Such factors might be increasing water holding capacity or more importantly the effect of different climatic seasons. The effect of changing the soil water holding capacity has been already discussed in the previous section when the soil water storage errors were considered. The following section focuses on the effects of different climatic seasons.

This section proceeds on the assumption that the soil water balance model outlined is reasonably accurate. It is not necessarily precise enough to give absolute estimates on moisture parameters, but accurate in that the trends between sites and years show relative differences. These relative differences will be used as the basis of discussion on possible implication of soil water to future cropping in the Manawatu - Rangitikei region.

To study the year to year variability climate data from previous seasons were used. October is usually the month when the crop is sown, germination occurs and the young seedlings start developing. Moisture stress over this month is not common as rainfall is high enough to meet the crops demands. Therefore, years were selected on the basis of rainfall for the November - December period, a critical time for crop development. Moisture stress in these months will have repercussions on the plant development, grain fill, and ultimately yield.

A wet, average, and dry November - December period should provide moisture stress data covering the range of possible climatic conditions. From the previous 15 years the last 3 seasons best cover this range. Rainfall data from the Ohakea meterological station used for the selection is shown in Table 5.2 along with the long term mean and percentile values.

The model was run on a selection of the sites for each of the seasons. It was assumed that sowing occurred on October 10th and harvesting 3 months later. Moisture stress parameters were accumulated to 14 days prior to harvesting as was done in the previous section.

5.5.2 Results

The sites chosen were Kiwitea-2, Marton-1, Tokomaru-2, and Kairanga-1. These sites represent the range of soil types and water holding capacities for the soils investigated. The years and corresponding season conditions are, 1985/86 - wet, 1984/85 - average, and 1983/84 - dry. Figure 5.7 shows the moisture stress day

Table 5.2 Rainfall data from Ohakea showing long term mean, 10 and 90 percentiles values for the months of November and December. The following years shall be used for wet (1985/86), average (1984/85), and dry (1983/84). Note, the dry season is not near the 10 percentile value.

	Monthly Rainfall (mm) Nov	Dec	Total
Ohakea			
90 percentile values	121	134	
Mean (1949-80)	68	84	152
10 percentile values	28	28	
1985/86	80	198	278
1984/85	83	77	160
1983/84	37	80	117

distribution and Figure 5.8 the ratio of Ta/Tp. It should be noted that the results for the 1985/86 season here are slightly different from those of the previous section. This is because all sowing and harvest dates have been assumed to be the same. This is to allow comparison of sites between years.

The following points can be made from Figure 5.7;

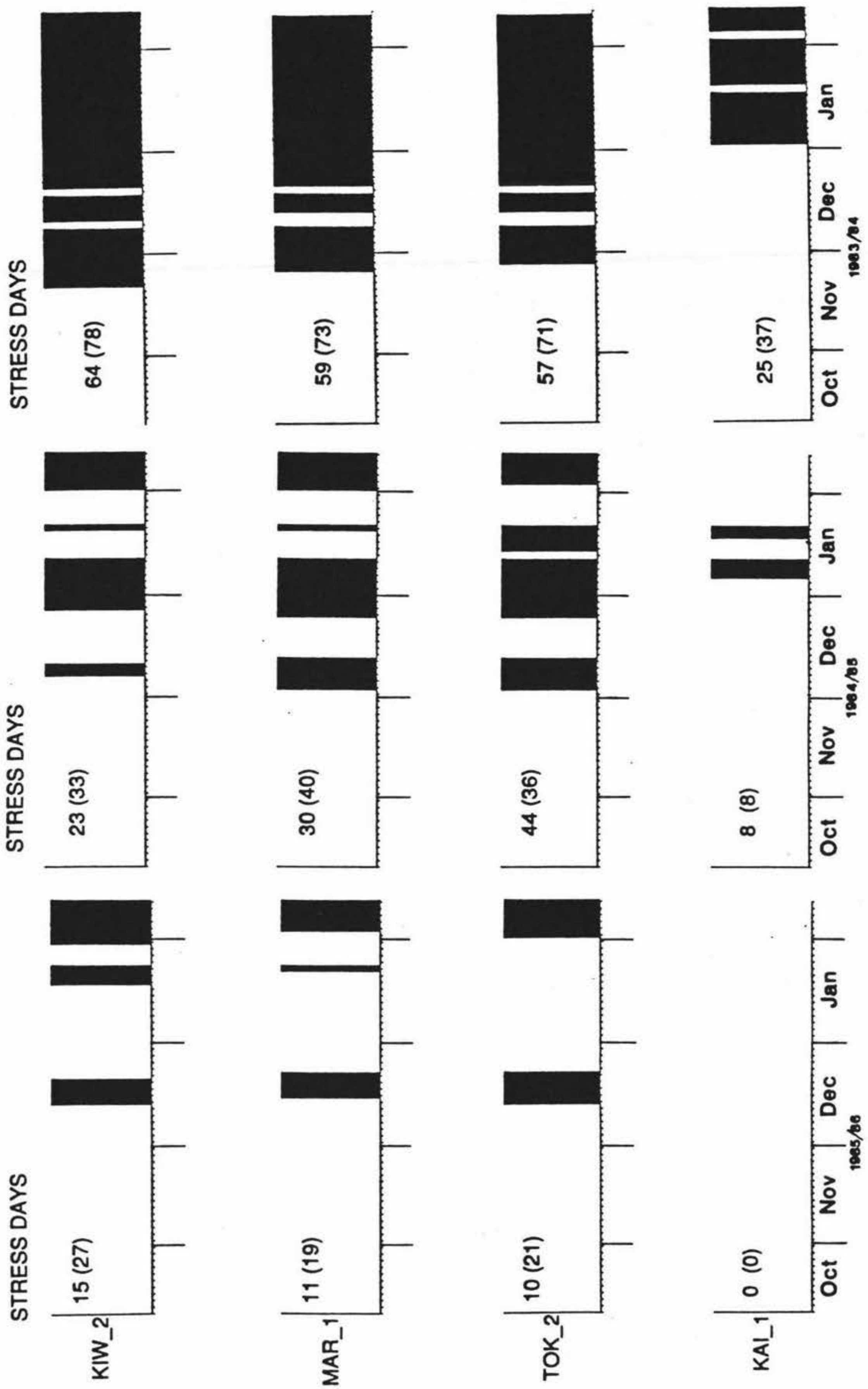


Figure 5.7 Distribution of moisture stress days for the wet (1985/86), average (1984/85), and dry (1983/84) seasons at four selected sites. The first day is 10th October when the hypothetical crops were sown, and the last day 10th Feburary when they are harvested. Included is the number of moisture stress days until 14 days before harvesting and in brackets the total number of moisture stress days until harvesting.

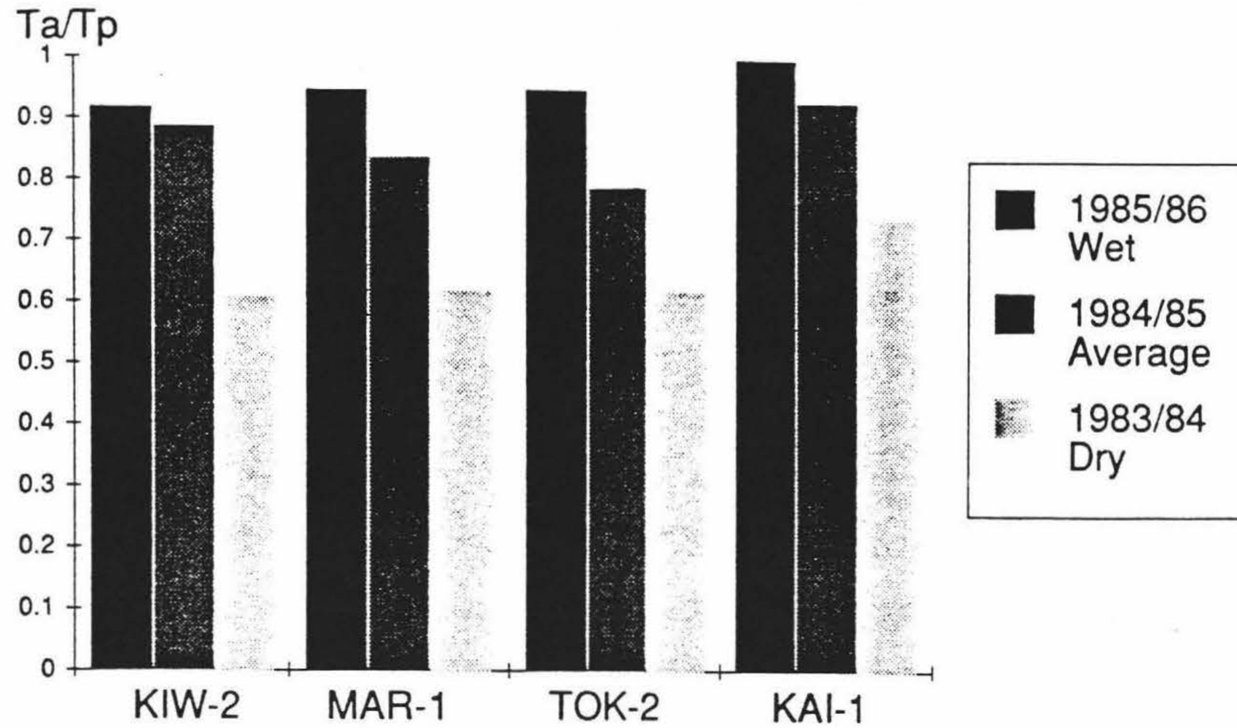


Figure 5.8 Ratio of actual transpiration and potential transpiration (Ta/Tp) for the wet (1985/86), average (1984/85), and dry (1983/84) season at four selected sites.

- The number of moisture stress days increased in the drier season.

- The frequency of moisture stress days varies between sites.

- No moisture stress occurred in October and little occurred in November. The earliest onset of stress was 20th November, which came in the 1983/84 season.

- The drier the season the earlier moisture stress starts occurring.

- For all seasons and sites (except for Kairanga-1 in a wet season), moisture stress always occurs in late January - February.

- An obvious feature is the distinct difference of Kairanga-1 to all the other sites. The Kairanga-1 site always has fewer moisture stress days than the high terrace soils, and all the high terrace soils behave similarly.

The ratio of Ta/Tp (Fig. 5.8) supports the above points concerning moisture stress from figure 5.7 (ie. increased stress in a drier season, variation in moisture stress between sites, and Kairanga-1 is distinctly different to the other sites). There is little difference in Tp between seasons for each soil type, so potential yield for each season would almost be the same. Assuming soil moisture is the only limiting factor, then from equation 5.1 the results indicate that actual yield compared with potential yield for each year: is not significantly reduced (<8%) in the wet season; a 10 - 20% reduction could be expected in an average year; and for a dry year, a 25% and 40% reduction for the Kairanga-1 soil and the high terrace soils respectively, could be expected.

5.5.3 Discussion

The problem of low available water capacity in the soils is compounded by them occurring in areas of low summer rainfall. Moisture stress in the Manawatu-Rangitikei region will be a significant factor in all but the wettest season for limiting potential crop yields. As a guide, yield reduction due only to moisture stress are of the order 10

- 20% in an average year and 40% in a dry year (for the high terrace soils). It should be noted that, the worst possible condition has not been assessed for the dry end of the range, as the year used for the dry season (1983/84) is nowhere near the driest possible (Table 5.2). In a wet season aeration is likely to be a limiting factor.

The variability in the number of moisture stress days and the ratio Ta/Tp between sites and seasons indicates that there is likely to be significant variability in actual crop yield. There is a large difference between seasons for all soils, and also within a season between the high terrace soils and the river plain soils. The timing of moisture stress will have an important influence on the final yield and should be considered in more detailed soil water - plant studies.

The rapidity with which a crop is placed under stress will be influenced in part by the physical properties of the soil on which it is grown. For example, the large RAWC of Kairanga-1 leads to this site having many fewer moisture stress days than the other sites.

Not considered in the model, but important to the Kairanga soils is the upward movement of water from a ground water table. For a clay loam soil, in mid summer, with a water table at a depth of 1.7m, 1 mm-day^{-1} could be added to the available water content (Marshall and Holmes, 1979).

It is rare for moisture stress to occur before 1st December. The occurrence of moisture stress days between 1st December and 2 weeks before harvesting (ie. total of 58 days) for the dry season is nearly every day. For an average season 1 day in 2 could be expected to be a stress day, although the stress days would normally be expected to occur in groups and towards the end of the season.

It has been assumed that nutrients are not limiting to crop yield. But it is likely that before moisture stress occurs, the soil surface would be dry and nutrient stress would have already started to limit plant development. This is an important interaction that will need to be considered when more complex soil water balances are used.

5.6 Conclusions

The following conclusions may be drawn:

i) The simple model developed shows fluctuations in soil water storage over a cereal growing season. The model was not validated, due to unforeseen circumstances.

ii) There was a good relationship between the available water capacity and moisture stress. The soils with higher available water capacities had a lower number of moisture stress days.

iii) The relatively wet season combined with a low macroporosity, would have lead to poor soil aeration problems being a significant limiting factor to potential yield for the 1985/86 season.

iv) There was no relationship between moisture stress and yield for the 1985/86 season. This was due to the nature of season where other factors were more limiting - disease, excess water, and air temperature.

v) The river plain soils behaved distinctly differently from the high terrace soils. This follows a similar pattern outlined by the soil physical properties in Chapter 3.

vi) The water balance model covered a wet, average, and dry November to December period. It showed that soil moisture was highly variable between years. The drier the year the earlier the onset of water stress. The earliest predicted onset was 20th November, for the 1983/84 season.

vii) The low available water capacities for the high terrace soils makes them very prone to drought conditions. In an average year 1 day in 2 can be a moisture stress day for the December to January period, increasing to almost every day for a drier season. This leads to a predicted reduction in potential yield of 10 - 20% for an average year and 40% for a drier year. The Kairanga-1 soil is less prone to drought with 1 day in 6 a moisture stress day, and a predicted yield reduction of 20% for the driest year.

viii) The model showed that there is a large difference in moisture stress for all soils from year to year, and within a season between the soil types on the high terraces and the river plains. These results indicate that seasonal variations will have a significant effect on crop yields and that yield variation may occur between the high terrace soils and the river plain soils.

CHAPTER 6

CHAPTER 6

SYNTHESIS

6.1 Introduction

The preceding chapters outline the affect of soil physical properties on root development, and the influence this has on available water holding capacity. Using a soil water balance model this information is combined with climatic data to assess the potential impact of moisture stress on yields for some of the major cropping soils in the Manawatu-Rangitikei region. In this chapter the information is summarized to give an overview of the influence that soil physical fertility has on cropping in the region. Important areas requiring further research are identified and briefly discussed. Finally, the major conclusions from this study are stated.

6.2 An Overview

6.2.1 Factors affecting yield

These factors are outlined in Chapter 2. Of these, soil conditions, specifically soil physical properties are focused on. To do this the impact of the other factors on crop growth and yield must be minimized. In a study limited in duration, such as this one, minimizing the variation of the other factors, especially crop management on yield is difficult. Therefore sites were selected where yield data were being collected for other studies, so as to maximise the availability of complementary data.

6.2.2 Soil types

In Chapter 3, it is shown that the four soil types chosen can be divided into two distinct groups, ie. (i) soils on the high terrace developed in loess (Kiwitea mottled, Marton, and Tokomaru silt loams) and, (ii) the soils on the river plains developed in alluvium (Kairanga silt loam). This division was supported by comparing and contrasting soil profile descriptions and the soil physical measurements.

6.2.3 Soil physical properties

The high terrace soils can be characterised by their friable silt loam topsoil, with a medium bulk density (1.25 $Mg\text{-}m^{-3}$) and a saturated hydraulic conductivity (200-500 $mm\text{-}^{-hr}$) which will allow free drainage; over a compact, clay loam subsoil with dominant low chroma colours, a high bulk density (1.5 - 1.7 $Mg\text{-}m^{-3}$), and low saturated hydraulic conductivity (0-20 $mm\text{-}^{-hr}$); the boundary between the topsoil and subsoil has associated with it a zone of small concretions, indicative of water table fluctuating in this region. In contrast the alluvial river plain soils have weakly developed profiles, with a very friable, silt loam topsoil, however the subsoils are markedly different. One site (Kairanga-1) had a compact sandy loam subsoil with high chroma mottles, the other site (Kairanga-2) had a firm clay loam subsoil. The difference between the Kairanga soils highlights the large spatial variability of soil properties in these recent soils, both mapped as Kairanga silt loam. Topsoil bulk density is 1.3 and 1.0 $Mg\text{-}m^{-3}$ for the Kairanga-1 and Kairanga-2 soils respectively, and for the subsoil 1.5 and 1.2 $Mg\text{-}m^{-3}$. The saturated hydraulic conductivity is slightly higher in Kairanga-2 than Kairanga-1 throughout the profile. But both soils are better draining ($40mm^{-hr}$ in the subsoil) than the high terrace soils.

The soil physical properties that describe the growing environment of the plant are discussed in Chapter 3. Soil temperature over the October-February period is near an optimum level for plant growth and development. Compacted subsoil horizons, particularly in the Yellow-Grey Earths (Marton and Tokomaru soils) were a major limitation to deep root proliferation. The Kairanga-2 soil was the only one where subsoil strength was not high enough to impede roots. Water movement in all soils was restricted, particularly for the high terrace soils where the compacted clay loam subsoil had low saturated hydraulic conductivity. In a wet season, (for example 1985/86), excess water was prevented from draining away through the profile and tended to saturate the upper soil horizons. Therefore artifically drained soils with a high proportion of macropores particularly in the topsoil (Kairanga and Kiwitea) would be better aerated over these wet periods. Crops on these soils appeared to be less stressed, and were more likely to yield higher than the Yellow-Grey Earth soils. Aeration would not normally be expected to be a limitation to crops over the summer growing season.

6.2.4 Soil water storage

As this season was wet and there was little need for roots to search extensively for water. Roots would not be expected to explore the soil much deeper in a drier season because of the soil physical properties, especially the soil strength impeding downward root development. Maximum visual root depth in all soils was about 70cm, although the majority of roots occurred in the topsoil. In a drier year it would be expected that roots would explore the same depth of soil more extensively, particularly in the topsoil, and also in the subsoil for the Kairanga soils. The high terrace subsoil ped strength would be very difficult for roots to penetrate.

Rooting depth and distribution is one of the main factors that determine the available water capacity. In Chapter 4 it can be seen how shallow rooting depth lead to most of these soils having low available water-holding capacity. An average value for the total available water-holding capacities are: Kiwitea - 65mm, Marton - 77mm, Tokomaru - 80mm, Kairanga silt loam on sandy loam - 116mm, Kairanga silt loam on clay loam - 80mm. More important to crop growth is the readily available water. Of the TAWC for the high terrace soils 60% was readily available. In contrast, Kairanga-1 and Kairanga-2 soils have 90% and 50% of TAWC readily available, respectively.

6.2.5 Soil type differences

The data clearly shows the contrasting trends that occurred between soil types in this study. The two Yellow-Grey Earth soils (Marton and Tokomaru) behave very similarly and the other high terrace soil type (Kiwitea) follows a similar pattern. The Kairanga soils behave distinctly differently from the high terrace soils and the difference within this soil type exemplifies the variability found within these recent alluvial soils. Parent material of the alluvial soils is not uniform, because of sedimentation from changing river flood patterns and intensities. Variability between soils of the same type on the high terrace was negligible. This is due to the uniform soil parent material, loess.

6.2.6 Water balance model

To analyse the onset, and extent of moisture stress on these sites a soil water balance model was developed in Chapter 5. The model was not validated by field measurements. However, because it has a sound physical basis a significant error is not anticipated. Rather than give an absolute measurement of moisture stress, the model was used to indicate relative differences between sites. The two inputs to the model were available water capacities and climatic data. Rainfall, the main climatic variable was nearly constant over the region in 1985/86. Therefore available water-holding capacity at each site, the other main input, had an important influence on the number of moisture stress days.

6.2.7 Moisture stress and yield

For the 1985/86 season there was no correlation between crop yield and the number of moisture stress day or the ratio of Ta/Tp, as shown in Chapter 5. It is likely that the lack of correlation was due to an unusual wet spring-summer growth season. The wetter than average season prevented any significant moisture stress occurring, and the wet, warm, humid conditions provided an ideal environment for diseases. Disease was a major direct factor governing the estimated 30% reduction in average yield compared to long term averages (Hampton and Milner, 1986). In Chapter 2, when sites were selected it was stated that crop yields depend on the most limiting factor, and that this was the soil condition, specifically soil physical properties. The influence of disease on yield was assumed to not be a major determinate of yield between sites and no account was made on how disease may have affected each yield. In hindsight this assumption for the 1985/86 season is incorrect. However, the diseases may have been a manifestation of the soil physical properties (soil temperature, soil moisture, and soil aeration). This study indicates that other factors related to poor drainage and aeration may also have been a contributing factor to yield reduction, as discussed above. As well, the wet January conditions posed problems harvesting the crop at its optimum quality because of traction problems on the poorly drained soils.

6.2.8 Water balance model extensions

Other studies (Kerr et al, 1986; Ritchie, 1980; Gales, 1983) have shown that climate and soil type are usually the major causes of yield differences between sites and between seasons. The soil data presented in Chapter 3 and Chapter 4 does not vary between seasons. The soil physical properties are specific to the sampled site and generally applicable to a soil of the same soil type. Although care has to be taken with the river plain soils because of the soil variability.

The advantage of a water balance model is that various scenarios can be run to indicate what may happen under certain conditions. This was done in Chapter 5 with selected wet, average, and dry climatic seasons, for a few sites using the same available water-holding capacity data. Again, it was assumed that disease, nutrient status, and management had no influence on final yield.

The soil water balance model showed that the soil moisture status was highly variable between seasons, and between the soils on the high terrace and those on the river plain. For the drier season (1983/84) the initial onset of moisture stress occurred as early as 20th November. The model computed 25-64 moisture stress days occurred, depending on soil type. This caused a predicted reduction in yield due to moisture stress of 40% and 25% for the high terrace soils and Kairanga-1 soil respectively. For an average season, 8-44 moisture stress days occurred depending on soil type, causing a predicted 10-20% reduction in yield for all soils. The extent of moisture stress for a particular season depends on the ability of the soil to hold available water. The low available water-holding capacities for all sites (except Kairanga-1) makes these soils prone to drought conditions. Soil conditions could, therefore, account for a large part of long term yield variation, both directly, and indirectly through interactive effects with the weather. Date of sowing could also account for some of the variation but this is usually dependent on soil conditions anyway.

6.3 Implication Of Soil Physical Fertility To Land Use

Soil versatility describes the suitability of the soil for alternative land uses. It is mainly assessed in terms of physical properties, as soil nutrient limitations are highly management dependent and can be overcome. The river plain soils are more versatile than the high terrace soils, as they have higher plant available water capacities, lower subsoil bulk densities, higher macroporosity, and better soil drainage (the ground water table will need to be controlled however). The Kiwitea soil is more versatile than the Marton and Tokomaru soils, as it has a more stable topsoil structure, a higher volume of macropores, and better subsoil drainage, making it suitable for many land uses. Low available water holding capacity is a handicap to Kiwitea soils but it is partly compensated for by the slightly higher and evenly distributed rainfall found in this part of the region. There is no difference between the versatility of the two Yellow-Grey Earth soils. Both soils have low macroporosity, a subsoil difficult for roots to penetrate, and poor drainage.

The 1985/86 season illustrated how excess moisture in the growing season indirectly reduced yield and prevented harvesting at the optimum stage. More importantly, a wet early spring will delay cultivation and seedbed preparation. Therefore the crop will be sown later, having serious consequences on the crop development and making it more vulnerable to the probable moisture stress in the latter part of the season. The beginning of the 1986/87 season illustrates this point. Many farmers were not able to sow their crops on these soils because of a wet September - October. They are now having to consider other options as it is too late to sow cereal crops. An advantage of growing barley is its ability to develop in the cool spring temperatures, and to mature rapidly, taking advantage of the available rainfall in early summer before the summer drought conditions begin. Control of soil profile drainage and water tables is thus important. The installation of some kind of field drainage system becomes a necessity with intensive use of these soils.

Rooting depth in the high terrace soils is severly impeded by the compact subsoil. Farmers have queried whether deep ripping of the soil would be advantageous. It is recommended that mole ploughing on the soils is a better option as it serves a dual purpose of removing excess moisture, and encourages deeper rooting through cracks and improved soil aeration.

6.4 Further Research

1) In this study it was demonstrated that the longest cropped site in each of the Marton and Kairanga soils had a lower organic carbon content than the other site of the corresponding soil type, and the longest cropped soils out of the eight sites had the lowest organic contents, indicating that topsoil structure stability is at risk. Clearly there is a need for detailed studies, indicating to farmers the effects on yield of:

i) continuous cropping on soil structure and cultivating the soil under inappropriate conditions;

ii) if structural instability does reduce yield, then an estimate of the number of years a particular soil type (under a particular management) can be used.

iii) investigating whether incorporation of stubble back into the soil, to improve organic matter content, is more benefical than burning it to control disease, which proliferates in a monocrop system;

iv) an economic analysis taking into account yield reductions and the increase in the effort to prepare a seedbed over time.

2) The soil physical data used in this study have been interpreted for a barley crop and integrated into a soil water balance model. They equally could be applied to other cereal crops and/or land uses. A further extension of the water balance model would be to

assess the viability of irrigating a particular soil.

3) Early sowing provides higher and better quality yields, provided the soil is suitable for drilling. Gallagher (1983) outlines three reasons why:

i) longer period of growth achieved,

ii) better root growth,

iii) slower development before anthesis and slightly cooler temperatures during grain growth are associated with bigger grains.

Timing of cultivation is crucial, as the soil should not be worked when the moisture content is above the plastic limit. This will cause major trafficability problems, and deterioration of the soil structure. It is necessary for farmers to identify when the soil can be readily and safely cultivated. To do this farmers need a simple measure of when the soil is workable.

4) The interaction of soil moisture and nutrient uptake has been ignored in this study. These processes may sometimes significantly interact with plant growth rate and may affect final yield. This interaction needs to be considered with respect to the soil moisture status and weather.

5) Soil aeration was identified as a major soil limitation for plant growth. Further research is needed to assess the rate of soil aeration on plant growth and yield.

6) Disease was an important factor in reducing yield. The

interaction between disease and soil properties needs to be investigated.

6.5 Conclusions

The main conclusions that can be drawn from this study are:

1) The soils investigated in this study can be divided into two distinct groups, i) high terrace soils (Kiwitea mottled, Marton, and Tokomaru silt loams) developed in loess and ii) river plain soils (Kairanga) developed in alluvium. This is based on profile descriptions and soil physical data. The soil parent material has a major influence in determining the soil differences between these groups.

2) Most barley roots were observed in the top 30cm of the soil profile, and only a few below this depth to about 70cm. Compacted subsoils (1.5-1.7 Mg/m^3), slow saturated hydraulic conductivity (<20 mm/hr), and poor aeration (<10% large pores) were the probable causes restricting root depth in the high terrace soils. River plain soils gave results which indicated a more suitable rooting environment than the high terrace soils.

3) Restricted rooting depth lead to low (65-80 mm) TAWC for the high terrace soils and higher but more variable TAWC (80-116mm) for the Kairanga soils.

4) In the year of this study (1985/86) there was a range in moisture stress days (0-27 days) dependant on soil type. However, there was no correlation between the computed number of moisture stress days and crop yield. Thus other factors related to poor drainage and aeration, and disease problems affected yield more than moisture stress.

5) In a complex system such as the soil-plant-atmosphere one, this study has highlighted the difficulty of isolating one parameter, physical fertility, and the physical properties associated with it, and then to relate them to crop development and yield. This is especially true in a real field situation, as opposed to controlled trials where other variables are kept constant.

6) All sites (except Kairanga-1) had low available water-holding capacities. Therefore crops on these sites are prone to moisture stress. For a dry season the model computes 25-64 moisture stress days, and for an average season 8-44 days, depending on soil type. This caused a predicted yield reduction ranging from 10-20% in an average year to 40% (for a high terrace soil) in a dry year.

7) The rapidly maturing barley crop is suited to the conditions in this region. The important growth and development stages requiring moisture correspond to the period of seasonally high rainfall (November to December).

8) The compacted subsoils of the high terrace soils have very slow hydraulic conductivity. This combined with low macroporosity has

important implications on crop management for machine trafficability and maintenance of soil structure.

9) The two major land use limitations for these soils both involve water, namely poor drainage and the low available water holding capacity. Furthermore, both these limitations can be overcome by drainage and irrigation, if it is economic to do so. An economic evaluation can only be based on quantitative– research data concerning the drainage and irrigation effects on crop yield.

Appendix A

Appendix A
Profile Descriptions

A.1 Kiwitea mottled silt loam (1) (Kiw-1)

Location/Grid Reference: NZMS1 N143 866743 Marton, Bryces Line.

Landscape position: slope of hill on high dissected terrace; planar midslope, 3 degrees, length 70m, aspect south.

Elevation: 200m.

Drainage: Imperfectly drained.

Ap	0-17cm	Dark grey (10YR4/1); silt loam; slightly moist; weakly developed medium nut breaking to moderately developed fine nut and granular structure; sticky; slightly plastic; very friable; firm penetration resistance; many fine roots; distinct irregular boundary.
AB	17-20cm	Yellowish brown (10YR5/4) plus 40% dark grey (10YR4/1); silty clay loam; slightly moist; weakly developed medium nut breaking to weakly developed fine nut and granular structures; sticky; slightly plastic; friable; firm penetration resistance; common fine roots; diffuse irregular boundary.
Bw	20-34cm	Yellowish brown (10YR5/4); silty clay loam; slightly moist; weakly developed medium blocky breaking to weakly developed fine nut and granular structure; sticky; plastic; friable; firm penetration resistance; common very fine roots; indistinct wavy boundary.
Bg	34-130cm	Yellowish brown (10YR5/8); silty clay; slightly moist; abundant (30%) medium and fine prominent light yellowish brown (2.5Y6/3) mottles; massive structure; sticky; slightly plastic; firm; firm penetration resistance; At 85cm concretions start to appear, brittle 5mm diameter, black (7.5YR2/1); few very fine roots to 70cm; indistinct irregular boundary;
Cg	130-135+cm	Grey; silty clay; moist; massive structure; sticky; plastic; firm; no roots.

A.2 Kiwitea mottled silt loam (2) (Kiw-2)

Location/Grid Reference: NZMS1 N143 866743 50m downslope south of Kiwitea-1, in same paddock.

Landscape position: slope of hill on high dissected terrace. Planar midslope-toeslope, 3 degrees, 70m length, southerly aspect.

Elevation: 200m.

Drainage: Poorly drained.

Ap	0-23cm	Very dark brown (10YR2/2); silt loam; slightly moist; weakly developed fine nuts and fragments; slightly sticky; slightly plastic; friable; soft penetration resistance; abundant fine roots; distinct irregular boundary.
ABc	23-26cm	Light brownish grey (2.5Y6/2) plus 25% very dark brown (10YR2/2); silt loam; slightly moist; weakly developed medium blocky structure; slightly sticky; slightly plastic; firm; firm penetration resistance; many fine roots; 15%, 7mm diameter, hard, black (7.5YR2/1) concretions; diffuse irregular boundary.
Bgc	26-42cm	Light brownish grey (2.5Y6/2); gritty silt loam; slightly moist; weakly developed medium nuts and fragments; slightly sticky; slightly plastic; firm; firm penetration resistance; many fine roots; 35% concretions as above; distinct wavy boundary.
Bg	42-73cm	Pinkish grey (7.5YR6/2); silty clay loam; slightly moist; many (15%) medium distinct light brownish grey (2.5Y6/2) mottles; massive structure; sticky; plastic; firm; stiff penetration resistance; 15% concretions as above, predominantly in upper 20cm; few very fine roots; sharp smooth boundary.
C	73-83+cm	Highly weathered brittle sandstone.

A.3 Marton silt loam (1) (Mar-1)

Location/Grid Reference: NZMS1 N143 922696 Marton, Calico Line.

Landscape position: Surface on high slightly dissected terrace.

Elevation: 160m.

Profile Drainage: Poorly drained.

Ap	0-22cm	Very dark greyish brown (10YR3/2); silt loam; moist; moderately developed fine nut plus fragment structure; slightly sticky; plastic; friable; firm penetration resistance; many very fine roots; sharp irregular boundary.
ABg	22-25cm	Colours mixture of above and below; silty clay; moist; few distinct dark brown (7.5YR3/3 mottles; moderately coarse blocky structure; sticky; plastic; firm; stiff penetration resistance; many very fine roots; few fine black (10YR2/1) concretions; diffuse irregular boundary.
Bg1	25-57cm	Strong brown (7.5YR5/8); Clay; moist; profuse (60%) medium prominent light grey (5Y7/1) mottles; strongly developed coarse blocky breaking to strongly developed fine blocky structure; very sticky; very plastic; firm; stiff penetration resistance; common distinct black (7.5YR2/1) organic coatings and/or concretions; common very fine roots often in fissures; indistinct wavy boundary.
2C	57-62cm	Light grey (5Y7/1); silty clay; moist; abundant (30%) medium prominent strong brown (7.5YR5/8) mottles; massive breaking to weakly developed medium blocky structure; very sticky; very plastic; very firm; very stiff penetration resistance; common very fine roots; indistinct wavy boundary; (Aokauterre Ash).
Bg2	62-90cm	Light grey (5Y7/1); clay; moist; abundant (30%) medium prominent strong brown (7.5YR5/8) mottles; massive breaking to weakly developed medium blocky structure; very sticky; very plastic; very firm; stiff penetration resistance; common distinct black (7.5YR2/1) organic and/or Fe/Mn coatings; common very fine roots to 75cm; diffuse irregular boundary.

uABg 90-110+cm Yellowish brown (10YR5/8); clay; moist; profuse (50%) coarse prominent grey (5Y6/1) mottles; massive breaking to moderately developed fine blocky structure; very sticky; very plastic; very firm; very stiff penetration resistance; common, distinct, black (7.5YR2/1) concretions; no roots.

A.4 <u>Marton silt loam (2)</u> (Mar-2)

Location/Grid reference: NZMS1 N143 926618 Greatford, S.H. 1.

Landscape position: Flat surface on high slightly dissected terrace.

Elevation: 100m.

Profile drainage: Poorly drained.

Ap 0-24cm very dark greyish brown (10YR3/2); silt loam; slightly moist; moderately developed medium nuts and fragments; slightly sticky; slightly plastic; friable; firm penetration resistance; many fine roots; indistinct irregular boundary.

ABg 24-27cm Yellowish brown (10YR5/8), plus 30% very dark greyish brown (10YR3/2), plus 30% grey (2.5Y6/0); silty clay loam; slightly moist; weakly developed medium blocky structure; slightly sticky; plastic; friable; firm penetration resistance; many fine roots; distinct irregular boundary.

Bg1 27-52cm Light brownish grey (2.5Y6/2); silty clay; slightly moist; abundant (40%) medium prominent yellowish brown (10YR5/8) mottles; massive breaking to weakly developed blocky structure; sticky; plastic; firm; firm penetration resistance; common very fine roots; 5% hard, fine, distinct, very dark brown (7.5YR2/2) concretions; diffuse wavy boundary.

Bg2 52-110cm light brownish grey (2.5Y6/2); silty clay; slightly moist; abundant (30%) coarse prominent yellowish brown (10YR5/8) mottles; massive breaking to weakly developed coarse blocky structure; sticky; plastic; firm; firm penetration resistance; few very fine roots in upper part of horizon to 70cm depth; 15% concretions as above; indistinct wavy boundary.

Cg 110-120+cm same as above but clay loam texture.

A.5 Tokomaru silt loam (1) (Tok-1)

Location/Grid Reference: NZMS1 N143 923512 Sanson, on Wanganui-Levin State Highway.

Landscape positon: Flat surface on high terrace.

Elevation: 45m.

Profile Drainage: Poorly drained.

Ap	0-20cm	Very dark greyish brown (10YR3/2); silt loam; moist; weakly developed coarse block breaking to weakly developed _ medium fragment and blocky structure; sticky; plastic; friable; soft penetration resistance; many fine and very fine roots; diffuse irregular boundary.
ABgc	20-27cm	Very dark greyish brown (10YR3/2) and 30% grey (2.5Y6/1); gravelly silty clay loam; moist; abundant (30%) medium prominent yellowish brown (10YR5/8) mottles; massive breaking to weakly developed medium blocks and fragment structure; sticky; plastic; friable to firm; firm penetration resistance; 15-20% concretions, 10mm diameter, brittle, black (7.5YR2/1); many fine and very fine roots; indistinct irregular boundary.
Bg	27-48cm	Grey (2.5Y6/1); silty clay loam; moist; profuse (60%) coarse prominent yellowish brown (10YR5/8) mottles; massive structure; very sticky; very plastic; firm; firm penetration resistance; common very fine roots; at base (45-48cm) of horizon 25% concretions, 10mm diameter, hard; indistinct boundary.
Btg	48-68cm	Light olive grey (5Y6/2); clay; slightly moist; 20% grey (2.5Y6/1) material washed down vertical cracks; abundant (30%) coarse prominent yellowish brown (10YR5/8) mottles; massive structure; very sticky; very plastic; firm; firm penetration resistance; few very fine roots mainly in fissures; distinct wavy boundary.
Cxg	68-94+cm	Greyish brown (2.5Y5/3) prism colour; silty clay loam; 25% greyish brown (2.5Y5/2) material down cracks; abundant (35%) medium prominent yellowish brown (10YR5/8) mottles; massive structure; very sticky; very plastic; firm; firm penetration resistance; no roots.

A.6 Tokomaru silt loam (2) (Tok-2)

Location/Grid Reference: NZMS1 N143 923312 45m south of site Tok-1.

Landscape position: Flat surface on high terrace.

Elevation: 45m.

Profile Drainage: Poorly drained.

Ap	0-20cm	Very dark greyish brown (10YR3/2); silt loam; moist; weakly developed coarse blocky breaking to weakly developed fine blocky and fragment structure; sticky; plastic; friable; soft penetration resistance; many fine roots; distinct wavy boundary.
ABgc	20-26cm	Light brownish grey (2.5Y6/2) plus 30% very dark greyish brown (10YR3/2); silt loam; moist; abundant (30%) fine distinct brownish yellow (10YR6/6) mottles; weakly developed medium blocky breaking to fragment structure; plastic; friable; firm penetration resistance; many fine roots; at top of horizon 30% 3-10mm diameter, hard concretions;indistinct irregular boundary.
Bg	26-53cm	Light olive grey (5Y6/2); silty clay loam; slightly moist; 25% grey (10YR6/1) humus coatings down cracks; abundant (30%)fine prominent brownish yellow (10YR6/8) mottles; massive structure; sticky; plastic; firm; stiff penetration resistance; common very fine roots; indistinct wavy boundary.
Btg	53-73cm	Light olive grey (5Y6/2); silty clay; slightly moist; 20% grey (10YR6/1) humus coatings down channels; profuse (55%) coarse prominent brownish yellow (10YR6/8) mottles; massive structure; very sticky; plastic; firm; stiff penetration resistance; few very fine roots in fissures; diffuse wavy boundary.
Cxg	73-100+cm	Light olive grey (5Y6/2); silty clay loam; slightly moist; 10% grey (10YR6/1) humus coatings down cracks between prisms; 50% coarse prominent brownish yellow (10YR6/8) prism colour; weakly developed coarse prismatic structure; sticky; plastic; frim; stiff penetration resistance; no roots.

A.7 Kairanga silt loam (1) (Kai-1)

Location/Grid Reference: NZMS1 N148 975344 Kairanga, Lockwood Rd.

Landscape position: Flat surface on low river terrace.

Elevation: 10m.

Profile drainage: Imperfectly drained.

Ap	0-21cm	Brown (10YR4/3);loam; slightly moist; moderately coarse blocky breaking to weakly developed fine fragment and blocky structure; slightly sticky; slightly plastic; very friable; firm penetration resistance; many fine and very fine roots; distinct wavy boundary.
Bgc	21-31cm	Grey (2.5Y5/1); loam; slightly moist; abundant (30%) medium distinct strong brown (7.5YR4/6) mottles; massive breaking to weakly developed medium blocky structure; slightly sticky; slightly plastic; very friable; firm penetration resistance; common fine and very fine roots; 10% medium distinct very dark brown (7.5YR2/2) soft concretions; indistinct irregular boundary.
Bg	31-77cm	Strong greyish brown (2.5Y4/2); fine sandy loam; slightly moist; abundant (50%) medium distinct dark yellowish brown (10YR4/6) mottles; massive breaking to moderately developed medium blocky structure; slightly sticky; non plastic; friable; firm penetration resistance; few fine and very fine roots; distinct irregular boundary.
Cg	77-110+cm	Grey (5Y5/1); fine sandy loam; slightly moist; abundant medium distinct dark yellowish brown (10YR4/6); massive; slightly sticky; slightly plastic; firm; firm penetration resistance; few very fine root in upper part of horizon; alternating layers of sandy loam and fine sandy loam.

A.8 Kairange silt loam (2) (Kai-2)

Location/Grid reference: NZMS1 N148 934333 Glen Oroua, corner Rongotea-Rangiotu Rd. and Pawaua Rd.

Landscape position: Flat surface on low river terrace.

Elevation: 10m.

Profile drainage: Imperfectly drained.

Ap	0-20cm	Dark greyish brown (10YR4/2); silt loam; slightly moist; moderately developed fine fragment structure; slightly sticky; slightly plastic; friable; firm penetration resistance; many fine roots; diffuse irregular boundary.
ABg	20-28cm	Greyish brown (2.5Y5/2) and 30% dark greyish brown (10YR4/2); silt loam; slightly moist; abundant (30%) fine distinct yellowish brown (10YR5/8) mottles; weakly developed coarse blocky breaking to moderately developed fine blocks and fragment structure; sticky; plastic; firm; firm penetration resistance; common fine roots; pronounced mixing and tounging of topsoil into subsoil; indistinct irregular boundary.
Bgr	28-65cm	Greyish brown (2.5Y5/2); silty clay; slightly moist; abundant (40%) medium distinct yellowish brown (10YR5/8) mottles; massive breaking to weakly developed coarse blocky structure; very sticky; slightly plastic; firm; firm penetration resistance; common fine roots; indistinct irregular boundary.
Brg	65-100+cm	Greyish brown (10YR5/2); silty clay; very moist; abundant (30%) fine distinct yellowish brown (10YR5/8) mottles; massive; very sticky; slightly plastic; firm; firm penetration resistance; no roots;
	Note:	A peat horizon pinches in at the eastern 1/4 of the paddock, at 30-39cm; 5YR2/2; silty peat; slightly moist; loose; soft penetration resistance; very weak medium block breaking to single grain structure; distinct irregular boundary. Horizon sequence Ap-ABg-peat-Bgr.

Appendix B

Appendix B
Summary of Soil Profile Results

B.1 Kiwitea mottled silt loam (1) (Kiw-1)

Horizon	Sample Depth cm	Root Mass $g\text{-}m^{-3}$	Bulk Density $Mg\text{-}m^{-3}$	Particle Density $Mg\text{-}m^{-3}$	Organic Carbon %	Sat. Hyd. Cond. mm/hr
Ap	3-8	41.2	1.08	2.60	3.90	780-1500
Ap	10-15	46.0	1.18	2.60	3.90	320-680
Bw	25-30	7.1	1.51	2.70		110-200
Bg	50-55	2.3	1.52	2.74		20-70
Bg	75-80		1.46	2.81		4-10

Sample Depth cm	Volumetric Water Content -15 bars V/V	-1bar V/V	-0.05 bar V/V	Total Porosity V/V
3-8	0.29	0.33	0.39	0.59
10-15	0.32	0.36	0.41	0.54
25-30	0.29	0.32	0.39	0.44
50-55	0.33	0.36	0.41	0.44
75-80	0.40	0.43	0.47	0.48

B.2 Kiwitea mottled silt loam (2) (Kiw-2)

Horizon	Sample Depth cm	Root Mass $g\text{-}m^{-3}$	Bulk Density $Mg\text{-}m^{-3}$	Particle Density $Mg\text{-}m^{-3}$	Organic Carbon %	Sat. Hyd. Cond. mm/hr
Ap	3-8	27.6	1.18	2.59	3.88	120-650
Ap	12-17	11.7	1.18	2.59	4.14	220-490
ABc	23-28	2.0	1.55	2.69		70-450
Bg	43-48	1.8	1.61	2.77		20-100
Bg	60-65		1.38	2.90		0-1

Sample Depth cm	Volumetric Water Content -15 bars V/V	-1bar V/V	-0.05 bar V/V	Total Porosity V/V
3-8	0.29	0.34	0.44	0.55
12-17	0.29	0.35	0.43	0.55
23-28	0.27	0.30	0.34	0.42
43-48	0.27	0.29	0.37	0.42
60-65	0.46	0.50	0.51	0.52

B.3 Marton silt loam (1) (Mar-1)

Horizon	Sample Depth cm	Root Mass $g\text{-}m^{-3}$	Bulk Density $Mg\text{-}m^{-3}$	Particle Density $Mg\text{-}m^{-3}$	Organic Carbon %	Sat. Hyd. Cond. mm/hr
Ap	3-8	88.6	1.36	2.57	3.35	30-100
Ap	12-17	92.0	1.32	2.58	3.22	170-680
Bg1	31-36	41.4	1.54	2.69		0
Bg1	45-50	32.7	1.30	2.62		0-30
2C	57-62	20.8	1.27	2.54		0-680
Bg2	70-75		1.45	2.69		0-7

Sample Depth cm	Volumetric Water Content -15 bars V/V	-1bar V/V	-0.05 bar V/V	Total Porosity V/V
3-8	0.33	0.37	0.43	0.47
12-17	0.32	0.35	0.44	0.49
31-36	0.33	0.35	0.41	0.43
45-50	0.38	0.45	0.49	0.50
57-62	0.34	0.37	0.48	0.50
70-75	0.29	0.33	0.44	0.46

B.4 Marton silt loam (2) (Mar-2)

Horizon	Sample Depth cm	Root Mass $g\text{-}m^{-3}$	Bulk Density $Mg\text{-}m^{-3}$	Particle Density $Mg\text{-}m^{-3}$	Organic Carbon %	Sat. Hyd. Cond. mm/hr
Ap	3-8	164.0	1.29	2.56	3.82	180-320
Ap	15-20	102.6	1.27	2.56	4.04	35-240
Bg1	35-40	15.1	1.56	2.72		25-120
Bg2	65-70	6.0	1.62	2.72		1-15

Sample Depth cm	Volumetric Water Content -15 bars V/V	-1bar V/V	-0.05 bar V/V	Total Porosity V/V
3-8	0.30	0.37	0.44	0.50
15-20	0.31	0.35	0.47	0.50
35-40	0.32	0.35	0.41	0.43
65-70	0.33	0.36	0.40	0.41

B.5 Tokomaru silt loam (1) (Tok-1)

Horizon	Sample Depth cm	Root Mass $g{-}m^{-3}$	Bulk Density $Mg{-}m^{-3}$	Particle Density $Mg{-}m^{-3}$	Organic Carbon %	Sat. Hyd. Cond. mm/hr
Ap	3-8	126.8	1.27	2.58	2.79	35-140
Ap	11-16	99.3	1.26	2.58	2.90	180-970
Bg	30-35	8.8	1.61	2.69		0-20
Btg	49-54	0	1.67	2.72		0-1
Cxg	73-78		1.68	2.73		0-1

Sample Depth cm	Volumetric Water Content -15 bars V/V	-1bar V/V	-0.05 bar V/V	Total Porosity V/V
3-8	0.26	0.33	0.46	0.51
11-16	0.26	0.32	0.44	0.51
30-35	0.30	0.36	0.38	0.40
49-54	0.29	0.33	0.37	0.39
73-78	0.25	0.29	0.37	0.38

B.6 Tokomaru silt loam (2) (Tok-2)

Horizon	Sample Depth cm	Root Mass $g{-}m^{-3}$	Bulk Density $Mg{-}m^{-3}$	Particle Density $Mg{-}m^{-3}$	Organic Carbon %	Sat. Hyd. Cond. mm/hr
Ap	3-8	88.0	1.28	2.58	2.62	160-210
Ap	12-17	88.0	1.26	2.60	2.69	45-380
ABc	20-25	23.0	1.60	2.67		9-35
Bg	37-42	15.0	1.65	2.70		1-3
Btg	55-60	12.0	1.73	2.70		1-30
Cxg	83-88		1.66	2.73		20-65

Sample Depth cm	Volumetric Water Content -15 bars V/V	-1bar V/V	-0.05 bar V/V	Total Porosity V/V
3-8	0.25	0.33	0.46	0.50
12-17	0.25	0.32	0.46	0.51
20-25	0.26	0.28	0.36	0.40
37-42	0.30	0.32	0.37	0.39
55-60	0.26	0.30	0.35	0.36
83-88	0.27	0.33	0.37	0.39

B.7 Kairanga silt loam (1) (Kai-1)

Horizon	Sample Depth cm	Root Mass $g\text{-}m^{-3}$	Bulk Density $Mg\text{-}m^{-3}$	Particle Density $Mg\text{-}m^{-3}$	Organic Carbon %	Sat. Hyd. Cond. mm/hr
Ap	3-8	110.5	1.28	2.61	2.38	100-210
Ap	11-16	100.6	1.40	2.60	2.36	55-520
Bgc	23-28	25.5	1.51	2.69		10-620
Bg	40-45	6.6	1.51	2.68		13-40
Cg	80-85		1.56	2.68		0-25

Sample Depth cm	Volumetric Water Content -15 bars V/V	-1bar V/V	-0.1bar V/V	-0.05 bar V/V	Total Porosity V/V
3-8	0.24	0.25	0.35	0.42	0.51
11-16	0.28	0.30	0.36	0.41	0.46
23-28	0.15	0.16	0.28	0.33	0.44
40-45	0.08	0.09	0.23	0.33	0.44
80-85	0.23	0.29	0.35	0.41	0.42

B.8 Kairanga silt loam (2) (Kai-2)

Horizon	Sample Depth cm	Root Mass $g\text{-}m^{-3}$	Bulk Density $Mg\text{-}m^{-3}$	Particle Density $Mg\text{-}m^{-3}$	Organic Carbon %	Sat. Hyd. Cond. mm/hr
Ap	3-8	225.2	0.98	2.59	3.95	680-1400
Ap	12-17	173.5	1.00	2.56	3.56	680-1400
ABg	25-30	30.0	0.91	2.67		10-470
Bgr	45-50	8.7	1.19	2.69		40-190
Brg	77-82		1.08	2.65		34-380

Sample Depth cm	Volumetric Water Content -15 bars V/V	-1bar V/V	-0.05 bar V/V	Total Porosity V/V
3-8	0.38	0.42	0.47	0.62
12-17	0.41	0.45	0.49	0.61
25-30	0.52	0.55	0.62	0.66
45-50	0.36	0.45	0.51	0.56
77-82	0.43	0.48	0.57	0.59

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