A STUDY OF THE COMBINED EFFECTS OF IRRIGATION FREQUENCY AND PHOSPHORUS FERTILITY ON SUMMER PASTURE PRODUCTION

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ABSTRACT

During the last five years, there has been an increase in both the area of irrigated pasture in New Zealand and the intensity of this irrigation. Research has failed to keep pace with this change: the benefits of irrigation to pasture production have not been studied in a sustained manner since the 1980s. Since then a number of factors have changed including; a change in the type of irrigation system commonly employed, the productive potential of new pasture cultivars, an appreciation of the importance of relationships between water and nutrient uptakes by plants, and a heightened awareness of the environmental implication of irrigation.

It is claimed that the ability of irrigation systems such as centre pivot and long lateral systems to increase irrigation frequency affords a major advantage to pasture production. As yet, these claims are largely unsubstantiated in New Zealand. In addition, there has been no research of the mechanisms or processes that might account for this phenomenon. The study described here set out to quantify the benefits of more frequent irrigation (in the readily available water range) to ryegrass and white clover production, including the relationship with increased nutrient status, and to elucidate the mechanism(s) that might explain this response.

The responses of ryegrass and white clover to irrigation frequency (within the readily available water range) and nutrient addition, particularly phosphorus (P) were investigated with a pot experiment using Ramiha silt loam. The rate of fertiliser addition to the pots had a significant and consistent effect on a number of indicators of ryegrass and clover performance including total yield. In contrast, irrigation frequency did not significantly or consistently affect total pasture production. It was concluded that when soil, nutrients and plants roots constitute a relatively homogenous mix (i.e. the pot environment), more frequent watering is not significantly advantageous to plant growth and, therefore, all of the readily available water is equally available.

Although there was no response in pasture production to irrigation frequency in the pot experiment, it was hypothesised that irrigation frequency (in the readily available range) in the field, where P values vary with depth in the soil profile, would affect pasture production. The response of swards of ryegrass and white clover growing in Manawatu fine sandy loam to irrigation frequency and P status was measured in a field experiment during the summer of 2000/01. Three irrigation frequencies within the readily available water range (irrigation triggered at soil water deficits of 20 mm (I-20), 40 mm (I-40) or 60 mm (I-60)) were combined with two P fertility treatments (no P fertiliser added or 40 kg P ha^{-1} applied). For comparative purposes, there were also 4 non-irrigated, non-P fertilised plots outside the main trial block. Plant production, nutrient content of plant material, soil moisture content, soil N and P contents, and nitrate-N, ammonium-N and phosphorus concentrations of soil water samples were measured. The herbage on the plots was cut and removed i.e. there was no grazing.

In the field, irrigation frequency had a significant effect on ryegrass and clover production. Irrigation of ryegrass and white clover at I-20, over the summer period resulted in the greatest pasture production and was associated with the most efficient water use (defined as k with units kg DM ha^{-1}) of the irrigated treatments, I-60 gave the smallest production and water use efficiency. Application of the recommended quantity of P fertiliser (40 kg ha^{-1}) significantly enhanced total pasture production and hence water use efficiency. Soil P and N was most concentrated in the surface soil. The results of the field trial support the hypothesis that ryegrass and white clover production is greatest when the plant is taking most of the water it requires from the surface soil where nutrients are most concentrated i.e. the frequent (I-20) irrigation case. Production is smaller when the plant is extracting large quantities of water from depth where nutrient concentrations are smaller i.e. the less frequent irrigation (I-60) case.

The effects of irrigation frequency and P fertility on root re-growth activity of ryegrass and white clover swards were evaluated using a modified refilled core method. Root growth of both species decreased with depth. Fertiliser P application significantly increased root growth of both species in two of the three sampling depths at the December and February harvests. In only one root harvest did irrigation frequency significantly affect root activity. At the April harvest, the greatest root growth in the surface soil was observed for I-60, P-0 plots. It is suggested that in addition to encouraging more moisture uptake from nutrient-rich surface soil, an additional benefit of frequent irrigation is that in soils that are consistently moist, plants need to produce fewer roots.

A simple water balance model was developed to simulate volumetric soil water contents in the three depths of the Manawatu fine sandy loam that are most closely related to the three irrigation frequencies i.e. 0-150 mm, 0-300 mm, and 0-450 mm. The model illustrates how initially the plants extract most of their water requirement from the surface soil and then as the profile dries they remove more water from lower depths. Accordingly, it highlighted differences in soil water contents between the irrigation frequencies particularly in the surface soil (0 - 150 mm).

Soil water sampling was conducted using ceramic suction cups. Estimated total nitrate-N losses until 31 July, 2001 indicated that irrigation frequency of ryegrass during the previous summer did not have a major effect on the overall nitrate-N leaching losses during the late autumn/early winter period but nitrate-N losses under clover tended to be lower under less frequent irrigation. P and ammonium-N leaching losses were negligible.

Using the understanding developed in the pot and field trials, a model was constructed to predict ryegrass and clover production on Manawatu fine sandy loam under the

different irrigation frequency and P fertility regimes. The model relates pasture production (G) to evaporation from a series of soil water deficit ranges (E_i) according to $G = k_1E_1 + k_2E_2 + \ldots + k_nE_n$ (where k_iE_i is the pasture production when soil water is in the i^{th} soil water deficit range, and k_i is the water use efficiency when soil water is in the i^{th} soil moisture deficit). The k_i values were derived using the production data from the field trial. The model was used to simulate the effect of irrigation frequency and P fertility on seasonal (1 November to 30 April) pasture production for a range of climate conditions using the past 26 years weather data.

The simulation illustrates how pasture production under irrigation varies markedly with climate, irrigation frequency, P fertility status and the ryegrass:clover composition of the sward. Increasing irrigation frequency from I-60 to I-20 increased pasture production, on average, by 1473 kg DM ha^{-1} (23%) and 1105 kg DM ha^{-1} (19%) for P-0 and P-40, respectively. For the farmer contemplating the adoption of irrigation, the purchase of a system that allows more frequent irrigation is as significant a consideration as the decision to adopt irrigation itself. On a cautionary note, the model suggests that I-20 irrigation typically increases drainage losses by about 40 mm (42%) compared to I-60 irrigation.

This thesis is dedicated to my father (late Mr.H.A.Mohotti Appuhamy), mother (Mrs.G.Meyhamine) and brother (late H.A.Peries) and teachers, all of them expected me to fulfil this task one day.

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CANDIDATE'S DECLARATION

This is to certify that the research carried out for my Doctoral thesis entitled "*A study of the combined effects of irrigation frequency and phosphorus fertility on summer pasture production*", in the Institute of Natural Resources, Massey University, Turitea Campus, New Zealand, is my own work, and that the thesis material has not been used in part or in whole for any other qualification.

Candidate's Name: Hewana Arachchige Sumanasena

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SUPERVISOR'S DECLARATION

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CERTIFICATE OF REGULATORY COMPLIANCE

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(a) is the original work of the candidate, except as indicated by appropriate attribution in the test an/or in the acknowledgements;
(b) that the text, excluding appendices/annexes, does not exceed 100,000 words;
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_____

Candidate's Name: Hewana Archchige Sumanasena **Supervisor's Name:** David J. Horne

Signature: _____ **Signature:** _____

Date: 11 June 2003 **Date:** 11 June 2003

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H.A.Sumanasena (Sena)

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CHAPTER 1

GENERAL INTRODUCTION AND RESEARCH OBJECTIVES

1.1. INTRODUCTION

In most pastoral farming systems in New Zealand, 85% or more of the total feed for livestock is grazed pasture (Matthews *et al.*, 1999a). Hence, pasture productivity is a key determinate of the quantity of animal produce sold from pastoral farms. The variability in pasture growth that occurs throughout the year is due, in part, to fluctuations in the climate. In many parts of New Zealand, a lack of soil moisture in summer prevents the realisation of potential pasture production (Coulter, 1973; McAneney *et al.*, 1982; Korte and Chu, 1983; Kerr *et al.*, 1986; Rickard *et al.*, 1986), and so pasture production does not adequately match animal requirements. The "summer feed gap" is a major challenge to management on numerous farms (Matthews *et al.*, 1999b). A range of different strategies are available and used on farms to fill this summer feed deficit. These strategies include; the feeding of conserved hay and silage, feeding concentrates, use of specialist forage crops, and the irrigation of pasture.

There is increasing concern about climate warming and the increasingly variable nature of summer seasons and the threat that these pose to New Zealand's land based industries (Martin, 2003). There is increasing interest in how land managers might adapt to this changing environment and its associated risks: there is evidence that many farmers plan to resort to irrigation.

There are about 500,000 ha of irrigated land in New Zealand. All the projections are that the area under irrigation in New Zealand is going to increase. There are a number of

feasibility investigations underway at present for new schemes, totalling over 300,000 ha (http://www.maf.govt.nz). For example, the agricultural area in the Manawatu-Wanganui region that was irrigated in 2000 was 8,000 ha and it is estimated to increase by 50% by 2010 (http://www.maf.govt.nz). That such increases can be sustained at the national level is questionable.

Water is a precious natural resource and of strategic economic importance. Consequently, there are competing demands by a range of different end-users. According to Hawke *et al.* (2001), existing practices for allocation of water to competing users, based essentially on demand and the size of the water resource, are increasingly leading to conflict. Irrigated agriculture uses significant quantities of water. For example, horizons.mw recently estimated that $ 145 million worth of water is currently used in agriculture in the Manawatu-Wanganui region, and of this total, approximately $ 18 million is used in the irrigation of pasture (http://www.horizonsmw.govt.nz).

There is insufficient information available to make informed decisions about the likely expanded role of irrigation in the future management of New Zealand's grasslands in a changing climate. Questions that need answering include: how much extra pasture is irrigation capable of producing; what will be the financial cost of this extra production; how much water will be required; and what will be the impact of irrigation on the soil and water resources? To date, this last area has received no attention, despite the fact that the problem of leaching of nutrients and other potential pollutants in drainage water has been clearly identified (Ledgard *et al.*, 1996; Di and Cameron, 2000) and the likelihood that irrigation will exacerbate this problem.

Research on the irrigation of pasture has been conducted over the past 40 years, much of it on border strip irrigation on the Canterbury plains (Rickard, 1977; McBride, 1994). Historically, irrigation research has focused on comparing plant performance under

irrigation with the non-irrigated situation (e.g. Colman and Lazenby, 1975; Garwood and Sinclair, 1979a; McAneney and Judd, 1983). In these studies, 'irrigation' involved recharging the whole root zone when it was depleted to a soil water potential of -100 kPa or below (e.g. Moss *et al.*, 1996; Dunbabin *et al.*, 1997; Bahmani *et al.*, 2001) i.e. replacement of the 'readily available' water.

Despite this history of irrigation research, there is very little information about irrigation that is current, and therefore, applicable to present day pastoral production systems. A number of factors besides climate have changed since the early 1980s when the benefits of irrigation to pasture production were last studied intensively. These include; a greater appreciation of the inter-relationships between water and nutrient uptake; the need to account for the impacts of land management on soil and water quality (McLaren and Cameron, 2000); an acknowledgment of the scarce and valuable nature of the water resource as highlighted by the competing demands of multiple users; an intensification in most land uses and an increase in the demand for quality information for decision support on-farm. Equally importantly, it is claimed that irrigation technology has improved, although this is largely untested.

Some manufacturers of irrigation equipment and some farmers made the claim that more frequent irrigation is advantageous to pasture production. Under some systems irrigation is scheduled to occur at deficits of 20 to 30 mm even when soils store 40 to 60 mm of readily available water. However, there is limited research into the quantity of the benefits of more frequent irrigation (in the readily available water range) or the mechanisms responsible for any such increase in pasture production.

The pastoral land use where many of these issues are best illustrated is dairy farming. Over the last five years there has been an increase in the area irrigated and the intensity of irrigation on dairy farms. The major reasons for this are a combination of increased demands on dairy farms and the availability of more efficient long lateral and centre pivot irrigation systems (Treloar, 2000; Ebeling, 2002). With the adoption of these

sprinkler irrigation systems there is a trend towards the use of shorter return intervals (more frequent irrigation) to increase pasture yield.

Given this background, a study of the impact of irrigation frequencies and water use efficiency on pasture production is timely. The present research was initiated to study the efficient use of water and nutrients in the root zone of irrigated pasture, along with leaching losses under frequency of pasture irrigation in summer. It was hoped that the results generated will be helpful to improved irrigation management practices. The outline of the Thesis is shown in Fig.1.1.

1.2. RESEARCH OBJECTIVES

The specific objectives of this study can be summarized as follows:

To quantify the response of ryegrass and white clover production during summer to a number of irrigation frequencies (within the readily available water range) and P fertility levels.

To measure the effects of irrigation frequency and P fertility regimes on root growth.

To develop some understanding of how relationships between irrigation frequency, soil nutrient status, and root activity might determine the production responses of ryegrass and white clover to irrigation frequency. In other words, to develop a mechanism or process that might explain or account for an increase in pasture production with more frequent irrigation (in the readily available water range).

Investigate any likely effects of irrigation frequency and fertiliser application in summer on leaching patterns under ryegrass and white clover during both the irrigation season and subsequent autumn-early winter drainage season.

To develop a model that will predict soil water content and seasonal pasture production for different irrigation frequency and P fertility scenarios.

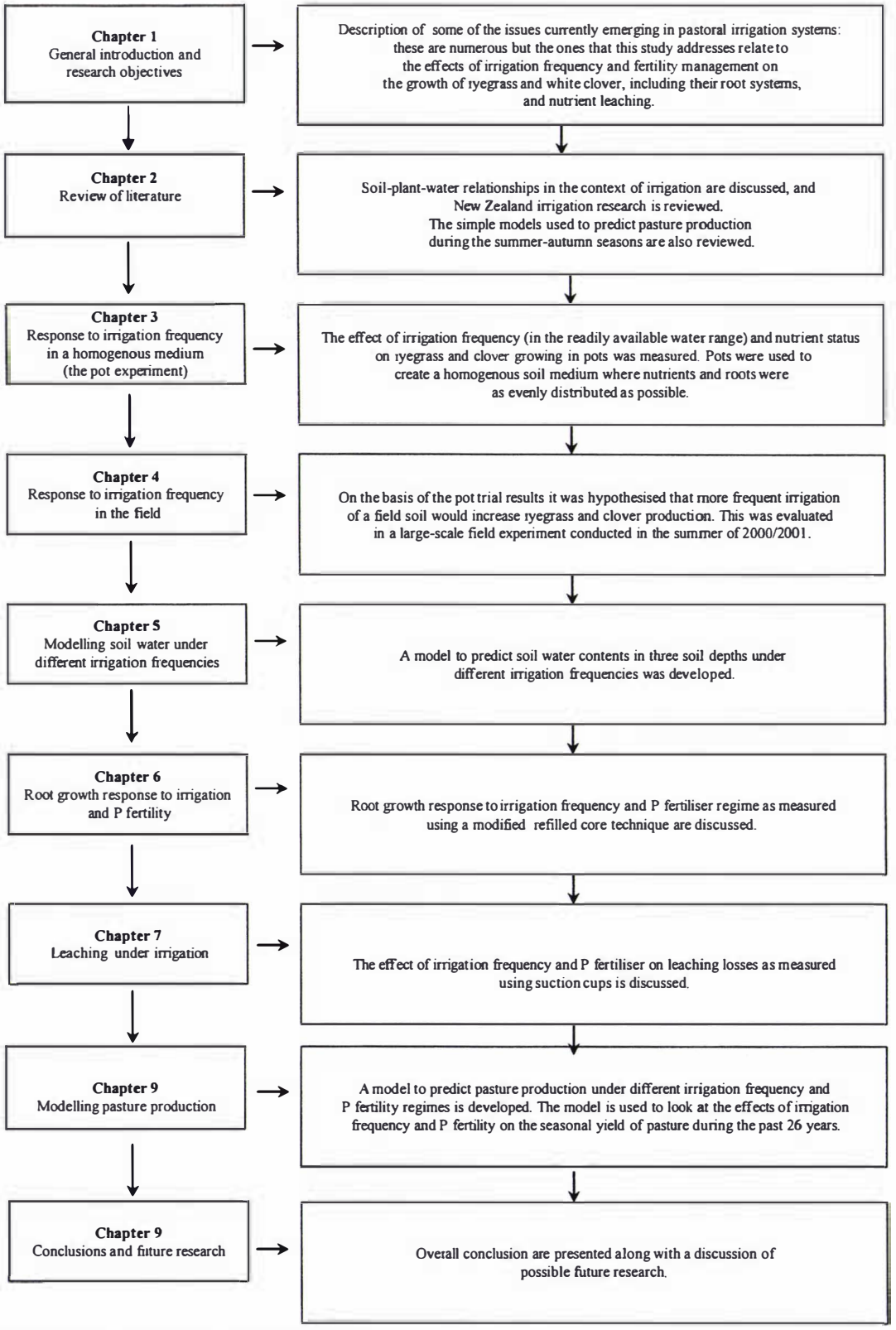


Figure 1.1 The outline of the Thesis

CHAPTER 2

LITERATURE REVIEW

2.1. INTRODUCTION

A word or two about the scope of this literature review is in order. Given that a general review of the response of plants to irrigation would be too broad to attempt here, the focus will be on research that deals with the irrigation of pasture. In addition, although phosphorus fertility is an important component of the research described in this Thesis, this review will not consider all of the voluminous literature on the effects of nutrient status on pasture yield or root characteristics but will be confined to those studies that endeavoured to specifically relate nutrient uptake by pasture to soil moisture content. Finally, as the benefits of irrigation of pasture depend on, among other things, the climate and the nature of the production system, and are therefore country specific, New Zealand research will be emphasised.

2.2. SOIL-PLANT-WATER RELATIONSHIPS

Theories of soil water flow and chemical transport have vital field applications for irrigation management and the conservation of water resources. The first part of the review will address important theoretical considerations.

The size of the soil moisture deficit that accumulates during the summer months is dependent on the plant-available water holding capacity of the soil which can be defined as: "the maximum amount of water that can be held within the root zone of the soil that is available for plant growth" (McLaren and Cameron, 2000). The water holding

capacity is highly dependent on factors such as crop species, root zone depth, and soil properties.

Early experimental results were interpreted to mean that the internal drainage rate generally becomes negligibly small or even zero in just a few days after heavy rains or irrigation. The water content at which internal drainage supposedly stopped was termed the field capacity value. For example, Viehmeyer and Hendrickson (1949) defined field capacity as "the amount of water held in soil after excess water has drained away and the rate of downward movement has materially decreased, which takes place within 2-3 days after rain or irrigation in pervious soils of uniform structure and texture". As a result, field capacity has been widely accepted as a physical characteristic of soil. Some early workers believed it to result from a static equilibrium or a discontinuity in capillary water (Ahuja and Nielsen, 1990).

The field capacity value is still widely employed as a useful approximation to the upper limit of plant available water (Ahuja and Nielsen, 1990; Woodward *et al.*, 2001). Ratliff *et al.* (1983) defined the upper limit of availability in the field as the soil water content where the daily rate of drainage, following a thorough wetting of the soil, was reduced to between 0.1 and 0.2% of the stored water. The conventional estimation of field capacity of a soil in the laboratory is generally made by measuring the water content at a pressure potential of somewhere between -5 and -30 kPa.

Nowadays, field capacity is no longer considered a constant or an intrinsic soil property, but has a certain degree of arbitrariness to its value (Ahuja and Nielsen, 1990; Hillel, 1980; Hillel, 1998). According to Woodward *et al.* (2001), estimates of field capacity of New Zealand soils have been determined using pressure potentials ranging from -4.9 kPa to -10 kPa. Scotter (1977) suggested that the soil water content in equilibrium with matric suction of 5 kPa is an appropriate value for the field capacity of surface soil of mole-pipe drained Tokomaru silt loam soil. Likewise, Ahuja and Nielsen (1990) quoted field measurements of some United States soils that showed that the soil water suction attained after 2 to 3 days of drainage is in the range of 5 to 10 kPa.

Generally speaking, the purpose of irrigation is to apply water to the soil so as to meet the deficit and return the root zone to field capacity. The amount of irrigation to be applied at any time is based on the deficit from the field capacity of the soil zone to be wetted.

Soil water is essential for pasture production process including photosynthesis, translocation, leaf extension and evaporative cooling (McKenzie *et al.*, 1999). Veihmeyer and Hendrickson (1949) postulated that soil water is equally available to plants in the range of soil water contents from field capacity to permanent wilting point, both of which are constant values for a given soil. The permanent wilting point was defined as the soil water content at which plants wilt and do not recover turgidity even when placed in a 100% relative humidity atmosphere for 12 h. This concept was widely accepted for many years.

Later on it was recognized that the energy status of soil water, rather than the soil water content, might be a better and more universal indicator of water availability to plants. The upper and lower limits of water availability were, therefore, defined in terms of soil water suction, as 10 or 33 kPa and 1500 kPa, respectively (Richards and Weaver, 1944; Slater and Williams, 1965). In contrast to the theory of uniform availability of water for plants over the total range of available soil water, Ritchie *et al.* (1972) showed that soil water availability to plants decreases as the soil water content decreases from field capacity to permanent wilting point for cotton (*Gossypium hirsutum L.*) and grain sorghum (*Sorghum bicolor L.*) crops, i.e., the plant growth rate is usually reduced long before the wilting point is reached. Soil water in the upper three-quarters of the available range was readily available, after which the availability decreased approximately linearly. Rooting depth, and the density, proliferation and extension of roots, physiological adjustment of plants to water stress, and soil's water conducting properties at varying moisture contents determine the rate of actual uptake and transpiration in response to the imposed demand (Penman, 1949; Gardner, 1960).

In simple and practical terms, suited to irrigation management, the total available water in the root zone is expressed as the difference between the volumetric water contents at field capacity and wilting point.

$$W_T = (\theta_{fc} - \theta_{WP})\, Z_r \qquad (2.1)$$

where

W_T = the total available soil water in the root zone [mm],

θ_{fc} = the water content at field capacity [$m^3\ m^{-3}$],

θ_{WP} = the water content at wilting point [$m^3\ m^{-3}$],

Z_r = the rooting depth [mm].

Similarly, the fraction of total available water that a crop can extract from the root zone without suffering water stress is the readily available water as defined by the following equation.

$$W_R = p\, W_T \qquad (2.2)$$

where

W_R = the readily available soil water in the root zone [mm],

p = average fraction of W_T that can be depleted from the root zone before moisture stress (reduction in evaporation) occurs.

Allen *et al.* (1998) suggest that p normally varies from 0.3 for shallow rooted plants at high rates of crop evapotranspiration (> 8 mm d^{-1}) to 0.7 for deep-rooted plants at low rates of crop evapotranspiration (< 3 mm d^{-1}). Moreover, they suggested p values of 0.5 for clover-hay (with 0.6 to 0.9 m root depth), and 0.6 for ryegrass (with 0.6 to 1 m rooting depth).

Parfitt *et al.* (1985a and 1985b) reported that growth started to decrease at 50 mm and 60 mm soil water deficit in Judgeford silt loam and Stratford silt loam, respectively, during summer drying under ryegrass and white/clover pasture. Total water holding capacities were 120 mm and 125 mm for Judgeford silt loam and Stratford silt loam, respectively, giving p values of 0.4 and 0.5. Ahuja and Nielson (1990) state that the measured transpiration rate of corn began to fall below the demand rate at a soil water suction of about 100 kPa under an estimated evapotranspiration demand of 3 to 4 mm day^{-1}. The quantity of soil water held between field capacity (5 kPa) and 100 kPa suction levels within the root zone is often considered to correspond to W_R for pasture.

McAneney and Judd (1983) found that, relative to irrigated production, dryland pasture yields on Horotiu sandy loam were reduced at a soil water deficit of 34 mm and growth had ceased at a deficit of 103 mm.

The plant available water threshold (PAW_t) is a parameter used in modelling plant responses to water deficits by Sadras and Milroy (1996) and Nable *et al.* (1999). They

arrived at the PAW_t by plotting the typical responses of leaf expansion rate against what they termed FPAW defined as

$$FPAW = (\theta_a - \theta_{ll})/(\theta_{ul} - \theta_{ll}) \quad (2.3)$$

where

FPAW = Fraction of plant available water as a ratio

θ_a = actual volumetric soil water content

θ_{ul} = volumetric soil water content at upper limit of plant available water

θ_{ll} = volumetric soil water content at lower limit of plant available water

The typical responses of leaf expansion and gas exchange rate to FPAW have been described with two straight lines (Ritchie *et al.*, 1972; NeSmith and Ritchie, 1992; McIntyre *et al.*, 1993; Sadras *et al.* 1993), where PAW_t is the FPAW threshold at which the rate of plant performance in stressed plants starts to diverge from the reference value. A range of values from 0.85 to 0.25 was given for the PAW_t for tissue expansion from either field or pot trials taking into account both soil and plant factors for straight line models (Sadras and Milroy, 1996). Nable *et al.* (1999) graphically showed the procedure for obtaining PAW_t using shoot extension ratio or transpiration ratio (Fig. 2.1 and Fig. 2.2).

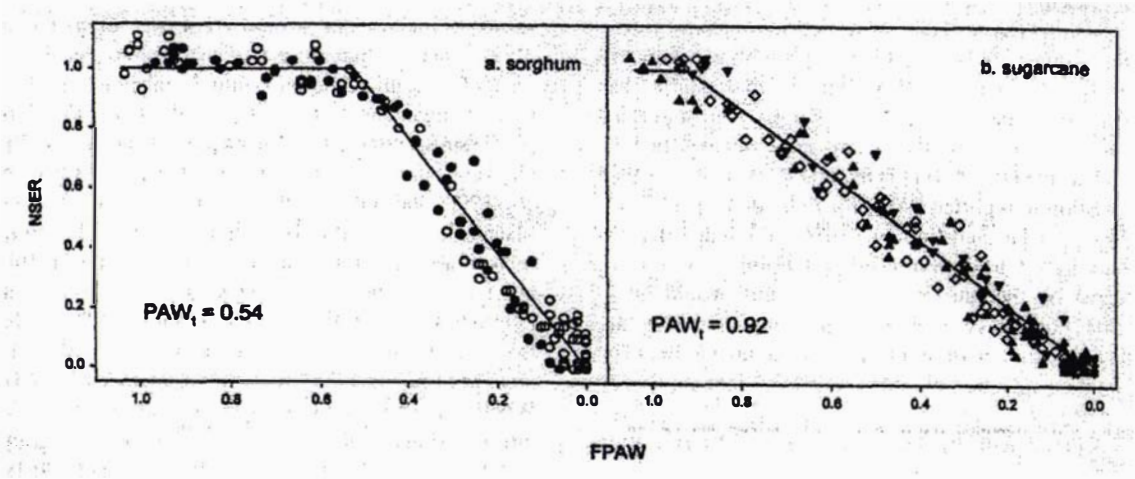


Figure 2.1 PAW$_t$ obtained from normalized shoot extension ratio (NSER) as a function of the fraction of plant available water (FPAW) remaining on each day of a drying cycle for each pot of (a)) sorghum and (b) sugarcane (after Nable *et al.*, 1999).

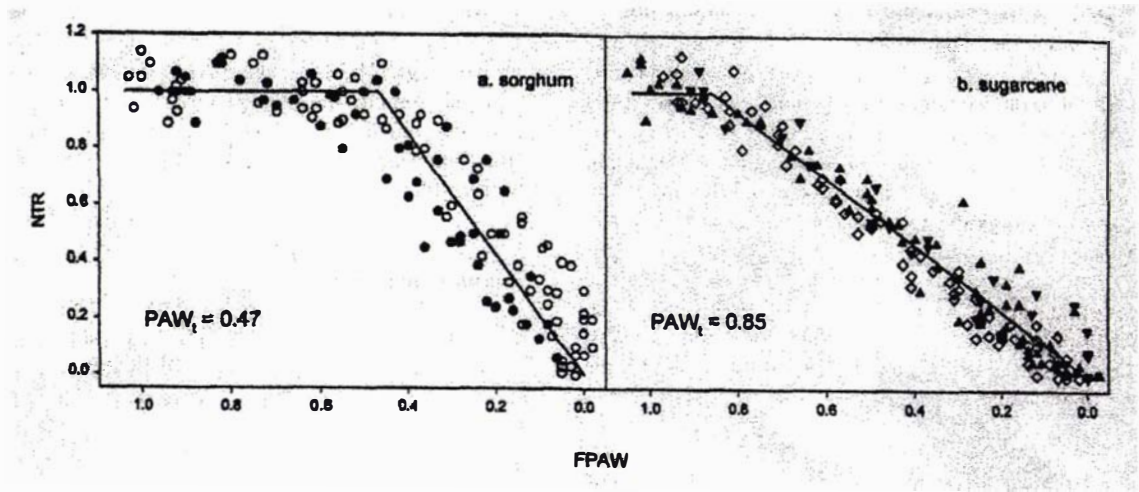


Figure 2.2 PAW$_t$ obtained from normalized transpiration ratio (NTR) as a function of the fraction of plant available water (FPAW) remaining on each day of a drying cycle for each pot of (a)) sorghum and (b) sugarcane (after Nable *et al.*, 1999).

2.3. RESPONSE TO IRRIGATION

2.3.1. Pasture growth response to irrigation

During at least three months of the year, evapotranspiration exceeds rainfall for most of New Zealand's pastoral areas. Variation in the September to February rainfall accounts

for about 60% of the annual variation in total pasture production (McKenzie *et al.*, 1999). Some places throughout New Zealand experience drought conditions during this period with very little if any rain and in many parts of New Zealand, pasture and animal production is greatly reduced by water stress during the summer months (Korte and Chu, 1983).

Jones *et al.* (1980a) state that the growth of temperate grasses is severely restricted by soil water deficits in excess of 50 mm and since a deficit of this magnitude can develop after only ten days of dry weather in summer in New Zealand, the yields of pasture crops are often reduced. However, even though the growth rates are reduced, pasture can survive prolonged drought periods and resume growth when water is available. Barker (1983) reported that growth components of grass (particularly tillers and leaves) were reduced when the soil water deficit exceeded 104-111 mm in Tokomaru silt loam soil. At this point the soil water potential corresponded to -100 kPa at 300 mm and this critical point was characterized by a 600 kPa decrease in dawn leaf water potential (Barker, 1983). At deficits exceeding this critical value, the reduction in grass yield was attributable to a reduction in the rate of tiller appearance, an increase in the rate of tiller death, and a reduction in the rate of leaf production (Barker, 1983).

The presence and magnitude of seasonal water deficits, and their implication for pasture and crop growth were modelled for various regions of New Zealand by Kerr *et al.* (1986). Water deficits were predicted to result in average annual losses of 1000, 2300, 4000 and 4500 kg DM ha^{-1} for Southland, Waikato, Manawatu and Canterbury, respectively (Kerr *et al.*, 1986). Numerous other workers have demonstrated the need for supplemental irrigation if pasture yield is to be consistently increased during summer/autumn in New Zealand (Scotter *et al.*, 1979; McAneney and Judd, 1983; Hayman, 1985; Scotter and Clothier, 1986: Andrewes, 1995; Paton and Greenwood, 1994; Moss *et al.*, 1996).

Pastoral farmers who have introduced irrigation into their dairying system have found that they are able to produce substantially more pasture per year. A trial in Canterbury (a region known for its severe droughts) showed that non-irrigated pastures produced a

mean of 6600 kg DM ha^{-1} yr^{-1}, while irrigating when the top 100 mm of the profile dried to 20% moisture level for Lismore stony silt loam increased production to an average 11700 kg DM ha^{-1} yr^{-1} (Moss *et al.*, 1996). McKenzie *et al.* (1999) state that irrigation reduces the year-to-year coefficient of variation in annual pasture production from 48% to 12% in Canterbury.

According to Andrewes (1996), a sequence of summer droughts around 1994 created interest in long lateral irrigation systems in Northland (of the *Van den Bosch* type). It was found that pasture growth increased on the irrigated area during the spring, summer and autumn seasons corresponding with periods of moisture stress. Pasture production increased by 5020 kg DM ha^{-1} in 1993/94, and 3300 kg DM ha^{-1} in 1994/95 when the drought period was shorter.

Gamble (1995) found that when irrigation was applied in Northland using long lateral irrigation system, the pasture growth rate increased consistently, ensuring a reasonable supply of pasture during the months when soil water deficits occur. For example pasture growth rates of 43 and 13 kg DM ha^{-1} d^{-1} were observed for irrigated and non-irrigated pasture, respectively, during November/December. The difference between irrigated and non-irrigated pasture yield (48 kg DM ha^{-1} d^{-1}) was even greater during January/February (Gamble, 1995). The above results show that irrigation has the potential to benefit pasture production considerably.

2.3.2. Effect of irrigation frequency on pasture

The correct scheduling of irrigation is an important management practice. The interval between irrigation applications will determine the response of pasture production to irrigation. Moss *et al.* (1996) reports large responses to irrigation on both a shallow and a deep soil, and that the benefits were considerably greater when irrigation was at 21 rather than 35-day intervals (Table 2.1). Irrigating at 35 instead of 21-day intervals reduced the pasture production to a greater extent on the shallow soil than on the deeper soil. This result reflects the increased water holding capacity of the deeper soil.

Table 2.1 Effects of irrigation return interval and soil type on pasture production over January-April (mean 1993-1995) (after Moss *et al.*, 1996).

Irrigation Frequency	DM production mean (kg ha^{-1})	DM production Response (kg)	Growth rate DM (kg $ha^{-1}day^{-1}$)
Shallow soil site			
No irrigation	2518		24
Irrigated every 21 days	4033	1515	38
Irrigated every 35 days	3193	675	30
Deep soil site			
No irrigation	4393		42
Irrigated every 21 days	5244	851	50
Irrigated every 35 days	4824	431	46

Work by McBride (1994) at Winchmore also demonstrated the importance of the scheduling of irrigation to pasture production. These included plots irrigated when the top 100 mm of soil profile dried to 50% W_T, 25% W_T, or 0% W_T (wilting point), plus one irrigation every 21 days. There was 17 mm of available water in the surface 100 mm depth of stony silt loam soil. Irrigating at 50% W_T produced larger quantities of pasture than irrigating at 25% W_T or 0% W_T (Table 2.2). The 50% W_T treatment approximately corresponds to irrigating when soil water dropped to -100 kPa potential (lower limit of W_R). McBride (1994) drew two further conclusions from long-term observations. Firstly, as irrigation frequency increases, the yield variation between years decreases. Secondly, after 34 years of irrigation, yields on the 50% W_T treatment were higher than they were at the beginning, but the number of irrigations applied as required by the protocol of that treatment has decreased: these changes were attributed to the improvement of soil physical properties over time under frequent irrigation. Over the past 10 years, the 50% W_T treatment required an average of 6.2 irrigations. McBride (1994) stated that local farmers apply a somewhat greater number of irrigations than 6.2 irrigations. This implies that some Canterbury farmers already schedule their irrigation within the range prescribed by W_R.

Table 2.2 Pasture production (kg DM ha^{-1}) from Winchmore research trail – average of 34 years (after McBride, 1994).

Season Irrigation Treatment	Winter	Spring	Summer	Autumn	Total
No irrigation	725	3650	1295	1040	6710
0% W_T	715	4010	3515	1615	9855
25% W_T	705	4330	3970	1785	10790
50% W_T	725	4480	4645	2065	11915

W_T = available soil moisture (FC-PWP)

In a similar manner, Paton and Greenwood (1994) found that less frequent irrigations (irrigated at 0% W_T) resulted in lower pasture yields due to increased water stress, compared to more frequent irrigation (irrigated at 50% W_T) in the MacKenzie Basin (Table 2.3). On average, over 6 years, the maximum annual yield was observed with the most frequent irrigation (50% W_T). The middle irrigation frequency (irrigated at 25% W_T) produced 680 kg DM $ha^{-1}yr^{-1}$, less pasture than the frequent irrigation (50% W_T). Irrigation at 0% W_T, resulted in a further loss of 1720 kg DM ha^{-1} compared to the middle irrigation frequency (25% W_T).

Table 2.3 Pasture production (ton DM ha^{-1}) on MacKenzie shallow stony soils under three border strip irrigation regimes (after Paton and Greenwood,1994).

Treatment	Pasture yield (ton ha^{-1})						
	1980/81	1981/82	1982/83	1983/84	1984/85	1985/86	Mean (1980-86)
Dry	1.20	1.52	1.38	1.84	2.70	1.39	1.65
0% W_T	5.97	5.13	4.52	6.18	7.79	6.36	5.99
25% W_T	7.75	6.94	6.08	8.92	8.23	8.32	7.71
50% W_T	7.36	7.75	7.95	8.69	8.97	8.59	8.39
LSD(P<0.05)	1.59	1.48	1.98	1.26	0.76	0.71	0.50

W_T =Avaialble water capacity

Paton and Greenwood (1994) observed year-to-year variations in pasture production. They demonstrated that as the moisture deficit increases, the response to irrigation also increases both within and between years. Over the six years of the experiment, the 1981 - 82 growing season was the driest, with dryland soil water contents below 25% W_T for

more than half of the season. During that year, 6 irrigations were applied to the 25% W_T treatment, while in the season with the highest rainfall (1983-84), only four irrigations were required.

Bahmani *et al.* (2001) obtained a 19% yield improvement of dairy pasture over summer on Te Kowhai clay loam soil at Hamilton when irrigating at about 40% W_T at 150 mm depth compared with non-irrigation.

It is important to note that the majority of the irrigation research on pasture responses has compared pasture yield under a wide range of moisture conditions from field capacity (-10 kPa) to permanent wilting point (-1500 kPa) (e.g. D'Aoust and Tayler, 1968; Garwood and Sinclair, 1979a and 1979b; Paton and Greenwood, 1994). However, there is a trend to irrigate within a more narrow range of soil water deficits, that is, more frequent irrigation with a smaller amount of water applied at each irrigation event.

Ward and Burch (1999) state that, if production is to be maximised, pasture should be irrigated by the time that half W_T in the root zone is depleted. For a soil with 58 mm of W_T, a root zone depth of 30 cm (the Allansford site), deferring irrigation until the moisture deficit reached 36 mm significantly ($P<0.05$) reduced the yield of the pasture compared to treatments irrigated at deficits of 12 and 24 mm. There were no yield differences between the 12 and 24 mm deficits treatments. In six experiments conducted across five different soil types, the critical tensiometer readings for irrigation start-up were found to be 35 kPa and 30 kPa for tensiometers installed at 20 cm and 30 cm, respectively. Pasture losses of up to 1450 kg DM ha^{-1} were found for a 20 day delay in irrigation start-up time. In the following year pasture was irrigated at 3, 6, 9 and 12 day intervals. Extending the irrigation interval from 3 to 9 days at the Allansford site reduced pasture yields by an average of 25%, and by 36% for a 12 day interval. This was despite the same quantity of water being applied under each irrigation interval (Ward and Burch, 1999).

2.3.3. Combined effect of soil fertility and irrigation

While there is a great deal of information on the nutrient requirements of pasture in New Zealand, in general, there is a paucity of data on the combined effects of irrigation and soil nutrient status on pasture yield. In most pastoral systems, fertiliser is required for profitable and sustainable pasture production. The benefits of adopting an irrigation system often need to be enhanced by increasing fertiliser application, in order to maximise profit from this large capital investment. Nguyen *et al.* (1989) reported from a pasture grazing experiment irrigated at 25 % WT at 100 mm depth of Lismore stony silt loam in mid Canterbury spanning 34 years that the absence of P or S fertiliser inputs could lead to a severe reduction in pasture production and deterioration of the pasture sward towards weeds and weed grasses at the expense of high quality ryegrass and white clover.

It has been frequently demonstrated that uptake of nitrogen and phosphorus is reduced when plants are water stressed (D'Aoust and Tayler, 1968; Colman and Lazenby, 1975; Begg and Turner, 1976; Hegde, 1987). When water is non-limiting for grass growth there is often a highly significant linear relationship between nitrogen applied and that recovered in the plants. This relationship becomes curvilinear even when water stress is relatively mild (Colman and Lazenby, 1975). Consequently, water stress can act indirectly to reduce growth of the plant by reducing nutrient uptake. Colman and Lazenby (1975) reported a substantial reduction in the response of *Lolium perenne* to nitrogen under increased moisture stress. The reduction in response was greatest at the highest rate of nitrogen application. D'Aoust and Tayler (1968) also examined the interaction between nitrogen and irrigation on a sward of *Lolium multiflorum* (Italian ryegrass), and they concluded that the response to nitrogen was increased when irrigation improved the moisture status of the upper few inches of the soil. Similarly, Cookson *et al.* (1997) reporting on a lysimeter study found significant pasture and seed

yield improvement with N fertiliser when frequent irrigation maintained soil moisture contents within 70-90% of field capacity values.

It is a well-accepted that for most plant species, soil P absorption decreases with increasing soil water stress. For example, Begg and Turner (1976) state that the uptake of phosphorus is reduced slightly when the water potential of the root medium is reduced to -200 kPa and decreases linearly as the potential of the root medium reduces further, until at -1000 kPa, phosphorus uptake is negligible. Xia (1997) reported that the water stress created by 17-19 days of drought significantly decreased total seed nutrients per plant; the decreases being 34-45% for N uptake, 34-47% for P uptake, and 33-46% for K uptake by Faba bean (*Vicia faba*).

An important facet of the relationship between soil fertility and irrigation is captured in the concept of water use efficiency.

2.3.4. Water use efficiencies

Water use efficiency (WUE) is defined as the ratio of dry matter produced per unit area (kg DM ha^{-1}) per unit of evaporation (or evapotranspiration) hereafter called E (mm) (Viet, 1965; Begg and Turner, 1976; Jensen *et al.*, 1981) or, variations on this theme such as the harvestable (marketed) yield per unit of E (Begg and Turner, 1976). Consequently, some care should be taken when comparing different WUE values. Soil type, nutrient status, cultural and management practices, and variety choice also affect WUE. Crop breeders try to maximize water use efficiency (WUE) when breeding new varieties.

Several authors have proposed a proportionality constant (k), defined as the ratio of harvestable pasture yield per unit E (kg DM ha^{-1} mm^{-1}) for pasture in New Zealand (McAneney and Judd, 1983: Moir *et al.*, 2000a and 2000b; Blennerhassett, 2002). The

proportionality constant resembles the WUE. See section 2.5.3 for further discussion of *k*. Most of these workers report greater *k* values at increased soil fertility levels. Olsen P values are often used as an indicator of soil nutrient status.

Ward and Burch (1999) have reported on water use efficiencies under pasture in Victoria. As discussed earlier extending the irrigation interval from 3 to 9 days at the Allansford site reduced pasture yields by an average of 25%, and by 36% for a 12 day interval. This was despite the same quantity of water being used under all three irrigation treatments. The corresponding water use efficiencies (amount of pasture grown per megalitre of water applied), dropped from a mean of 1640 kg DM/Ml.ha for the 3 day interval to 1220 and 1060 kg DM/Ml.ha for the 9 and 12 day intervals, respectively. Water use efficiency fell from a mean for the season of 1040 kg DM/Ml.ha where 100% of estimated evapotranspiration was applied to 820 kg DM/Ml.ha where 70% was applied. Applying 30% more irrigation water than requirements did not increase ($P>0.05$) pasture yields but reduced the water use efficiency by 23%. (Ward and Burch, 1999)

Ward and Burch (1999) found that 77% of irrigators applied 30 mm or less, and 62% applied 25 mm or less irrigation water per week over the summer period. The comparable mean irrigation requirement over the summer period across trial sites was 33 mm per week. This work highlights the importance of matching irrigation to pasture water requirements to optimise water use efficiency. Singh *et al.* (2000) reported improvements in water use efficiency of clover at high P rates in dry soils.

2.3.5. Root system response to different irrigation and fertiliser treatments

A substantial quantity of information is available on root growth responses to variations in soil fertility and soil water content. Fine roots (< 2 mm in diameter) are the primary pathway for water and nutrient uptake by the plant (Jackson *et al.*, 1997). Reports that

describe the response of the root systems of pasture plants to variations in fertiliser application or water stress include those of Singh and Sale (1997), Wechsung *et al.* (1999), Sindhøj *et al.* (2000), and Steingrobe *et al.* (2001). The root distribution in irrigated and non-irrigated swards of six grass species was studied by Garwood and Sinclair (1979b).

Wilson (1988) reviewed models for explaining allocation of resources between root and shoot systems. A general principle established by Wilson (1988) is that a reduction in resource availability promotes increased re-allocation to the affected organs. Consistent with this principle, Singh and Sale (1997) observed the 'usual' increase in root:shoot ratio when P supply to white clover plants was reduced, but noted that this response was reversed under frequent defoliation, when root systems were also challenged. These authors suggested that increased root production promoted better exploitation of undepleted soil volumes.

Although the principle of reallocation is less well established for water than for nutrients, a number of studies indicate increased root:shoot ratio in response to water deficit. Garwood and Sinclair (1979b) observed greater root length per unit volume of soil (0-100 mm soil depth) under non-irrigated plots of a ryegrass-based sward in a UK study. Studies by Sindhøj *et al.* (2000) and Wechsung *et al.* (1999) also indicated increased root:shoot ratios in response to increased water deficit.

Cullen *et al.* (1972) studied the effect of irrigation depth on the root growth of perennial ryegrass, subterranean clover and white clover using 65 cm deep containers. They found that roots of both white clover and ryegrass were concentrated near the surface and large differences in the total weight of roots of different species were also observed. The roots of perennial ryegrass, constituted 24 per cent of the total pasture while in white clover it was 18 percent. They suggested that root growth is not a determinate of total production when the supply of nutrients is non-limiting.

Ehlers *et al.* (1980) reported that a plough layer between 20 and 30 cm depth induced greater rooting density at 10- 20 cm but a restricted density in the deeper layers, and water uptake rates were closely related to root length density, i.e. at a water potential of - 50 kPa, a root density of 2 cm cm^{-3} gave an uptake rate of 17.5 mm^3 H_2O cm^{-3} soil day^{-1}, while a density of 1 cm cm^{-3} gave a rate of 12.7 mm^3 H_2O cm^{-3} soil day^{-1}, and a root density of 0.5 cm cm^{-3} gave a rate of 8.1 mm^3 H_2O $cm^{-3}day^{-1}$. Similarly, Willatt and Olsson (1982), who assessed the effect of irrigation on soybeans, found that at a depth of 0.7-1.0 m the root density limited water uptake, even at high soil water potentials (> -20 kPa). Moreover, a root length density of 5 mm cm^{-3} corresponded to a water withdrawal rate of 0.016 cm^3 cm^{-3} day^{-1} and a density of 1.8 mm cm^{-3} a withdrawal rate of 0.005 cm^3 cm^{-3} day^{-1} for 0-30 cm soil depth (Willatt and Olsson, 1982).

2.4. ENVIRONMENTAL IMPLICATIONS RELATED TO IRRIGATED PASTURE

Fertiliser nitrogen (N) applications are a common component of pasture management in New Zealand, particularly on dairy farms. Farmers use N fertiliser to encourage high levels of pasture production to sustain profitable, competitive enterprises (Jarvis, 2000). Generally speaking, of the major nutrients, nitrogen not only provides the largest responses in crop yield, but is also the nutrient most readily lost to the non-agricultural environment (Davies, 2000). Nitrate leaching and contamination of ground and surface waters are a major concern in many countries (Di and Cameron, 2000). Nitrate is completely soluble in water and it is not absorbed. It is thus vulnerable to being leached from the soil by percolating rainfall or irrigation (Addiscot, 1996). Nitrate leaching from intensive pastoral systems, e.g. dairy farming systems is considered a major contributor to increased nitrate concentrations in ground waters (Ledgard *et al.*, 1996).

In limited areas of New Zealand, the recommended maximum nitrate-N concentration for drinking water of 11.3 mg nitrate-N L^{-1} (Ministry of Health, 1995) has been exceeded: this is mainly in areas with shallow ground water and where dairying and intensive horticulture are the predominant land use (Tillman, 1995). Clark (1997) has reviewed the use of fertiliser nitrogen on New Zealand dairy farms and he stressed the need to balance the preservation of water quality and the economics of dairying.

The time lag in N loss processes makes it difficult to reach firm recommendations regarding N fertiliser management strategies for sustainable pastoral systems. Clark (1997) suggested the following conclusions: (i) the total nitrate N leaching from dairy pastures is largely determined by the total amount of N cycling in the soil-pasture-animal system and the level of pasture utilisation; (ii) direct losses following fertiliser N application at 400 kg N $ha^{-1}yr^{-1}$ were 50 kg N $ha^{-1}yr^{-1}$, whereas losses were negligible at both 0 and 200 kg N $ha^{-1}yr^{-1}$; (iii) direct losses (up to 37%) at lower application rates can still occur if N is applied to free draining soils in early winter; (iv) single applications of N fertiliser should not exceed 50 kg N ha^{-}, and fertiliser should be applied to pasture that is just beginning its most active growth phase, if plant uptake is to be maximised.

Irrigation frequency will have a marked influence on drainage losses. Where irrigation is practised, it is commonly believed that leaching will be exacerbated due to a higher downward soil water flux (Nguyen *et al.*, 1996; Schneekloth *et al.*, 1996). For example, a change in application depth from 25 to 15 mm per irrigation resulted in less drainage and lower annual water use for supplementary irrigation in a pasture experiment in the Netherlands (Hack-ten Broeke, 2001).

It is also possible that irrigation reduces nitrate leaching because of improved water and nitrogen uptake by the plants. Hack-ten Broeke (2001) observed that the different

irrigation strategies referred to above had no significant effect on the nitrate-N concentration in the leachate from two dry fields, while for the relatively wet field in his study, an increase in irrigation water use apparently improved agricultural production and reduced nitrate-N concentrations at 1 m depth. Likewise, Burgess *et al.* (2002) reported that despite the irrigation treatment of their study having the greatest drainage volume, the irrigation treatment did not have the greatest amount of leaching from a dairy pasture in Reporoa, New Zealand. This was because irrigation enhanced pasture growth and N uptake during dry periods, resulting in more efficient use of the N applied (Burgess *et al.*, 2002).

2.5. MODELLING INTENSIVELY MANAGED IRRIGATED PASTURE PRODUCTION

2.5.1. Principles of Modelling

As one of the objectives of this thesis is to develop a model to predict the responses of soil water content and pasture production to different irrigation scenarios, a brief discussion of the principles of modelling is needed to introduce the logic behind the approach taken. Hillel (1977) stated, "The real world or indeed any perceivable system within it is altogether too complex for our limited intellect to comprehend or to define in its entirety. In dealing with any problem, therefore, we are obliged to take the easy way out, which is to imagine the system to be simpler than it really is, by considering only aspects of it which pertain to the problem at hand." The concept that Hillel (1977) was alluding to is that of a model which he defined as a simplified, and hence a more readily definable and more tractable, version of reality.

By checking if the predictions we achieve fit experimental results when circumstances change, we decide if the model is working and if not we revise it and try again.

Obviously the predictions from models can never be exact, and the conclusions that are drawn from them will bear further testing, as will the models themselves.

The very beginning of model development therefore, starts with *word models* and *conceptual models*. In order that the problem be precisely defined, and so that all involved can agree on the goals and objectives and on the essential elements of the model, verbal communication (to hypothesise) and formulation of concepts is perhaps the most basic but integral part of the modelling exercise. From a conceptual model, experiments are designed and conducted. By observing the experimental results, mathematical models are then formulated to describe how the system is thought to behave. The models are then validated by comparing model results with real-system data either by comparison with historical records or forecasting of future events. If the model simulates and predicts the variables of interest with sufficient accuracy, it will then open up new concepts, hypotheses and problems. Otherwise, we try again by improving current concepts, doing further experiments, and/or trying new mathematical models (Woodward, 2001).

The point to emphasise here is that the success of a model should be measured by how it opens up new insights and opportunities for expansion, and not just by exhibiting an 'excellent fit' with the real system. One of the most intriguing aspects of this process is that it helps improve knowledge as the models themselves evolve.

2.5.2. Soil water simulation Modelling

Estimating soil water status is often an important component of crop yield modelling (Hanks and Ritchie, 1991). In recent years, emphasis on environmental concerns has helped to heighten the interest in Modelling the storage and movement of water in soils.

Movement and transformation of nutrients and agrichemicals (e.g. pesticides) is also of particular interest (Heng *et al.*, 1991).

Soil water plays an important role in many agricultural management decisions including; optimising the rate and timing of fertiliser, pesticides and irrigation water applications, and in the design of drainage/irrigation systems. However, measurement of soil water content can be costly and time consuming, and is complicated by its inherent temporal and spatial variability. Consequently, numerous soil water simulation models have been developed with varying degrees of sophistication (De Jong and Bootsma, 1996). In one of the earliest models, average monthly precipitation and soil water storage were balanced against estimated E (Thornthwaite, 1948). Gradually, modelling procedures became more complex by using daily time steps, multi-layering of the soil profile and variable rates of extraction and movement of soil water from the various zones. More recently, sophisticated deterministic models, which attempt to utilize precise theoretical relationships, have been developed (De Jong and Bootsma, 1996).

Single layer balance models essentially treat the soil profile as a bucket into which water flows until it is full. Excess water is then treated as runoff and/or deep drainage beneath the root-zone (Fitzpatrick and Nix, 1969; Aase *et al.*, 1973; Barrs *et al.*, 1977; McAneney *et al.*, 1982; McAneney and Judd, 1983). In more advanced balance models (Baier and Robertson, 1966; Scotter *et al.*, 1979; Field, 1983) the soil profile is divided into zones; water from precipitation cascades from upper to lower zones when the upper ones reach field capacity. Results presented by Calder *et al.* (1983) indicate that the layered models are a considerable improvement over single bucket-type models. One of the strengths associated with single budget models is that they require a minimum amount of input data, namely field capacity, wilting point, an assumed rooting depth, daily precipitation and potential E.

Some inherent shortcomings of the budget approach relate to the concepts of field capacity and wilting point. As discussed earlier the field capacity concept is now recognized as arbitrary, and not an intrinsic physical property (Scotter, 1977; Hillel, 1980; Hillel, 1998). The distribution process is in fact continuous depending on the soil hydraulic properties, and exhibits no abrupt breaks or static levels (Warrick, 1990). Likewise, wilting point is also an idealized concept. Although originally presented as a solely soil dependent property, it is now generally accepted that plant characteristics and environmental conditions also influence the wilting point. Because of the complexity of all the factors involved, the root and soil coefficients used in modelling E remain empirical. They must be treated as being specific for certain soil-crops combinations and applicable only within a given range of climatic conditions (De Jong and Boostma, 1996).

According to a recent review by Woodward *et al.* (2001) of soil water balance models for prediction of soil moisture in New Zealand soils, the model of Scotter *et al.* (1979) represented an important advance in modelling the soil water deficit for flat pastoral soils in New Zealand by including a topsoil zone which is depleted and recharged preferentially, offering a solution to the problem (inability to account agronomic benefit of intermittent rains during a long drought) inherent in single-layer water balance models.

2.5.3. Application of proportionality constant (k) of pasture growth model

Recently, several workers (Faulalo, 1997; Moir *et al.*, 2000a and 2000b; Moir, 2000; Blennerhassett, 2002) have proposed a linear relationship between pasture growth and actual E for a range of W_T values under different fertility regimes for New Zealand hill country pasture. When cumulative pasture production is plotted against cumulative E, the gradient of the line is the proportionality constant (k) with units of kg of pasture per

mm of E per ha (kg ha^{-1} mm^{-1}). One of the major assumptions is that the assertion of Kerr *et al.* (1986) and Allen *et al.* (1998) that for full cover pasture (LAI> 3), nearly all of the E is transpiration, is true. In different contexts, e.g. irrigation studies, the proportionality constant (k) appears in another guise i.e. as one of the more commonly used and discussed measures of water use efficiency.

A number of studies (Rickard and Fitzgerald, 1970; Wright and Baars, 1976; Rickard *et al.*, 1986; Martin, 1990) have shown linear relationship between E and pasture production. Tanner and Sinclair (1983) argued that unless malnutrition is severe, k is not greatly affected by nutrient status. Ritchie (1983) and Power (1983) argued the opposite as follows. Ritchie (1983) stated that in most cases when water supply is fixed, any management factor that increases yield will increase k, quoting an example where irrigated maize biomass yield increased from 5241 to 10540 kg ha^{-1}, primarily due to N fertiliser application, while E only increased from 35.3 to 37.6 cm. Likewise, Power (1983) stated that water use efficiency increases with the level of fertility, and that often the greatest increases come from increases in fertiliser rates well below the optimum for maximum yield.

The following simple model was proposed by Moir *et al.* (2000a and 2000b).

$$G = k\,E \qquad (2.5)$$

Where

G = pasture growth (kg DM)

k = proportionality constant (kg DM ha^{-1} mm^{-1})

E = actual evaporation (mm)

Moir *et al.* (2000a and 2000b) assumed that the proportionality constant (k), which links pasture growth and E, depends in a large part on the soil fertility status.

McAneney and Judd (1983) measured a reduction in dryland pasture yield relative to irrigated production when the water deficits in Horotiu sandy loam reached 34 mm (Fig.2.3).

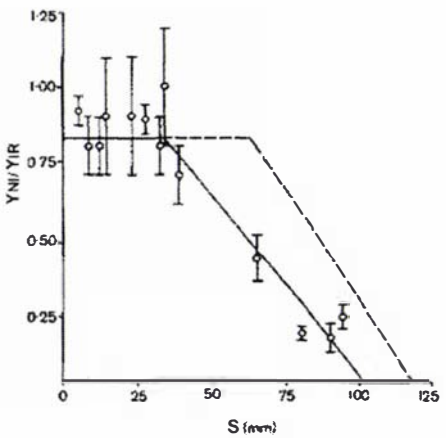


Figure 2.3 Ratio of the non-irrigated (Y_{NI}) to irrigated (Y_{IR}) pasture yield versus the soil moisture deficit (S). Error bars represent the SE caused by variability in yields from both the non-irrigated and irrigated paddocks. The dashed line represents E/E_{max} (after McAneney and Judd, 1983).

However, E/E_{max} did not begin to decline until approximately 60 mm deficit (approximately W_R) i.e. yields were first reduced at a significantly smaller deficit than was the case for E, but did not fall off as rapidly with increasing deficit. This implies that substantially different pasture yield responses may be obtainable for irrigation frequencies which trigger irrigation at various soil water contents within the readily available water range.

2.6. CONCLUSION

This review indicates that the combined effects of irrigation frequency and nutrient status on pasture production is yet to be fully explored in the context of efficient and sustainable management of pastoral systems in New Zealand. In particular there are some suggestions, if little evidence, that more frequent irrigation (within the readily available range) may result in increased pasture production.

This review indicates that there is a paucity of information on the response of roots to different irrigation and P fertility regimes.

It has also been established that while there is increasing concern about the impact of leaching under irrigation on water quality, current research findings are not conclusive on this matter.

CHAPTER 3

A POT STUDY OF THE EFFECTS OF IRRIGATION AND NUTRIENT STATUS ON RYEGRASS AND WHITE CLOVER PRODUCTION

3.1. INTRODUCTION

There are very few New Zealand studies of the combined effects of irrigation frequency and soil fertility on pasture production, and the majority of those that have been reported have compared pasture yield under the widest range of moisture conditions from field capacity (-5 kPa) to permanent wilting point (-1500 kPa). In other words, the benefits of irrigation to pasture production are usually measured at extreme - from the plant physiological point of view - soil water potentials. However, there are some indications that pasture production may increase under more frequent irrigation i.e. watering before the readily available water is depleted or at soil water potentials greater than -100 kPa.

It is obvious that the effects of irrigation and soil nutrient status on pasture production are most usefully assessed in the field. Yet soil profiles are complex not least of all because of the way that soil characteristics vary with depth. In addition, pasture root activity changes in a marked fashion with depth. Given this, an initial attempt was made to delineate and quantify the importance of the roles of water availability and nutrient availability to ryegrass and clover production. To achieve this, a homogenous soil medium where water, nutrients and roots were as evenly distributed as possible was required. The closest approximation to such uniformity is most practically achieved by the use of pots. Accordingly, the effect of irrigation frequency (in the readily available

water range) and nutrient status on ryegrass and clover growing was measured using pots in a glasshouse. Pots were used to create a homogenous soil medium where nutrients and roots were as evenly distributed as possible. A pot experiment appeared to be a prerequisite for a large scale field trial, yielding important understanding and shedding light on likely design and treatment parameters.

The objective of the study described in this Chapter is to measure the effects of irrigation frequency and nutrient status (especially P levels) on the production of ryegrass and white clover in controlled conditions (i.e. uniform distribution of nutrients and roots throughout the growing medium).

3.2. MATERIAL AND METHODS

3.2.1. Experimental layout

In this pot study, the effects of three irrigation frequencies and three fertiliser rates on two plant species were measured. There were 4 replicates of each treatment combined in a factorial design. There were 72 pots in total i.e. 3 irrigation treatments x 3 fertiliser treatments x 2 species x 4 replicates. Each pot grew a pure sward of either perennial ryegrass (*Lolium perenne* L.) or white clover (*Trifolium repens* L.) i.e. 36 pots of each. After they were packed with soil, the pots were arranged on four tables inside Glasshouse No 2 of the Plant Growth Unit, Massey University, Palmerston North. The pots were assigned to tables so that each table held one replicate i.e. 9 ryegrass pots and 9 clover pots.

Perennial ryegrass (15 seeds of cv. "Yatsyn I"/pot) and white clover (10 seeds of cv. "Grassland Sustain"/pot) were sown separately on 17-18 August 1999. On 15 September the ryegrass pots were thinned so that there were 13 plants per pot. All 10 clover plants were left to grow in each clover pot. All the pots were maintained near

'pot capacity' during the establishment phase. Grasses were trimmed to 6 cm height on 30 September. Irrigation treatments were imposed from 2 October 1999 onwards.

3.2.2. Establishment of pot parameters

3.2.2.1. The moisture characteristics of soil

The soil used was Ramiha silt loam which is classified as an Allophanic Brown Soil (Hewitt, 1998). This topsoil (0 – 150 mm) is commonly used as pot medium due to its responsiveness to P fertiliser and structurally stable nature. The soil was air-dried and passed through a 2 mm sieve. Soil moisture characteristics were determined using pressure plate apparatus (Ahuja and Nielsen, 1990) and disturbed samples. The gravimetric soil water contents at -100 kPa and -1500 kPa potential are 0.45 and 0.34, respectively. The gravimetric soil water content of 0.45 at -100 kPa potential was taken as the lower limit of W_R (Ahuja and Nielsen, 1990).

3.2.2.2. Preparation of pots

The dimensions of the tapered plastic pots are 19.0 cm in diameter at the top of the pot (the surface area of the top of each pot was 0.02835 m^2) and 16.5 cm at the bottom. The pots are 16.5 cm in internal height. A polythene bag (35 cm x 45 cm) was inserted into each pot prior to the packing of sieved soil. The purpose of laying polythene inner was to prevent the escape of nutrients or water through the bottom of the pot. Each pot was packed with 2680 g of soil (equivalent dry weight) to give a bulk density of 0.64 g cm^{-3}.

3.2.2.3. Calculation of pot capacity

$$\text{Pot capacity} = \text{Total porosity} - \text{air filled porosity} \quad (3.1)$$

$$\text{Maximum allowable water/pot} = (\text{Pot capacity}) \times (\text{Volume of soil in pot}) \quad (3.2)$$

Mass of W_R /pot = (Maximum allowable water/pot)

- (Mass of water retained at -100 kPa/pot) (3.3)

The following assumptions were made for the above calculations; particle density of Ramiha silt loam is 2.5 g cm^{-3}, the density of water is 1.0 g cm^{-3}, and the allowance for air filled porosity is 0.15 (Scotter, 1977). The W_R was found to be 1300 cm^3 for a packed pot. This latter value was integral to the design and operation of irrigation frequency treatments.

3.2.3. Irrigation frequency treatments

Three irrigation treatments were selected here as representatives, or at least spanning the range of, the scheduling options used by farmers to irrigate pasture.

The irrigation frequency treatments were:

I-15 Replenish soil moisture to pot capacity at 33% loss of W_R

(15 mm per unit area of pot surface)

I-30 Replenish soil moisture to pot capacity at 66% loss of W_R

(30 mm per unit area of pot surface)

I-45 Replenish soil moisture to pot capacity at 100% loss of W_R

(45 mm per unit area of pot surface)

The weight when the pot was watered to pot capacity was 5311.9 g. The pot weights at which watering was required for the I-15, I-30, and I-45 treatments were 4876.5 g, 4441.1 g and 3992.5 g, respectively. Irrigation to replenish the pot to 'pot capacity' was made when the pots reached the above target weights. I-30 and I-45 pots were weighed

every-other-day with an electric balance (reliable to $\pm$ 0.1 g). The frequent irrigation (I-15) pots were weighed every day.

3.2.4. Fertiliser rates

Three application rates of phosphorus (P) i.e. 5, 50 and 300 μg P g^{-1} of soil were selected as 'low', 'medium' and 'high' fertiliser treatment rates, respectively. The mean P requirement to attain solution P rates of 0.02 and 0.2 mg L^{-1} were identified from the P isotherm of Ramiha silt loam and these estimated initial phosphate requirements to attain solution P rates to 0.02 and 0.2 mg L^{-1} (μg ml^{-1}) were taken as the medium and high P rates, respectively (Hedley *et al.*, 1995). A low rate of 5μg of P g^{-1} soil was proposed to avoid extreme soil P deficiency in these pots. A full description of the method used to identify these values is given in Appendix 3.1. Using the P application rates as a guide, three rates of sulphur (S), nitrogen (N) and potassium (K) were selected for application to 'low', 'medium' and 'high' fertiliser treatments. The rate of nutrient application for each fertiliser treatment is given in Table 3.1.

Table 3.1 Nutrient application rate (kg ha^{-1}) for the three fertiliser treatments.

Fertiliser elements Treatments	Phosphorus (P)	Nitrogen (N)	Sulfur (S)	Potassium (K)
Low	5	50	10	46
Medium	47	150	47	138
High	284	400	236	368

Both the P and S fertilisers were thoroughly mixed with the soil before it was packed in the pots. Nitrogen and potassium were applied in solution, in four equal dressings, at monthly intervals. The source of P was calcium tetrahydrogenphosphate ($Ca(H_2PO_4)_2.H_2O$). Sulphur was added as a 3:1 ratio of $CaSO_4$ and $MgSO_4$. The source of nitrogen and potassium was a mixture of KNO_3 and NH_4NO_3 (2:1 ratio of NO_3^- nitrogen and NH_4^+ nitrogen).

3.2.5. Measurements

3.2.5.1. Pasture yield

Each pot was harvested at fortnightly intervals following the imposition of irrigation treatments (Plate 3.1 and Plate 3.2). The pots were harvested on 14 October, 30 October, 14 November, 30 November, and 20 December 1999. All the herbage material above 6 cm height was harvested. This herbage was oven-dried at 70 ^{0}C, weighed and recorded as pasture dry matter yield per pot (DM/pot). The yields from all the five harvests were aggregated and taken as total pasture yield. Water use efficiency (WUE) i.e. total pasture harvested per kg of water use (Begg and Turner, 1976) was calculated for each pot.

3.2.5.2. Leaf extension

The rate of leaf extension was measured for three randomly selected tiller-growing points on each ryegrass pot. A newly emerging, youngest visible leaf was selected and marked with a paint dot and its length (the distance between the leaf tip of the youngest visible leaf and the ligule of the uppermost fully emerged leaf) was measured (Davies, 1993), every other day, between 2 and 12 November. The rate of growth was calculated as length increment per day and is referred to as leaf extension for ryegrass.

The youngest leaf appearing on a randomly selected stolon was selected as a starting point for clover measurement and three such stolons per pot were used for monitoring. Petiole length development is reported to be linear with development stages of the leaf (Carlson, 1966). The length of petiole was measured from 2 - 12 November on every other day. The rate of growth was calculated as length increment per day. Hereafter, the petiole length increment of clover is referred to as leaf extension for clover.

3.2.5.3. Leaf stomatal resistance

Leaf stomatal resistance was measured with an automatic porometer MK3 (Delta T device, Burwell, Cambridge, England). Measurements were made on 3 recently, fully-

opened leaves per pot between 1 and 2 p.m. on three days. Midday observation is recommended for leaf stomatal resistance (Jones *et al.*, 1980b). The porometer was calibrated before and after each series of measurements using the perforated plate provided by the manufacturer.

3.2.5.4. Plant tissue nitrogen and phosphorus content

After oven drying (70^0C) and weighing, the herbage harvested on 30 October 1999 was ground using a CYCLOTEC 1093 sample mill. The ryegrass samples included all the leaf blades above 6 cm height while clover samples were composed of a mixture of leaves, petioles and some stolon parts. The ground samples were weighed accurately ($\pm$ 0.0001 g) and placed in a 100 ml Pyrex tube. Four millimetres of a digest mixture (250 g K_2SO_4 and 2.5 g selenium powder to 2.5 L H_2SO_4) was added and then the mixture was heated in an aluminum block at 350^0C for 4 hours. The tubes were cooled and diluted to 50 ml with deionised water and mixed thoroughly in a vortex mixture (McKenzie and Wallace, 1954). As a check on accuracy, a known, standard herbage sample was also digested routinely. Both total nitrogen content and total phosphorus content of each sample was determined using an auto analyzer (Technicon, 1976).

3.2.6. Statistical analyses

Data were analysed by Analysis of Variance (ANOVA), with the General Linear Model (GLM) procedure of the Statistical Analysis System (SAS Institute, 1990).

3.3. RESULTS

3.3.1. Pasture production

In general terms, pasture production differences, between the treatments were reasonably consistent for the five harvests. For this reason, and in the interest of brevity, only the total pasture production for all five harvests will be discussed here.

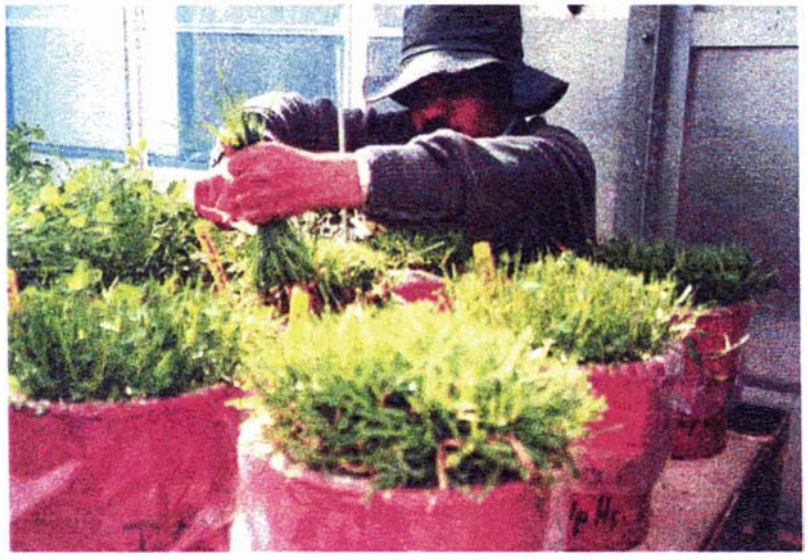


Plate 3.1 Harvesting pasture.

Plate 3.2 Some treatment effects on ryegrass. Pots shown are from left to right: I-45 with low fertiliser rate; I-30 with medium fertiliser rate; and I-15 with high fertiliser rate.

Production from the individual harvest are given in Appendix 3.2.

The overall mean productions of ryegrass and clover were 12.2 and 12.0 g DM/pot (Table 3.2) i.e. almost equal. The overall production per pot increased significantly ($P<0.0001$) with increasing fertiliser rate (Table 3.2) – the high rate producing approximately 150% more pasture than the low rate. Irrigation frequency did not significantly affect production – the overall productions were 12.3, 12.0, and 12.1 g DM/pot for irrigation frequencies I-15, I-30, and I-45, respectively. Significant interactions between species and fertiliser ($P<0.04$), as well as species and irrigation and fertiliser ($P<0.04$) were observed (Table 3.2).

Ryegrass production increased with fertiliser rate ($P<0.05$) at all irrigation frequencies - the greatest increase (approximately 70%) occurred between the medium and high rates (Table 3.2). When comparing the effects of fertiliser on production, the only non-significant difference was between low and medium fertiliser rates at I-45. In contrast, while ryegrass production tended to decrease with decreasing frequency of irrigation (i.e. from I-15 to I-45) for each fertiliser rate, irrigation frequency did not significantly affect production (Table 3.2).

As for ryegrass, clover production generally increased ($P<0.05$) with increasing fertiliser rate (Table 3.2). Unlike ryegrass, irrigation frequency had some effect on clover production. For least frequent irrigation (I-45), clover production was significantly ($P<0.05$) less than the productions at the other two frequencies at the low rate of fertiliser addition. In contrast, clover production for I-45 was significantly greater than the productions for I-15 and I-30 at the high fertiliser rate. There were no other significant differences between irrigation frequencies.

Table 3.2 Mean values indicating the effects of irrigation and fertiliser on the total production (g DM/pot) of ryegrass and clover.

Fertiliser rates	Low	Medium	High	Mean (n=12)	Mean (n=36)
Species and Irrigation					
Ryegrass					
I-15	7.3	12.0	20.8	13.4	12.2
I-30	6.1	11.4	17.6	11.7	
I-45	6.1	9.7	18.7	11.5	
Mean (n=12)	6.5	11.1	19.0		
Clover					
I-15	8.5	11.6	13.5	11.2	
I-30	9.2	11.7	15.7	12.2	12.0
I-45	4.6	12.9	20.2	12.6	
Mean (n=12)	7.5	12.1	16.5		
Mean (n=24)	7.0	11.6	17.7		
Statistical significance					
Fertiliser			P<0.0001		
Species * fertiliser			P<0.04		

LSD at P<0.05 = 3.9 g/pot (n=4).

The interaction (P<0.04) between species and fertiliser reflected the greater increase in the production of ryegrass (70%) than that of clover (36%) between medium and high fertiliser rates (Table 3.2). This may be attributed to the greater responsiveness of ryegrass to added P.

3.3.2. Water use

Ryegrass (10.8 kg/pot) used significantly (P<0.0001) more water than clover (8.9 kg/pot) (Table3.3). The effect of fertiliser rate on the overall total quantity of water used was significant (P<0.0001). Irrigation frequency did not effect water consumption.

Water use by ryegrass increased significantly (P<0.05) with increasing fertiliser rate for all irrigation frequencies. Water use at the high fertiliser rate was significantly (P<0.05)

greater (approximately 60%) than that for the low fertiliser rate. Irrigation frequency had no effect on water consumption by ryegrass.

Table 3.3 Mean values indicating the effects of species, irrigation and fertiliser on the water use (kg water /pot) of ryegrass and clover.

Fertiliser rates	Low	Medium	High	Mean (n=12)	Mean (n=36)
Species and Irrigation					
Ryegrass					
I-15	8.4	11.6	14.3	11.4	10.8
I-30	8.3	10.7	13.7	10.9	
I-45	7.9	10.1	12.4	10.1	
Mean (n=12)	8.2	10.8	13.5		
Clover					
I-15	8.3	9.2	9.1	8.9	
I-30	7.9	8.6	10.0	8.8	8.9
I-45	5.3	10.1	11.9	9.1	
Mean (n=12)	7.2	9.3	10.3		
Mean (n=24)	7.7	10.0	11.9		
Statistical significance					
Species			P<0.0001		
Fertiliser			P<0.0001		

LSD at P<0.05 = 2.4 (n=4).

For clover, the only significant (P<0.05) effect of fertiliser application was at I-45 where water use at the low rate of fertiliser use was smaller than at the other fertiliser rates. There was no consistent effect of irrigation frequency on water use by clover although there were two significant (P<0.05) differences; at the low fertiliser rate, water use at I-45 was lower than for the other two irrigation frequencies, and at high fertiliser rate, water use at I-15 was smaller than at I-45 (Table 3.3).

3.3.3. Water use efficiency

The water use efficiency (WUE) of clover (1.30 g DM kg^{-1} water) was significantly ($P<0.001$) greater than that of ryegrass (1.08 g DM kg^{-1} water). The overall effect of fertiliser rate on WUE was significant ($P<0.0001$). Overall, irrigation frequency did not significantly affect WUE. There was a significant interaction ($P<0.04$) between irrigation frequency and fertiliser rate (Table 3.4). The prominent feature of the interaction ($P<0.04$) between irrigation frequency and fertiliser rate for WUE was the high WUE for high fertiliser rate at I-45 (Fig. 3.1). This compares with a slight reduction in WUE between I-30 and I-45 at both low and medium fertiliser rates.

In general terms, the WUEs of both ryegrass and clover increased ($P<0.05$) with increasing fertiliser rate, at all irrigation frequencies. The WUE of both species at the high fertiliser rate was significantly ($P<0.05$) greater (approximately 55 - 75%) than that at the low fertiliser rate (Table 3.4). The maximum WUE for clover was observed at I-45 and high fertiliser rate (Table3.4).

3.3.4. Leaf extension rate

The overall effect of species, fertiliser rate and irrigation frequency were significant on leaf extension rate. Overall mean leaf extension rates of 11.0, 9.0, and 9.2 mm day^{-1} were observed for irrigation frequencies I-15, I-30, and I-45, respectively. The leaf extension rate at I-15 was significantly ($P<0.0001$) greater than those at both I-30 and I-45. The mean leaf extension rates of 9.2, 9.3, and 10.7 mm day^{-1} were observed for low, medium, and high fertiliser rates, respectively. Leaf extension rate for the high fertiliser rate was significantly ($P<0.0001$) greater than that for both low and medium fertiliser rates (Table 3.5).

Table 3.4 Mean values indicating the effects of species, irrigation and fertiliser on the WUE (g DM kg^{-1} water) of ryegrass and clover.

Fertiliser rates	Low	Medium	High	Mean (n=12)	Mean (n=36)
Species and Irrigation					
Ryegrass					
I-15	0.87	1.04	1.47	1.13	1.08
I-30	0.74	1.07	1.30	1.03	
I-45	0.79	0.96	1.51	1.09	
Mean (n=12)	0.80	1.03	1.42		
Clover					
I-15	1.02	1.23	1.48	1.25	
I-30	1.15	1.35	1.54	1.35	1.30
I-45	0.87	1.32	1.71	1.30	
Mean (n=12)	1.02	1.30	1.58		
Mean (n=24)	0.91	1.16	1.50		
Statistical significance					
Species			P<0.0001		
Fertiliser			P<0.0001		
Irrigation*fertiliser			P<0.04		

LSD at P<0.05 = 0.21 (n=4).

Leaf extension rates of ryegrass increased with increasing fertiliser rate and many of these increases were significant (P<0.05), particularly the increase between the low and high fertiliser rates at all irrigation frequencies (Table 3.5). Usually, the rate of ryegrass leaf extension decreased as irrigation frequency decreased. Leaf extension rate at I-15 was significantly greater than that at I-45 at all fertiliser rates.

Fertiliser rate did not have the same effect on the leaf extension rate of clover as it did for ryegrass. The only significant difference for clover was between leaf extension at the low and high fertiliser rate for I-15. Likewise, the effect of irrigation frequency on clover leaf extension was less consistent than that for ryegrass – the only significant effect of irrigation was at the high fertiliser rate where I-15 had a significantly (P<0.05) greater leaf extension rate than either I-30 or I-45 (Table 3.5).

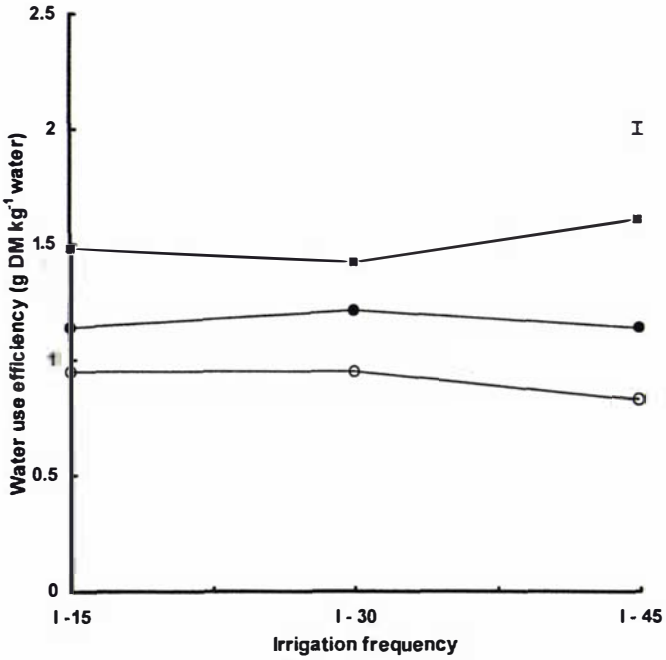


Figure 3.1 The interaction of irrigation and fertiliser rate for WUE. Symbols ○, ●, and ■ represent low, medium and high fertiliser rates, respectively. Error bar indicates standard error (P<0.05).

3.3.5. Leaf stomatal resistance (s cm^{-1})

In general, leaf stomatal resistance observations were highly variable, probably due to cloud movements. Relatively consistent observations were collected on 10 December. The coefficient of variation for the leaf stomatal resistance data set was high (66%). The overall mean leaf stomatal resistance for clover (2.1 s cm^{-1}) was significantly (P<0.0001) greater than that for ryegrass (1.1 s cm^{-1}) (Table 3.6). Overall mean leaf stomatal resistances of 1.5, 1.6, and 1.7 s cm^{-1} were observed for irrigation frequencies I-15, I-30, and I-45, respectively, i.e. they were almost equal. Likewise, the overall effect of fertiliser rate was non-significant (Table 3.6). There were significant (P<0.05) interactions between species and irrigation.

Table 3.5 Mean values indicating the effects of species, irrigation and fertiliser on the leaf extension rate (mm day^{-1}) of ryegrass and clover.

Fertiliser rates	Low	Medium	High	Mean (n=36)	Mean (n=108)
Species and Irrigation					
Ryegrass					
I-15	9.9	10.1	12.4	10.8	9.2
I-30	6.6	8.8	9.4	8.3	
I- 45	7.6	7.7	10.0	8.4	
Mean (n=36)	8.0	8.9	10.6		
Clover					
I-15	10.5	10.6	12.3	11.1	
I- 30	10.4	9.2	9.7	9.7	10.3
I- 45	10.4	9.2	10.5	10.0	
Mean (n=36)	10.4	9.6	10.8		
Mean (n=72)	9.2	9.3	10.7		
Statistical significance					
Species			P<0.0004		
Fertiliser			P<0.0001		
Irrigation			P<0.0001		
Species * fertiliser			P<0.01		

LSD at P<0.05 = 1.8 (n=12), three observations were taken per pot.

Fertiliser rate did not consistently affect the leaf stomatal resistance of ryegrass or clover. The mean value of stomatal resistance of ryegrass for I-45 was significantly greater than those for I-15 and I-30 suggesting a degree of ryegrass stress at the less frequent irrigation (I-45) treatment. In contrast, the mean values of stomatal resistance for clover across the three irrigation frequencies were almost equal, hence the significant ($P<0.05$) interaction between species and irrigation (Table 3.6).

3.3.6. Plant tissue phosphorus (P) content

The overall mean plant tissue P content for ryegrass (0.38%) was significantly ($P<0.0001$) greater than that for clover (0.32%). The overall effects of fertiliser and irrigation frequency were significant on tissue P content. The interaction effects of

species and irrigation (P<0.009), species and fertiliser rate (P<0.0001), irrigation and fertiliser rate (P<0.001) were significant for tissue P content (Table 3.7). The tissue P content of both ryegrass and clover increased significantly (P<0.05) with increasing fertiliser rate, and this increase appeared to be linearly related to the application rate of P fertiliser.

Table 3.6 Mean values indicating the effects of species, irrigation and fertiliser on the stomatal resistance of leaf (s cm^{-1}) of ryegrass and clover.

Fertiliser rates	Low	Medium	High	Mean (n=36)	Mean (n=108)
Species and Irrigation					
Ryegrass					
I-15	0.6	0.8	1.7	1.0	1.1
I-30	0.7	1.0	0.9	0.9	
I- 45	2.0	1.3	1.1	1.5	
Mean (n=36)	1.1	1.0	1.2		
Clover					
I-15	2.5	1.5	2.0	2.0	
I- 30	2.3	2.1	2.4	2.3	2.1
I- 45	1.6	2.6	1.8	2.0	
Mean (n=36)	2.2	2.1	2.1		
Mean (n=72)	1.6	1.5	1.7		
Statistical significance					
Species			P<0.0001		
Species*irrigation			P<0.05		

LSD at P<0.05 = 0.86 (n=12), three observations were taken per pot.

However, it is the low tissue P content of clover at I-45, low fertiliser rate that accounts for the statistical significance of the irrigation effect and some of the significant interactions (Table 3.7). Apart from this small value for clover, tissue P content was more or less consistent across all irrigation frequencies for all fertiliser rates. This features of the data set and its impact on the irrigation by fertiliser interaction is illustrated in Fig. 3.2.

Table 3.7 Mean values indicating the effects of species, irrigation and fertiliser on the plant tissue P concentration (%) of ryegrass and clover.

Fertiliser rates Species and Irrigation	Low	Medium	High	Mean (n=12)	Mean (n=36)
Ryegrass					
I-15	0.28	0.34	0.48	0.37	0.38
I-30	0.30	0.36	0.50	0.38	
I-45	0.28	0.36	0.50	0.38	
Mean (n=12)	0.29	0.35	0.49		
Clover					
I-15	0.27	0.33	0.38	0.33	
I-30	0.31	0.36	0.39	0.35	0.32
I-45	0.16	0.34	0.38	0.29	
Mean (n=12)	0.24	0.34	0.38		
Mean (n=24)	0.27	0.35	0.44		
Statistical significance					
Species			P<0.0001		
Fertiliser			P<0.0001		
Irrigation			P<0.008		
Species * irrigation			P<0.009		
Species *fertiliser			P<0.0001		
Irrigation*fertiliser			P<0.001		

LSD at P<0.05 = 0.04 (n=4).

3.3.7. Plant tissue nitrogen (N) content

Plant tissue N content for clover (5.38%) was significantly (P<0.0001) greater than that for ryegrass (4.19%). The overall effect of fertiliser rates on plant tissue N content was significant (Table 3.8).

In general, the tissue N content of ryegrass was significantly (P<0.05) greater at the high fertiliser rate than for the other two fertiliser rates at I-30 and I-45, and tissue N content for high fertiliser rate was significantly (P<0.05) greater than for the low fertiliser rate at I-15. The only effect of fertiliser on clover tissue N content was at I-45

for the low fertiliser rate which was significantly ($P<0.05$) smaller than the N content for the other fertiliser rates (Table 3.8).

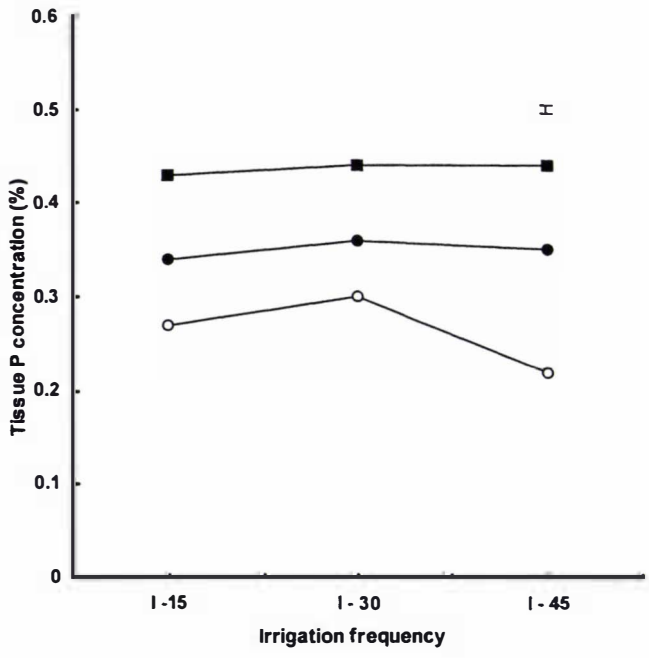


Figure 3.2 The interaction of irrigation and fertiliser rate for tissue P content. Symbols ○, ●, and ■ represent low, medium and high fertiliser rates, respectively. Error bar indicates standard error ($P<0.05$).

3.4. DISCUSSION

The soil in the pots was relatively uniform i.e. the soil had been sieved, packed to a constant bulk density, and where P fertiliser was added, this was thoroughly mixed with the soil before it was placed in the pot. It is commonplace to observe relatively uniform root growth within pots, and this was visually observed to be the case in the current experiment. In this environment, both ryegrass and clover growth increased with increasing fertiliser rate.

Both ryegrass and clover production increased with fertiliser at each irrigation frequency in this pot experiment. Water use efficiency (WUE) of each species also increased with addition of fertiliser. The responsiveness of plants growing in Allophanic soil such as Ramiha silt loam to P fertiliser has been well documented (Bolan *et al.*, 1997; Morton *et al.*, 1997; Cornforth, 1998). Water use was not affected by irrigation frequency.

Table 3.8 Mean values indicating the effects of species, irrigation and fertiliser on the plant tissue N concentration (%) of ryegrass and clover.

Fertiliser rates	Low	Medium	High	Mean (n=12)	Mean (n=36)
Species and Irrigation					
Ryegrass					
I-15	3.97	4.10	4.37	4.15	4.19
I-30	4.10	4.01	4.58	4.23	
I-45	4.19	3.84	4.57	4.20	
Mean (n=12)	4.09	4.01	4.51		
Clover					
I-15	5.36	5.29	5.65	5.43	
I-30	5.47	5.34	5.66	5.49	5.38
I-45	4.62	5.40	5.63	5.22	
Mean (n=12)	5.15	5.34	5.64		
Mean (n=24)	4.62	4.67	5.10		
Statistical significance					
Species			P<0.0001		
Fertiliser			P<0.0001		

LSD at P<0.05 = 0.38 (n=4).

The values for plant tissue N and P concentration support the notion that fertiliser rate had a much more significant impact on the growth of ryegrass or clover than did irrigation frequency.

The WUE values for ryegrass and clover are equivalent to 10.8 and 13.0 kg DM ha^{-1} mm^{-1}, respectively, and as such are comparable with the proportionality constants proposed by Moir *et al.* (2000a and 2000b). Begg and Turner (1976) report greater WUEs for dicotyledonous plants than for monocotyledons plants compared in a similar study. Singh *et al.* (2000) reported improvement of WUE of clover at high P rates in dry soils.

The interaction ($P<0.04$) between irrigation frequency and fertiliser rate for WUE in which the greatest WUE was for high fertiliser rate at I-45 may be partly attributed to the significant increase in clover production for high fertiliser rate at I-45 which in turn may be associated with better soil aeration at I-45.

Given that fertiliser rate impacted on both water use and growth, it is not surprising that WUE is sensitive to fertiliser rate i.e. the greater the fertiliser rate the greater the WUE of both ryegrass and clover. This suggests that it is important to optimize soil nutrient status under irrigation if large productions are to be realized, and this is particularly true under less frequent irrigation.

Davies (1993) reports that changes in rates of leaf extension often give the earliest indication that plants are under stress and the reduction in leaf extension rate of stressed plants and the consequent reduction in leaf area of stressed plants is the principal reason for reduced pasture production. The rate of leaf expansion varies with leaf ontogeny (Toshihiro and Takeshi, 1996). A slow initial extension rate is followed by a period with an approximately constant rate and, finally, a decreasing rate is characteristic of leaves approaching maximum area. The leaf extension measurements made here were confined to the period of linear growth. The significant differences observed between irrigation treatments suggest that during this phase of leaf growth, more frequent irrigation increased the rate of leaf extension. Arguably, this is the period when the plant is most sensitive to the water supply potential. That irrigation frequency did not significantly affect production implies that leaf extension rates in either one or both of the slower

phases of leaf extension may be greater for the less frequently irrigated treatments. However, leaf stomatal resistance did not support the suggestion of short term advantages of more frequent irrigation although, as was pointed out above, leaf stomatal resistance data were extremely variable.

As might be anticipated, fertiliser rate affected leaf extension rate. Other workers have made similar observations (D'Aoust and Tayler, 1968; Colman and Lazenby, 1975). Wilman and Fisher (1996) report that applied N increased the number of ryegrass tillers m^{-2}, the rate of leaf extension and the weight of new leaf produced per tiller and m^{-2} per week. The prominent feature of the interaction between species and fertiliser ($P<0.01$) was the increase in ryegrass leaf extension rate with the increase in fertiliser rate mentioned above. This may be due to the preferential response of ryegrass for the N component of the fertiliser mixture. In contrast, clover leaf extension rates across fertiliser rates are relatively constant (Table 3.5). Overall, the species and fertiliser interaction appeared to be an indication of the dependency of ryegrass on fertiliser N when soil water is unlimited (Wilman and Fisher, 1996).

The marked increase in N and P concentration of ryegrass and clover tissues with increasing fertiliser rate is to be expected and in part vindicates the application rates selected. If the values proposed by McNaught (1978) for deficient P (0.3% for both species) and N (4.0% and 4.3% for ryegrass and clover, respectively) nutrition of ryegrass and clover are considered then only a very few treatments had low values.

Irrigation frequency did significantly impact on P uptake (Table 3.7). However, this effect can be attributed to the low uptake of P by clover at low fertiliser rate and less frequent irrigation (I-45). Tissue P contents of white clover in the current pot experiment appeared to be deficient at all the irrigation rates for low fertiliser rate. This can be expected for the high P fixing Ramiha silt loam series of the Allophanic Brown Soil order, because legumes as a group appear to be less tolerant of soil low P than grasses (Caradus, 1980). Begg and Turner (1976) reported a reduction in phosphorus

uptake at -200 kPa potential and the observations reported here indicate that P uptake of clover seems to be sensitive even to the much lower soil water potential of -100 kPa.

The concentration of tissue P for ryegrass is typically between 0.26 and 0.4% (Kemp *et al.* 1999). Given this, values for ryegrass at the high fertiliser rate indicate the luxury absorption of P made possible by a vigorous root system (Caradus, 1980). Rendig and Taylor (1989) state that the ability to absorb luxury amounts of P in forage crops come from a soil P abundant medium.

What is of most interest in the results for plant tissue N and P concentrations is the lack of any consistent response to irrigation frequency as it has been demonstrated frequently that uptake of N and P is reduced when plants are water stressed (Begg and Turner, 1976; Colman and Lazenby, 1975). When water is non-limiting for grass growth there is often a highly significant linear relationship between nitrogen recovered in the plants and that applied and this relationship becomes curvilinear even when water stress is relatively mild (Colman and Lazenby, 1975). Consequently, water stress can act indirectly to reduce growth of the plant by reducing nutrient uptake.

In the relatively homogenous medium of potted soil, irrigation frequency did not effect the indicators of ryegrass and clover performance measured here (apart from leaf extension). This suggests that, as far as total production is concerned, all of the readily available water is 'equally' available i.e. where nutrients are mixed throughout well structured soil, through which roots proliferate, extraction of the first one-third (15 mm) of the readily available water (45 mm) does not facilitate significantly greater production of ryegrass or clover than extraction of the last one-third of readily available water.

3.5. CONCLUSION

The rate of fertiliser addition to the pots had a significant and consistent effect on a number of indicators of ryegrass and clover performance including total production. In contrast, the range of irrigation frequencies adopted here did not significantly or consistently affect indicators of ryegrass and clover performance including total production. Of the two factors studied here, irrigation frequency and fertiliser rate, nutrient status in the pots was of primary importance.

In this pot study, where soil, nutrients and plants roots were a relatively homogenous mix, more frequent watering was not significantly advantageous to plant growth. This suggests that as far as ryegrass and clover production is concerned, there is no distinction between increments of readily available water. That is, the extraction of the first 15 mm of readily available water was not associated with significantly greater production than uptake of the last 15 mm of readily available water.

CHAPTER 4

FIELD STUDIES OF THE PRODUCTION OF RYEGRASS AND WHITE CLOVER IN RESPONSE TO THE IRRIGATION FREQUENCY AND P FERTILITY STATUS

4.1. INTRODUCTION

Results from the pot experiment described in Chapter 3 were used to develop a field experiment. Although there was no response in pasture production to irrigation frequency in the pot experiment, it was hypothesised that irrigation frequency in the field would affect pasture production. This hypothesis was based on the significant effect that fertiliser application had on pasture production in Chapter 3. As soil nutrient availability will vary markedly with depth in a field soil, pasture growth rates might be expected to vary dramatically depending on the soil depth that roots are removing water, and hence nutrients, from. Consequently, pasture production responses may vary according to the depth to which the soil profile dries between irrigation events.

Some comments about the transition from the pot experiment to the field trial are in order. Firstly, the irrigation frequencies used in the field trial were the same as those used in the pot (i.e. plots were irrigated at the depletion of 33%, 66% and 100% of readily available water) because they correspond to the range of frequencies commonly employed by farmers. Secondly, as for the pot trial, the focus in the field trial was on the effects of P fertility on ryegrass and clover production. Thirdly, like the pot trial, both ryegrass and white clover were grown in the field. One important difference between the pot trial and field experiment related to soil type. Ramiha silt loam was used in the pot trial because of its responsiveness to P addition and its stable structure. However,

this soil is found mostly on hill tops and is not irrigated. The soil selected for the field trial is Manawatu fine sandy loam which is typical of many of the soils growing pasture under irrigation.

The objective of this chapter was to study the impacts of irrigation frequency and P fertility status on the production of both ryegrass and clover in the field, or more specifically to determine if more frequent irrigation would enhance ryegrass and white clover production by maintaining the surface soil in a moist condition and maximising moisture uptake from this depth where nutrients are most concentrated.

4.2. MATERIALS AND METHODS

4.2.1. General description

The field experiment was conducted at Massey University's Palmerston North campus at a site known as 'Frewens Block', near the Turitea stream. The soil at this site is Manawatu fine sandy loam (Plate 4.1), classified as a Weathered Fluvial Recent soil (Hewitt, 1998). The reference of the location: latitude is 40^0 23'S and longitude is 175^0 37'E, the elevation is 40 m above mean sea level. At the commencement of the experiment the soil Olsen P range (n = 8, CV 9%) for the topsoil layer (0-200 mm) was 11.6 - 15.3 mg kg^{-1} of soil.

The experiment comprised combinations of three irrigation frequency and two P fertility treatments (described below), applied to swards of perennial ryegrass (*Lolium perenne* L.) or white clover (*Trifolium repens* L.). There were 4 replicates of each treatment giving 48 plots in total. Plots were 1.5 m^2 in area and separated from neighbouring plots by 1 m wide buffer zones. On 14 January 2000, half the plots were sown with perennial ryegrass (cv. "Yatsyn I") and half were sown with white clover (cv. "Grassland

Sustain). Seeding rates were 30 kg ha^{-1} and 5 kg ha^{-1} for ryegrass and clover, respectively. The plots were laid out in a randomised complete block design (Fig. 4.1). Four non-irrigated, non-P fertilised plots were demarcated outside the main experimental area to indicate the soil-drying pattern and the response to irrigation.

4.2.2. Irrigation frequency treatments

In traditional irrigation design, W_R (i.e. water between -5 kPa and -100 kPa soil water potential) is commonly calculated for pasture by assuming a root depth of 450 mm. W_R for the upper 450 mm of the soil profile at the experimental site was determined using pressure plate apparatus as described by Ahuja and Nielsen (1990), and found to be 60 mm (see section 5.3). As for the pot experiment, W_R was divided into thirds and the irrigation frequencies selected accordingly. Therefore, the irrigation frequency treatments were:

I-20 Replenish soil moisture to field capacity at 33% loss of W_R (20 mm soil water deficit).

I-40 Replenish soil moisture to field capacity at 66% loss of W_R (40 mm soil water deficit).

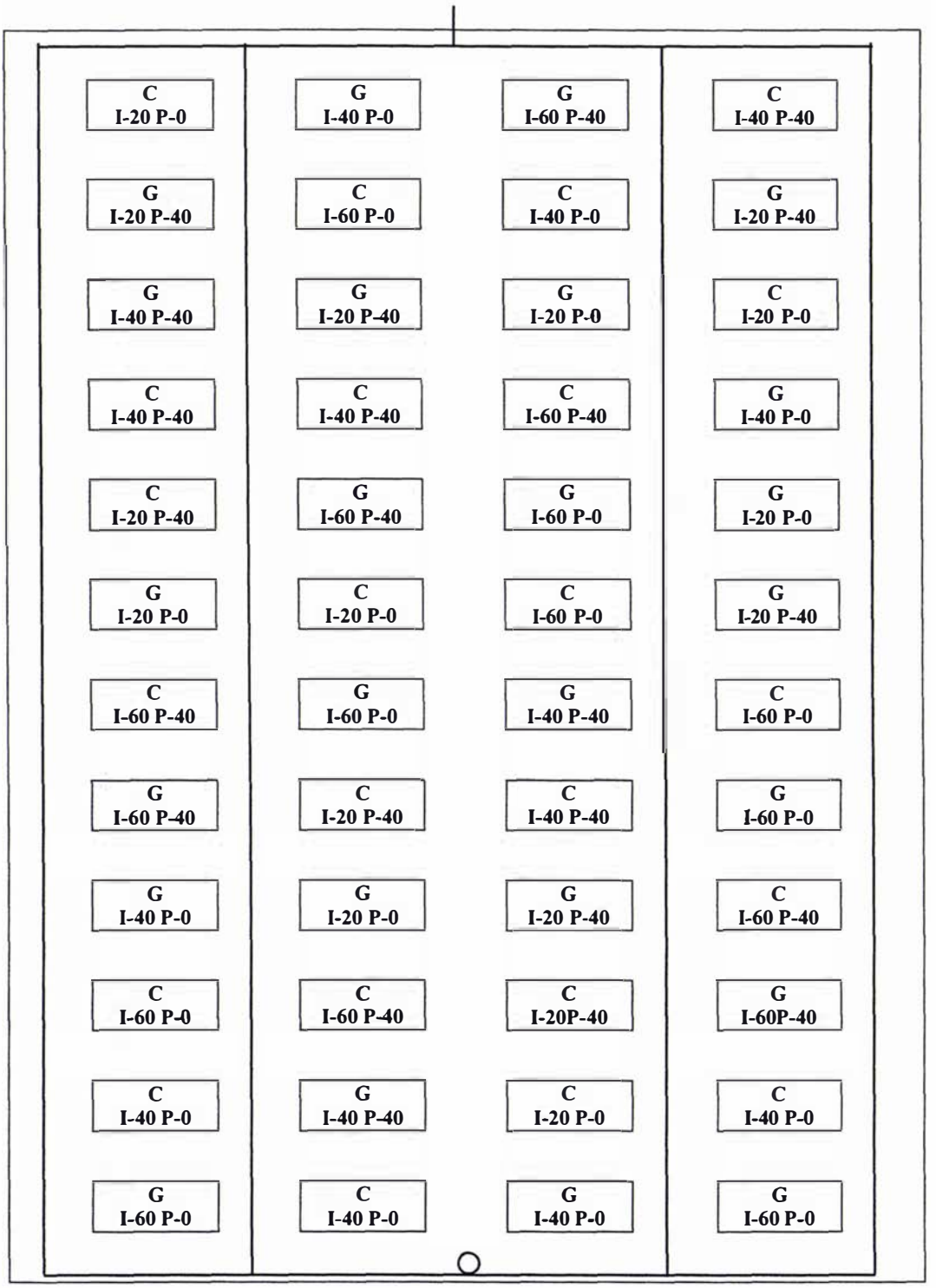
I-60 Replenish soil moisture to field capacity at 100% loss of W_R (60 mm soil water deficit).

For the purpose of scheduling irrigation, water loss from the soil profile (i.e. the cumulative soil water deficit) was estimated using climate data from two nearby meteorological stations and the water balance model proposed by Scotter *et al.* (1979). Rainfall was measured using a rain gauge at the site. The soil water balance and actual quantity of irrigation for each irrigation frequency treatment, and rainfall at the site are shown in Appendix 4.1. TDR soil water measurements on the non-irrigated plots suggested that there was 120 mm of total available water (W_T) (Appendix 4.2).

The main water supply line (25 mm diameter) was laid around the area and two additional parallel supply tubes between treatment blocks 1 and 2, and between blocks 3 and 4 were also connected (Fig. 4.1). The main supply line was connected to the water supply main for the paddock. One garden type mini-sprinkler was installed at the centre of each plot and a control valve was connected into the line connecting the sprinkler to the supply tube (25 mm diameter) which ran between blocks. The control valve provided the facility to control watering time for each plot according to treatment requirements. The design capacity of each sprinkler head was 48 L hr^{-1} at 100 kPa water pressure and the effective radius (normal) was 1.2 m. This is equivalent to 10.6 mm depth hr^{-1}. A 100 kPa vacuum control gauge was connected to the middle of the main water supply line.

Therefore, all parts of the watering network were maintained at 100 kPa pressure during the irrigation events. Catch can tests were carried out at the time of introducing the irrigation system to verify design criteria. Likewise, uniformity of irrigation across individual plots and between plots of the same treatment was established.

All the plots were irrigated to bring the root zone (450 mm) to field capacity on 30 November 2000 in preparation for the 2000/2001 irrigation season. Subsequently, irrigation took place when trigger values were reached as described above. Mini sprinklers were rechecked with a catch can test in November 2000 to ensure that the quantity of irrigated water on the plots equalled the treatment values of 20 mm, 40 mm or 60 mm.



G= Ryegrass C= Clover

Figure 4.1 Schematic diagram of field experiment (not to scale), Thick lines represents main water supply lines. The circle on the bottom main water supply line represents a 100 kPa vacuum control gauge. The non-irrigated, non-P fertilised plots are not shown.

4.2.3. P fertiliser treatments

The application rate of 40 kg of P per hectare per annum was selected on the basis of the soil Olsen P level (12 m g kg $^{-1}$) of the top 7.5 cm of the profile (Cornforth, 1998; Roberts *et al.*, 1994). The two contrasting P fertiliser treatments were:

P-0: No fertiliser P applied.

P-40: fertiliser P applied at 40 kg P ha^{-1}.

Single super phosphate was used as the fertiliser. The application for the 1999/2000 season was made to the fertilised plots on January 2000 and the application for the 2000/2001 season was made in the middle of November 2000.

Ammonium nitrate was applied as the source of nitrogen for the ryegrass plots- the quantity applied matched that which was removed in the preceding harvest (i.e. the concept of replacement of N in the harvested herbage). The exact quantity of N applications during the irrigation season is shown in Table 4.1.

4.2.4. Pasture production observations

All the plots were mowed at 5 cm height on 23 November 2000 prior to the commencement of the summer (2000/2001) irrigation cycle. Thereafter, all the herbage mass of the whole plot (1.5 m^2) was mowed to 5 cm height with a power operated hand shear. The shear was installed on a moveable trolley fitted with two small wooden wheels (5 cm diameter) thereby maintaining a constant grass cutting height of 5 cm above the ground (view of some plots prior to harvest are in plates 4.1 to 4.6). Dry weight of herbage mass (pasture production) for each plot was recorded following oven

drying at 70^0 C for 24 hr. Harvesting was conducted at approximately 3 weekly intervals during the irrigation season.

Table 4.1 Details of Nitrogen fertiliser (NH_4NO_3) application for ryegrass plots.

Date	Quantity N kg ha^{-1} at each N dressing	Cumulative N kg ha^{-1}
2 Dec. 2000	25	25
26 Dec. 2000	20	45
23 Jan. 2001	25	70
26 Feb. 2001	20	90
19 Mar. 2001	20	110
6 April. 2001	10	120
15 May 2001	20	140

The proportionality constant value (k), the water use efficiency term of Chapter 3, is obtained directly through division of cumulative seasonal pasture production by the cumulative evaporation for the whole irrigation season (Moir *et al.*, 2000a and 2000b; and Moir, 2000). Since all three irrigation frequencies maintained soil moisture contents within W_R, it was assumed that Priestly and Taylor potential evaporation values were equal to the actual evapotraspiration (E). On the non-irrigated plots it was assumed that E was equal to the Priestly and Taylor potential evaporation until a deficit of 120 mm. Thereafter E was zero.

4.2.5. Determination of tissue nitrogen and phosphorus concentration

Sub samples of the herbage harvested on 13 March 2001 were dried at 70^0C in an oven then separately ground for tissue analyses. The plant material of ryegrass included all the leaf blades above 5cm height from the ground surface and clover materials were a mixture of leaves, flowers and petioles above 5cm height. The procedure for measuring

total tissue N and tissue P extract was the same as that used for analyses of the pot experimental plant material (described in Chapter 3).

4.2.6. Soil sampling and analyses

4.2.6.1. Soil sampling

Soil samples were collected on 24 April 2001 from five different depths for determination of soil nitrate N content, soil ammonium N content and Olsen P of the soil. Sampling depth intervals were; 0-75 mm, 75-150 mm, 150-225 mm, 225-300 mm and 300-450 mm. Samples were collected from four randomly selected sites on each plot. Samples from each depth on a plot were bulked together. In order to reduce the workload to a manageable size without compromising the ability to observe treatment effects, soil samples were taken only from irrigation frequency treatments I-20 and I-60.

4.2.6.2. Determination of sodium bicarbonate extractable phosphate (Olsen P)

Olsen P was determined using the method of Olsen *et al.* (1954). This method involves accurately weighing 1 g of air-dried soil (< 2 mm sieved) into a 50 ml polypropylene centrifuge tube, then adding 20 ml of 0.5 M $NaHCO_3$ solution. This soil sample and solution were shaken together for 30 minutes, in an end-over-end shaker, followed by centrifuging at 8000 rpm for one minute, and filtration through Whatman No.1 filter paper. Inorganic P was then determined by the phosphomolibdate method of Murphy and Riley (1962).

4.2.6.3. Determination of nitrate-N and ammonium-N in moist soil

The method used for analysing nitrate nitrogen (nitrate-N) as well as ammonium nitrogen (ammonium-N) involved accurately weighing 4 g of crumbled moist soil into a centrifuge tube. Thirty ml of 2 M KCl solution was added to the soil sample and the

centrifuge tube was then shaken in an end-over-end shaker for 1 hour. The sample was then centrifuged at 8000 rpm for 3 minutes, followed by filtration through Whatman No.4 paper. The amount of nitrate-N and ammonia-N in the extracts were measured using a Technicon II auto-analyser (Technicon, 1976; Downes, 1978).

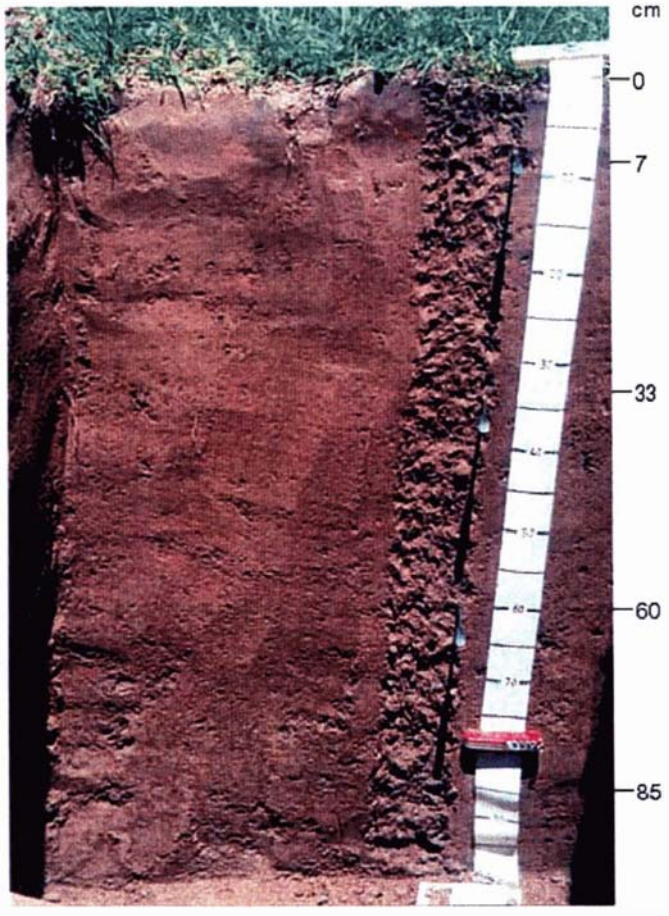


Plate 4.1 A profile of Manawatu fine sandy loam soil

Plate 4.2 Ryegrass on a plot irrigated at a deficit of 20 mm, with P fertiliser (I-20, P-40), the photograph was taken in late March 2001.

Plate 4.3 Clover on a plot irrigated at a deficit of 20 mm, with P fertiliser (I-20, P-40), the photograph was taken in late March 2001.

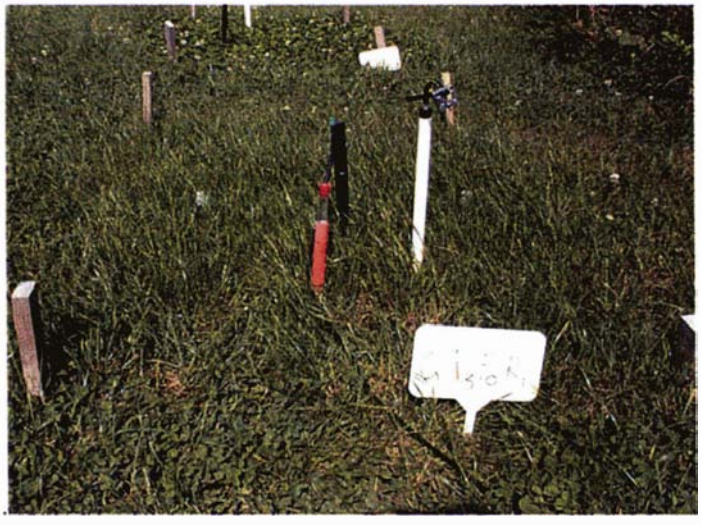


Plate 4.4 Ryegrass on a plot irrigated at a deficit of 60 mm, without P fertiliser (I-60, P-0), the photograph was taken in late March 2001.

A tensiometer (red), sprinkle head on stand (black) and porous cup soil water sampler (white PVC) with stop cock are seen inside the plot.

Plate 4.5 Clover on a plot irrigated at a deficit of 60 mm, without P fertiliser (I-60, P-0), the photograph was taken in late March 2001.

Plate 4.6 Appearance of ryegrass in a non-irrigated, non-P plot, the photograph was taken in late March 2001.

Plate 4.7 A general view of the experimental area, the photograph was taken in mid December 2000.

4.2.7. Statistical analyses

Data was analysed by Analysis of Variance (ANOVA), with the General Linear Model (GLM) procedure of the Statistical Analysis System (SAS Institute, 1990). When necessary, logarithmic transformations were applied to standardize the variances of the data. In such cases, actual means are presented in the tables or figures. As non-irrigated, non-P fertilised plots were located outside the main experimental design; they were not included in the statistical model. Statistical analysis for soil samples was made on an individual depth class basis.

4.3. RESULTS

4.3.1. Soil water content

The soil water contents were significantly different between irrigation treatments as expected. Neither species nor P fertility significantly affected soil water content. Soil water contents are described in Chapter 5. Soil water contents for the non-irrigated non-P fertilised plots are given in Appendix 4.2.

4.3.2. Ryegrass and clover production

In contrast to the pot experiment, irrigation frequency in the field ($P<0.0004$) significantly affected ryegrass and white clover pasture production (Table 4.2). Production decreased with decreasing irrigation frequency: mean cumulative productions for irrigation frequencies I-20, I-40, and I-60 were 7090, 6169 and 5773 kg DM ha^{-1}, respectively (not shown in the Table). The differences between I-20 and I-40 as well as I-20 and I-60 were significant but the difference between I-40 and I-60 was not significant ($P>0.05$, LSD=615 kg ha^{-1}) . The mean production of P fertilised (P-40)

plots was 6695 kg ha $^{-1}$, compared with only 5993 kg ha^{-1} for non-P fertilised plots (P-0).

Species (P<0.0001) and P fertility (P<0.007) also had significant effects on cumulative ryegrass and clover production for the irrigation season, 23 November 2000 to 30 April 2001 (Table 4.2). There were no significant interaction effects, and so it can be concluded that the factors investigated here acted independently of each other. The overall mean production of ryegrass (5578 kg DM ha^{-1}) was smaller than that for clover (7110 kg ha $^{-1}$).

Table 4.2 Mean values for ryegrass and clover production (kg DM ha^{-1}) for the irrigation period in 2000/2001 (23 November to 30 April).

Fertiliser levels	P-0	P-40	Mean (n=8)	Mean (n=24)
Species and Irrigation				
Ryegrass				
I-20	5685	6685	6185	5578
I-40	5098	5964	5531	
I-60	4938	5099	5019	
Mean (n=12)	5240	5916		
Clover				
I-20	7718	8271	7995	
I-40	6356	7259	6807	7110
I-60	6163	6893	6528	
Mean (n=12)	6746	7474		
Mean (n=24)	5993	6695		
Statistical significance				
Species		P<0.0001		
Fertiliser		P<0.007		
Irrigation		P<0.0004		

LSD at P<0.05 = 1231 kg ha^{-1} (n=4).

The I-20, P-40 treatment consistently grew more ryegrass from mid January onwards i.e. day number 50 onwards (Fig. 4.2). Cumulative productions for the treatments: I-60 P-40, and I-40, P-0 and I-60, P-0 were almost identical throughout the irrigation season (Fig. 4.2 and Table 4.2). The non-irrigated, non-P fertilised plots produced only 2717 kg DM ha^{-1} of ryegrass during the study period, and there was minimum ryegrass growth from mid January onwards (Fig. 4.2). Ryegrass growth of non-irrigated non-P fertilised plots resumed in April with the commencement of autumn rains. Non-irrigated, non- P fertilised plots produced only 40% of the total production of the I-20, P-40 plots.

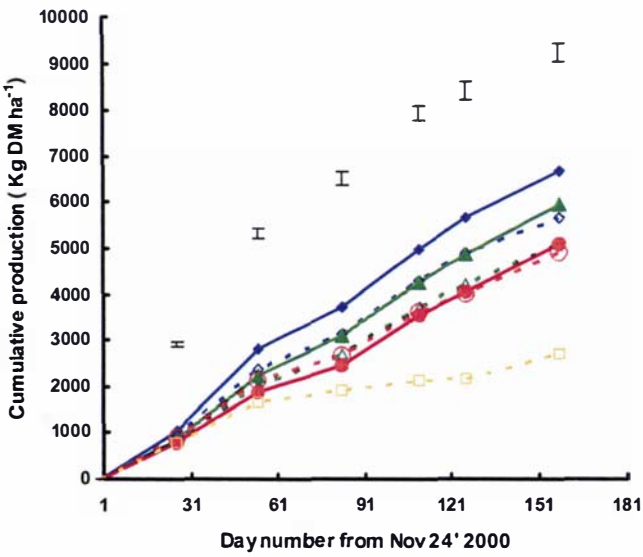


Figure 4.2 Cumulative production of ryegrass (kg DM ha^{-1}) during irrigation season. Symbols; ♦, ▲, ●, ◘ represent, I-20, I-40, I-60 and non-irrigated, non-P plots, respectively. Open symbols with dotted lines represent P-0 plots while closed symbols with solid lines represent P-40 plots. Vertical bars indicate standard error at $P<0.05$

Fig. 4.3 shows the curves for cumulative production of clover over the irrigation season. As for ryegrass, the treatments are ranked in a consistent manner from day 50 onwards with the most frequently irrigated, P fertilised plots producing more than less frequently irrigated, non-P fertilised plots.

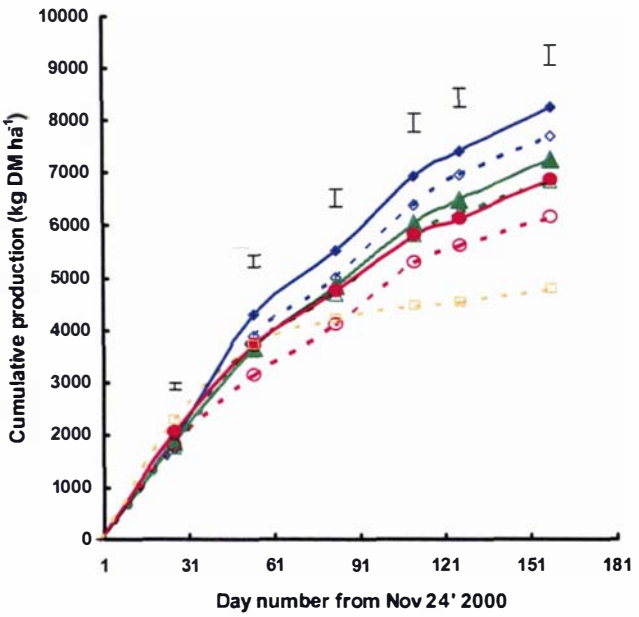


Figure 4.3 Cumulative production of clover (kg DM ha^{-1}) during irrigation season. Symbols; ♦, ▲, ●, □ represent, I-20, I-40, I-60 and non-irrigated non-P plots, respectively. Open symbol with dotted lines represent P-0 plots while close symbol with solid lines represent P-40 plots. Vertical bars indicate standard error at $P<0.05$

Plots with non-irrigation non-P fertilised grew only 4801 kg DM ha^{-1} of clover during the study period with little growth occurring from mid January to April (Fig. 4.3). These non-irrigated, non-P fertilised plots produced only 58% of the total clover production of the I-20, P-40 plots.

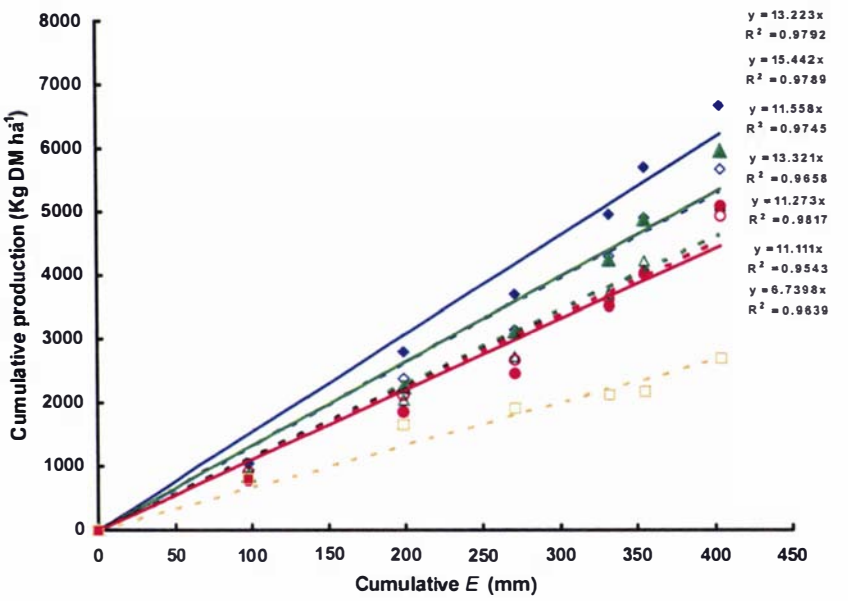


Figure 4.4 The linear relationship between cumulative *E* and cumulative ryegrass production for the irrigation season. Symbols; ♦, ▲, ●, ▣represent, I-20, I-40, I-60 and non-irrigated non-P fertilised plots, respectively. Open symbols with dotted lines represent P-0 plots while closed symbols with solid lines represent P-40 plots. Regression equations correspond to I-20, P-0, and I-40, P-40, and I-20, P-0, and I-20, P-40, and I-60, P-0, and I-60, P-40 treatments and non-irrigated plots from the top to bottom, respectively.

4.3.3. The relationship between *E* and production

The simple linear regressions between ryegrass and clover productions and *E* for the irrigation season (23 November 2000 to 30 April 2001) are shown in Fig. 4.4 and 4.5. Very strong linear regressions – with r^2 values greater than 0.95 – were observed for all the treatments. The linear relationship was slightly weaker (r^2 = 0.84) for non-irrigated non-P fertilised plots of clover.

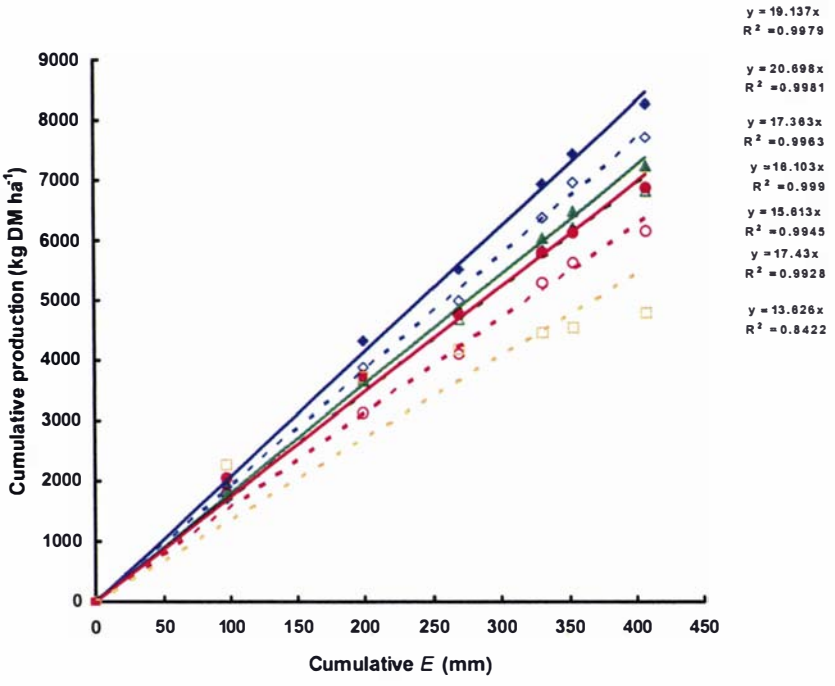


Figure 4.5 The linear relationship between cumulative evaporation and cumulative clover production for the irrigation season. Symbols; ♦, ▲, ●, ■ represent, I-20, I-40, I-60 and non-irrigated plots, respectively. Open symbols with dotted lines represent P-0 plots while closed symbols with solid lines represent P-40 plots. Regression equations correspond to I-20, P-0, and I-40, P-40, and I-20, P-0, and I-20, P-40 and I-60, P-0, and I-60, P-40 treatments and non-irrigated plots from the top to bottom, respectively.

4.3.4. Plant tissue phosphorus (P) content of herbage samples

At the March harvest, the overall mean tissue P concentration of ryegrass (0.347%) was significantly ($P<0.0004$) greater than that of clover (0.324%) (Table 4.3).

Predictably, fertiliser P application had a significant ($P<0.0001$) effect on tissue P content – application of fertiliser increased the tissue P of ryegrass and clover by 29 % and 23 %, respectively. The magnitude of the increases in tissue P concentration on the addition of P fertiliser was greater for ryegrass than for clover giving rise to a significant interaction ($P<0.007$) between species and applied P fertiliser (Table 4.3).

The irrigation treatments affected plant tissue P concentration of ryegrass and clover differently, and this interaction between species and irrigation frequency was significant ($P<0.01$). The tissue P concentration of ryegrass increased as the irrigation frequency decreased. In contrast to ryegrass, the tissue P concentration of clover decreased with decreasing irrigation frequency.

Table 4.3 Mean values of P concentration (%) of herbage harvested on 13 March 2001.

Fertiliser levels	P-0	P-40	Mean (n=8)	Mean (n=24)
Species and Irrigation				
Ryegrass				
I-20	0.286	0.388	0.337	0.347
I-40	0.309	0.385	0.347	
I-60	0.316	0.398	0.357	
Mean (n=12)	0.304	0.391		
Clover				
I-20	0.323	0.352	0.338	
I-40	0.284	0.358	0.321	0.324
I-60	0.284	0.341	0.313	
Mean (n=12)	0.297	0.350		
Mean (n=24)	0.300	0.370		
Statistical significance				
Species		P<0.0004		
Fertiliser		P<0.0001		
Species * fertiliser		P<0.007		
Species*irrigation		P<0.01		

LSD at P<0.05 = 0.028% (n=4).

4.3.5. Plant tissue nitrogen (N) concentration of herbage samples

The overall mean tissue nitrogen concentration of ryegrass (3.30%) was significantly ($P<0.0001$) smaller than tissue N concentration of clover (4.49%) (Table 4.4). No other main treatment effect or any interaction effect was statistically significant for tissue N concentration.

4.3.6. Soil Olsen P distribution

The effect of applied P fertiliser on Olsen P values in the 0-75 mm soil depth (surface soil) was highly significant (P<0.0001): the overall mean Olsen P for P-40 plots was 22 mg kg^{-1} soil compared with only 10 mg kg^{-1} soil for P-0 plots. Olsen P values decreased markedly with depth (Table 4.5).

Table 4.4 Mean values of N concentration (%) of herbage harvested on 13 March 2001.

Fertiliser levels	P-0	P-40	Mean (n=8)	Mean (n=24)
Species and Irrigation				
Ryegrass				
I-20	3.11	3.08	3.10	3.30
I-40	3.38	3.32	3.35	
I-60	3.26	3.62	3.44	
Mean (n=12)	3.25	3.34		
Clover				
I-20	4.54	4.43	4.49	
I-40	4.25	4.75	4.50	4.49
I-60	4.43	4.56	4.49	
Mean (n=12)	4.41	4.59		
Mean (n=24)	3.83	4.00		
Statistical significance				
Species		P<0.0001		

LSD at P<0.05 = 0.35% (n=4).

Irrigation frequency also had a significant effect (P<0.02) on mean Olsen P values in the 0-75 mm depth. The overall mean Olsen P value in this surface soil layer of the I-60 plots (overall mean value of 17.4 mg kg^{-1} soil) was significantly (P<0.022) greater than that of I-20 plots (overall mean value of 14 mg kg^{-1} soil). Irrigation had a significant effect (P<0.04) on Olsen P values in the 225-300 mm depth for no apparent reason.

Table 4.5 Mean values of Soil Olsen P (mg kg^{-1} soil) at different sampling depths for the experimental site on 24 April 2001.

Treatments	Sampling depths (mm)				
	0-75 mm	75-150 mm	150-225 mm	225-300 mm	300-450 mm
Ryegrass					
I-20, P-0	8.6	9.0	8.8	5.0	4.6
I-60, P-0	10.1	10.2	8.9	6.8	6.4
Mean (n=8)	9.3	9.6	8.9	5.9	5.5
I-20, P-40	17.5	11.9	11.9	5.6	5.1
I-60, P-40	28.6	11.0	11.7	6.4	5.1
Mean (n=8)	23.0	11.4	11.8	6.0	5.1
Mean (n=16)	16.2	10.5	10.3	6.0	5.3
Clover					
I-20, P-0	9.4	9.9	8.7	5.0	4.5
I-60, P-0	10.6	11.5	8.5	6.0	4.8
Mean (n=8)	10.0	10.7	8.6	5.5	4.6
I-20, P-40	19.9	11.9	10.0	6.1	5.0
I-60, P-40	20.4	12.3	9.8	9.1	7.4
Mean (n=8)	20.11	12.1	9.9	7.6	6.2
Mean (n=16)	15.1	11.4	9.2	6.5	5.4
$LSD_{at\ P<0.05(n=4)}$	6.0	3.5	4.9	3.3	3.0
Significance					
Irrigation	P<0.02	-	-	P<0.04	-
Fertiliser	P<0.0001	-	-	-	-

LSD= Least significant difference

Irrigation frequency did not significantly affect soil Olsen P levels under clover (Table 4.5). This difference in the impact of irrigation frequency on Olsen P under the two species was reflected in an interaction effect (P<0.07) between species and irrigation in the 0-75 mm depth. Olsen P values of non-irrigated, non-P fertilised plots were similar to the values of irrigated P-0 plots (Appendix 4.3).

4.3.7. Soil mineral nitrogen content

Only the effect of species was significant for the soil nitrate-N level in the 75-150 mm and 150-225 mm depths (Table 4.6) where the soil nitrate-N contents under clover were greater than those under ryegrass. In addition, there was a significant interaction ($P<0.04$) between species and fertiliser in the soil depth 300-450 mm. There were no significant treatment effects on the nitrate-N content of the 0-75 mm soil depth. Although soil nitrate-N contents generally decreased with increasing depth, irrespective of treatment, this trend was not consistent, and there were still substantial quantities of nitrate-N in the 300 -450 mm depth. Soil nitrate-N values for non-irrigated non-P fertilised ryegrass and clover plots (Appendix 4.3) were generally smaller than the values for irrigated plots except for the 0-75 mm soil depth where they were similar.

In general terms, soil ammonium-N contents were substantially smaller than the soil nitrate-N contents. Soil ammonium-N contents decreased with increasing depth irrespective of treatment. Neither species, irrigation, or P fertility treatments had a significant effect on soil ammonium-N content at any depth (Appendix 4.4).

The interaction between species and irrigation was significant ($P< 0.02$) for soil ammonium-N content for the soil depth 150-225 mm but the magnitude of the ammonium-N content in this soil layer was very small. Likewise, for the 300-450 mm depth where there was a significant effect ($P<0.04$) between species and applied P fertiliser.

4.4. DISCUSSION

Long term mean monthly rainfall values for Palmerston North are 94 mm, 79 mm, 67 mm, 69 mm and 81 mm for the months of December, January, February, March and

April, respectively (NZ Met Service, 1983). The monthly rainfalls measured at the experimental site located about 2 km away from the meteorological station were 108.5

Table 4.6 Mean values soil nitrate-N (mg kg^{-1} soil) at different sampling depths for the experimental site on 24 April 2001.

Treatments	Sampling depths (mm)				
	0-75 mm	75-150 mm	150-225 mm	225-300 mm	300-450 mm
Ryegrass					
I-20, P-0	7.9	9.1	10.3	7.3	6.8
I-60, P-0	7.1	7.3	7.3	8.0	6.0
Mean (n=8)	7.5	8.2	8.8	7.7	6.4
I-20, P-40	7.1	8.2	8.0	6.1	5.8
I-60, P-40	7.5	7.7	6.5	6.2	6.3
Mean (n=8)	7.3	8.0	7.2	6.1	6.0
Mean (n=16)	7.4	8.1	8.0	6.9	6.2
Clover					
I-20, P-0	7.8	10.6	12.5	6.2	4.7
I-60, P-0	7.8	12.0	12.7	6.0	4.3
Mean (n=8)	7.8	11.3	12.6	6.1	4.5
I-20, P-40	8.9	9.7	10.4	7.4	6.6
I-60, P-40	14.7	13.5	12.1	7.4	6.9
Mean (n=8)	11.8	11.6	11.3	7.4	6.7
Mean (n=16)	9.8	11.5	11.9	6.8	5.6
$LSD_{\text{at } P<0.05 (n=4)}$	7.2	4.1	4.3	3.1	2.5
Significance					
Species	-	P<0.002	P<0.001	-	-
Species*P fertiliser	-	-	-	-	P<0.04

LSD= Least significant difference

mm, 39.5 mm, 57.5 mm, 36.6 mm and 47.2 mm for the months of December 2000, and January, February, March and April 2001, respectively. Both the monthly rainfall figures of January to April 2001, and the soil moisture content values measured in non-

irrigated plots (Appendix 4.2) illustrate the dry nature of the summer of 2001. In other words, this was a good year to measure the response of pasture to irrigation in dry conditions.

As for the pot trial, the application of P fertiliser significantly improved the production of both ryegrass and clover. However, in contrast to the pot experiment, more frequent irrigation (in the W_R range) significantly improved pasture production in the field i.e. ryegrass and clover production significantly increased when irrigation frequency increased from I-60 to I-20. Scheduling irrigation according to I-60 criteria resulted in production losses even though watering operates within the range that has traditionally been thought of as being readily available.

Likewise, McAneney and Judd (1983) reported that production was reduced at a smaller deficit than was E and did not fall off as rapidly with increasing deficits. Ward and Burch (1999) suggest that pasture should be irrigated by the time half the total plant available water (W_T) in the root zone has been used if production is to be maximised. In a soil with 58 mm of plant available water, deferring irrigation until the moisture deficit reached 36 mm reduced production compared to treatments irrigated at deficits of 12 and 24 mm. There were no differences in production between pasture irrigated at 12 and 24 mm deficits (Ward and Burch, 1999).

Parfitt *et al.* (1985a) reported a similar decline in ryegrass performance. In their studies leaf elongation rate went from 10 mm day^{-1} in moist Judgeford silt loam soil to 5 mm day^{-1} when the water potential was about -100 kPa. Similarly, the ryegrass leaf elongation growth on irrigated plots averaged about 7 mm per day^{-1} compared with a rate of 5 mm day^{-1} at 60 mm deficit (about -100 kPa potential) in Stratford silt loam (Parfitt *et al.*, 1985b).

The effect of irrigation frequency on the production of both ryegrass and clover in this experiment can be related to the concept of plant available water threshold (PAW_t) proposed for other crops (NeSmith and Ritchie, 1992; Sadras *et al.*, 1993). When the lower limit of available water is taken as -120 mm for the 450 mm depth (Appendix 4.2), the irrigation frequency treatments I-20, I-40 and I-60 correspond to 0.83, 0.66 and 0.5 of PAWt, respectively. Sadras and Milroy (1996) quoted a range of values i.e. 0.85 to 0.25 for PAW_t.

The relationship between *E* and ryegrass/white clover production was strong for all the irrigated plots in this experiment. Martin (1990) reported a strong linear correlation between pasture growth and cumulative *E* for irrigation on Templeton silt loam soil and his gradients (*k* values) are comparable to values given here in Fig. 4.4 and Fig. 4.5. This linear relationship was slightly weaker (r^2 = 0.84) for non-irrigated, non-P fertilised clover in the current field experiment and this may be attributed to severe moisture stress encountered during the transition period from vegetative to reproduction growth during late summer to early autumn. The water use efficiencies of pasture obtained for a range of irrigation frequencies in Victoria (Ward and Burch, 1999) are comparable to the *k* values reported here. Maximum productivity and water use efficiency were observed at very frequent irrigation (3 day irrigation) in Victoria.

Ryegrass had a greater tissue P concentration than clover, and P fertiliser application increased the tissue P concentration significantly. If the values proposed by McNaught (1978) and Evans *et al.* (1986) for deficient tissue P concentrations (0.3% for both species) are considered, only I-20, P-0 plots of ryegrass and both I-40, P-0 and I-60, P-0 plots of clover had low plant tissue P concentrations. In contrast, all the tissue P concentrations of all P-40 plots were above 0.3%. The interaction ($P<0.007$) between species and fertiliser showed ryegrass accumulated P on application of P fertiliser to a greater extent than clover. This may be a result of greater absorption of P by the more

extensive root system of ryegrass (Chapter 6). The interaction ($P<0.01$) between species and irrigation reflects the sensitive nature of P uptake by clover to water 'stress', even in the range approaching -100 kPa soil water potential. Similar observations were made in the pot experiment (Chapter 3).

Moir *et al.*, (2000a and 2000b) suggest that Olsen P is a useful surrogate for the measure of soil nutrient status and its impact on the proportionality constant for pasture production. Moir *et al.* (2000a and 2000b) reported that New Zealand hill country pasture production was strongly related to soil Olsen P status during periods when soil moisture was not limiting plant growth.

The important observation regarding the distribution of soil Olsen P over the root zone was the sharp decrease in value from the 0-150 mm depth to the 150-300 mm depth and then the 50% reduction at 300-450 mm. Comparable soil Olsen P profile gradients have been observed for pasture soils by several authors (Blennerhassett, 1998; Hepp, 2003; Senarath, pers. Com.).

Fertiliser addition increased P fertility status of surface soil. This has been observed by a number of workers. Sorn-srivichai (1985) reported that fertiliser P addition resulted in a larger increase in water-extractable P in the 0-40 mm sampling depth than those in the 0-75 mm depth in a Tokomaru silt loam profile under ryegrass/white clover pasture. Moreover, the relative increase in water-extractable P as a result of fertiliser P addition was larger than that of Olsen extractable P (Sorn-srivichai, 1985).

Irrigation frequency had a significant effect on soil Olsen P values in the 0-75 mm (surface layer). Some of the effect of irrigation frequency on Olsen P value can be attributed to differences in ryegrass production. This lower Olsen P value for I-20 in the 0-75 mm depth may be due to increased P removal in harvested plant material.

Furthermore, it is likely that under frequent irrigation (I-20) conditions, increased microbial activity could result in increased immobilization of added P (McLaren and Cameron, 2000). There is no evidence of P leaching from the surface soil to deeper layers at this experimental site i.e. the data shown in Table 4.6 support the generalization that P movement in percolating water is negligible (Sharpley *et al.*, 2001).

There were no significant treatment effects on the nitrate-N content of the 0-75 mm soil depth. The nitrate-N content for soil under ryegrass remained almost equal between fertiliser treatments with 6.4 and 6.0 mg kg^{-1} for P-0 and P-40, respectively, while soil nitrate-N content under clover increased from 4.5 to 6.7 mg kg^{-1} from P-0 to P-40. There was a similar, less significant interaction ($P<0.06$) in the 225-300 mm depth. The interaction is negative and this may be attributed to either more efficient absorption of applied nitrate-N by ryegrass or more efficient assimilation of atmospheric N_2 by clover and subsequent mineralization in the presence of P fertiliser, or combination of both of these processes.

This soil P profile gradient is the underlying reason for the production response to irrigation frequency in the field experiment. Under I-20 irrigation, nearly all water uptakes by the plant were from the 0-150 mm soil depth (Chapter 5): as this soil depth had the greatest Olsen P value it had the greatest k value and hence the largest growth rate for each millimetre of E. Under I-60 and I-40 irrigation, some of the plants water requirements were met by uptake from deeper depths (Section 5.4) where the Olsen P values were smaller. Consequently, k values would have been smaller and therefore there was less growth rate per millimetre of E.

Moir *et al.* (2000a and 2000b) proposed a simple relationship (i.e. the proportionality constant) between pasture production and evaporation: it was assumed that growth rate

is constant for all E without differentiation. Such a discrimination in k values could account for the observation by McAneney and Judd (1983) that there is a period where although evaporation occurs at the reference crop rate, growth is no longer at the optimum rate. The results reported here suggest that there is scope to extend the idea of a single k value proposed by Moir *et al.* (2000a and 2000b) to account for this difference in growth according to the depth of soil from which the majority of water is being taken at any one time. This will be attempted in Chapter 8.

4.5. CONCLUSIONS

In the field, irrigation frequency affects ryegrass and clover production. Irrigation of ryegrass and clover at 20 mm depletion of readily available water, I-20, in Manawatu fine sandy loam soil over the summer period resulted in maximum pasture production and water use per unit pasture production for irrigated pasture (proportionality constant k value). Less frequent irrigation i.e. applications of 60 mm of water at the total depletion of readily available water, I-60 resulted in substantial production loss and reduction in water use efficiency. Application of recommended quantity of P fertiliser (Cornforth, 1998; Roberts *et al.*, 1994) for low P fixing Manawatu fine sandy loam soil (40 kg ha^{-1}) enhanced total pasture production and hence water use efficiency.

Overall, it is reasonable to assume that the production decrease in less frequently irrigated plots (I-60) results from decreased P supply to the pasture caused by drying of the topsoil where most of the soil P is stored (see Chapter 5 for details). Subsequent to the drying of surface soil, plants extract water from soil depths with less available P. Given this, if the benefits of irrigation are to be modelled, there would appear to be the need to extend the notion of the proportionality constant developed by Moir *et al.* (2000a and 2000b) so that it can accommodate the differences in pasture growth

associated with the nutrient status of the soil depth from which the majority of water is being extracted at any period of time.

CHAPTER 5

MODELLING SOIL WATER CONTENT UNDER IRRIGATION

5.1. INTRODUCTION

Seasonal soil water deficits limit pasture production in many areas of New Zealand (Coulter, 1973). Thus the soil water balance provides a basic tool for farm management - especially for planning and scheduling irrigation (Rickard, 1977; Woodward *et al.*, 2001). A variety of soil water models exist in the literature, ranging from simple water balances to detailed mechanistic models based on Richards' equation (Feddes *et al.*, 1988; De Jong and Bootsma, 1996; Akinremi and McGinn, 1996). Multi-layer water balance models are preferred over those that treat the root zone as a single layer (Calder *et al.*, 1983). To date, most of the models have been designed only for deep, permeable soils at flat sites.

The simple, two-layer water balance model of Scotter *et al.* (1979) was an important advance in modelling the soil water deficit for flat pastoral soils in New Zealand, because it includes a topsoil zone which is depleted and recharged preferentially. This development offers a solution to a major problem of single-layer water balance models (e.g. Barrs *et al.*, 1977; McAneney *et al.*, 1982; McAneney and Judd, 1983), namely that they often under-predict pasture transpiration and growth following short lived re-wetting of the topsoil by intermittent rain during a prolonged dry period, and by early autumn rainfall following prolonged summer drought.

The objective of the work described in this chapter was to develop a water balance that could simulate the effect of different irrigation frequencies (in W_R range) on soil water content. Subsequently, the soil water balance will be used to help predict the effects of soil fertility status and irrigation frequency on pasture growth (Chapter 8). Comparisons are made between TDR measured and predicted soil water contents for different irrigation frequencies at the field research site described in Chapter 4. Both the field data and the model illustrate the soil drying pattern referred to in Chapter 4.

5.2. MATERIAL AND METHODS

The details of the field experiment and site are presented in Chapter 4. In December 2000, a pair of 150 mm long TDR wave-guides was installed in each plot. Similarly, a pair of 300 mm long TDR wave-guides and a pair of 450 mm long TDR wave-guides were installed in replicates 1 and 2 of each irrigation treatment (These three depths correspond to the irrigation treatments in a manner explained below). Also, in December 2000, pairs of 150 mm, 300 mm and 450 mm long TDR wave-guides were installed in each of the non-irrigated, non-P fertilised plots. A TDR (Time-Domain Reflectometry) moisture meter (6050X1 Trase system- Soil Moisture Equipment Corporation, CA, USA) was used to measure volumetric soil water contents from January to April 2001.

5.3. MODEL DEVELOPMENT

The basic soil water balance constructed here is a development of the model described by Scotter *et al.* (1979). This simple one dimensional soil water balance model uses the basic soil water balance equation.

$$\Delta S = P + I - E - D \qquad (5.1)$$

Where

ΔS = the change in water storage in the soil profile of depth equal to or greater than the effective pasture rooting depth for any period (commonly for one day),

P = rainfall,

I = irrigation,

E = actual evaporation,

D = deep drainage.

The soil water storage in the root zone (S) is referenced to "field capacity" where it is assigned the value of zero. Field capacity is considered to be the quasi-equilibrium soil water content -following heavy rainfall- at which drainage beyond the root zone is insignificant in comparison with other modes of water loss from the soil.

To a first approximation, evaporation (E) from established pasture is controlled either by the energy or water supply, whichever is limiting. A number of methods are available for estimating the energy-limited E from meteorological data. The E from an extensive area of well-watered, full cover pasture is designated E_w, and is often referred to as the "potential evapotranspiration". E_w was calculated here using a method described by Scotter *et al.* (2000).

Since the experimental site is almost flat and the soil profile is permeable, surface runoff is assumed to be zero. Hence, D represents drainage from the root zone.

The field capacity of soil samples collected from the experimental site was estimated using pressure plate apparatus at a potential of -5 kPa. This value was almost constant (0.41 m^3 m^{-3}) over the top 450 mm soil depth (Table 5.1). In close agreement with this estimate is the mean volumetric water content of 0.43 m^3 m^{-3} measured by TDR wave-guides on 18 June 2001, following 22 mm of rainfall on 16 June 2001 and 0.5 mm rainfall on 17 June 2001. Therefore, field capacity (θ_{fc}) i.e. when $S = 0$, was taken as 0.42 m^3 m^{-3} throughout the 0-450 mm depth.

The maximum readily available water in the root-zone (W_R) was taken to be the water in the upper 450 mm of the soil profile between -5 kPa and -100 kPa soil water potential (Ahuja and Nielsen, 1990). Nine replicate samples from each of 5 soil depths (0-100 mm, 100-200 mm, 200-300 mm, 300-400 mm, and 400-500 mm) were placed in pressure plate apparatus. Intact core samples were used at -5 kPa and -100 kPa potential. Disturbed soil was used for measurements at -1500 kPa potential.

W_R at the experimental site was 60 mm. This value was used in Chapter 4 as the basis of the selection of irrigation frequencies I-20, I-40 and I-60 (i.e. 33%, 66% and 100% W_R). The 20 mm increments associated with these irrigation trigger deficits appear to be evenly divided among the profile depths 0-150 mm, 150-300 mm and 300-450 mm i.e. 20 mm of W_R in each of these depths (Table 5.1). Obviously, W_R could have been partitioned in numerous ways in both the choice of irrigation frequencies and the depths over which to model soil moisture. The values for soil depths used here i.e. 0-150 mm, 150-300 mm and 300-450 mm were chosen because of the correspondence with the depths of water applied under each of the three irrigation frequencies.

Following Scotter *et al.* (1979) a surface layer soil water storage (S') of 20 mm was defined to account for the preference of pasture to extract water from the topsoil (taken here to be the 0-150 mm layer) rather than the subsoil, and for the effect of intermittent

rain rewetting just the topsoil when the whole soil profile is relatively dry. Schematic representation of W_R distribution within assumed root zone is shown in Plate 5.1

Table 5.1 Soil volumetric water contents (m^3 m^{-3}) at different pressure potentials for the samples from the profile at the experimental site.

Profile depth (mm)	- 5 kPa	- 100 kPa	- 1500 kpa
0 - 100	0.40	0.28	0.22
100 - 200	0.46	0.31	0.23
200 - 300	0.40	0.27	0.24
300 - 400	0.40	0.27	0.24
400 - 500	0.41	0.28	0.25

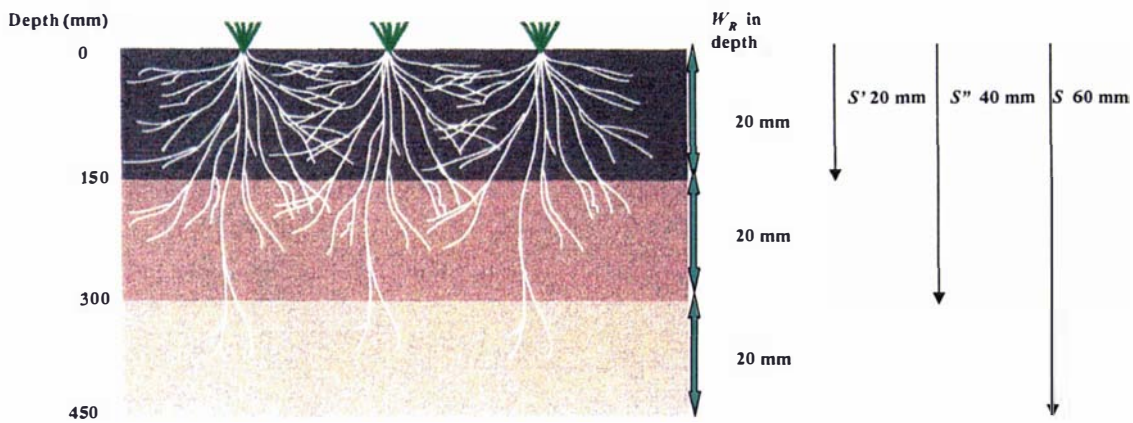


Plate 5.1 Schematic presentation of readily available soil water (W_R) distribution within the assumed root zone of 450 mm depth below pasture (not to scale). Storage terms *S'*, *S"* and *S* are also shown.

It was assumed that if there was sufficient water stored in *S'*, then it could be evaporated at E_w regardless of the total profile deficit (*S*). This is the W_R stored in the surface 150 mm soil depth. Scotter *et al.* (1979) proposed a similar value of 25 mm of storage for *S'* for Tokomaru silt loam. Additional storage terms with maximum values of 40 mm (*S''*) are also introduced. *S''* accounts for up to 40 mm of depletion from the 0-300 mm depth, regardless of *S*. Similarly *S* accounts for up to 60 mm of depletion that can occur

from the top 450 mm at E_w. The site-specific model may then be summarized as follows.

As the soil water deficit was never allowed to drop below 60 mm in any of the irrigated plots,

$$E = E_w \tag{5.2}$$

at all times,

where

E_w = the Priestly and Taylor potential evapotranspiration,

E = the actual evapotranspiration,

Next, D is calculated as follows:

If $S_{n-1} + P + I - E < 0$

Then $D = 0$

Otherwise $D = S_{n-1} + P + I - E$ (5.3)

where

S_{n-1} = the soil water deficit for the whole root zone on previous day.

Updating of S' follows:

If $S'_{n-1} + P + I - E > 0$

then $S'_n = 0$

If $S'_{n-1} + P + I - E \geq -20$ mm

then $S'_n = S'_{n-1} + P + I - E - D$

If $S'_{n-1} + P + I - E < -20$ mm

then $S'_n = -20$ mm (5.4)

where

S_n = the model predicted soil water deficit for the whole root zone on day n,

S'_n = the model predicted soil water deficit in the top 150 mm of the profile on day n.

Updating of S'' follows:

If $S''_{n-1} + P + I - E > 0$

then $S''_n = 0$

If $S''_{n-1} + P + I - E \geq -40$ mm

then $S''_n = S''_{n-1} + P + I - E - D$

If $S''_{n-1} + P + I - E < -40$ mm

then $S''_n = -40$ mm (5.5)

where

S''_n = the model predicted soil water deficit for the depth of 0-300 mm on day n.

Updating of S follows from

$$S_n = S_{n-1} + P + I - E - D \quad (5.6)$$

Usually by late winter the whole root zone has been fully replenished to field capacity, and so; S', S'', and S equal zero.

Priestly and Taylor potential evapotranspiration (E_w) is calculated for each day of the year as described by Scotter *et al.* (2000) (Appendix 5.1).

The above equations are readily executed using a spreadsheet such as Excel™, and so the model can be run for a whole year to obtain daily predicted S', S'' and S values. Daily predicted S', S'' and S values can be converted to volumetric water contents using

$$\theta_{15} = (S'/150) + \theta_{fc} \quad (5.6)$$

$$\theta_{30} = (S''/300) + \theta_{fc} \quad (5.7)$$

$$\theta_{45} = (S/450) + \theta_{fc} \quad (5.8)$$

Here θ_{15} is the average soil water content in the topsoil, θ_{30} is the average soil water content between depth 0-300 mm, and θ_{45} is the average soil water content in the depth 0-450 mm. As S', S'' and S cannot be positive, the predicted values for θ_{15}, θ_{30} and θ_{45} cannot be greater than θ_{fc}.

5.4. RESULTS AND DISCUSSION

Means of measured soil water content values for the most frequently irrigated plots, I-20, (ryegrass without applied P, ryegrass with applied P, clover without applied P, and clover with applied P) are compared to volumetric water contents predicted by the model for I-20 in Fig. 5.1. The period covered is from 1 January 2001 (Julian day number 1) to 30 April 2001 (Julian day number 120). Except for the days when the measured values were wetter than field capacity, the measured and predicted values are in close agreement for the 0-150 mm soil depth. Moreover, observed soil water content

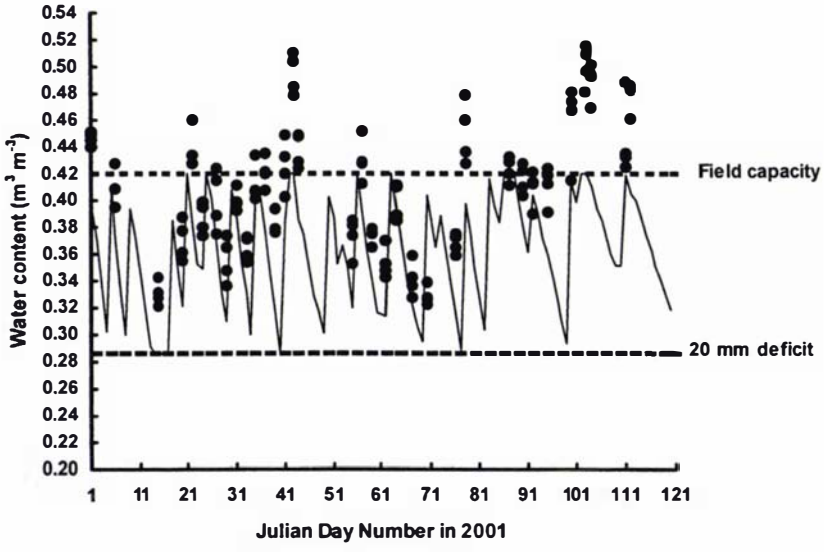


Figure 5.1 The measured (•)and predicted (—) volumetric water content values for the 0-150 mm depth for irrigation frequency I-20 during 1 January - 30 April 2001 (Julian day number 1-120), the volumetric water content values corresponding to field capacity and a deficit of 20 mm are shown as horizontal dashed line.

There are a number of days when volumetric water contents measured in the topsoil are greater than the model predicts for irrigation frequency I-20. This is probably due to the simple model assuming that the soil profile comes back to field capacity instantly

following rainfall or an irrigation event, whereas, in fact, the surface soil stays wetter than field capacity for a couple of days after heavier rain. When the 0-300 mm, and 0-450 mm depths are considered, both the number of days that the soil water content is greater than the field capacity value, and the magnitude of this difference decrease (Fig. 5.2 and Fig. 5.3). This indicates the reduced impact of the above feature on the modelling procedure, when the whole profile (0-450mm depth interval) is taken into account.

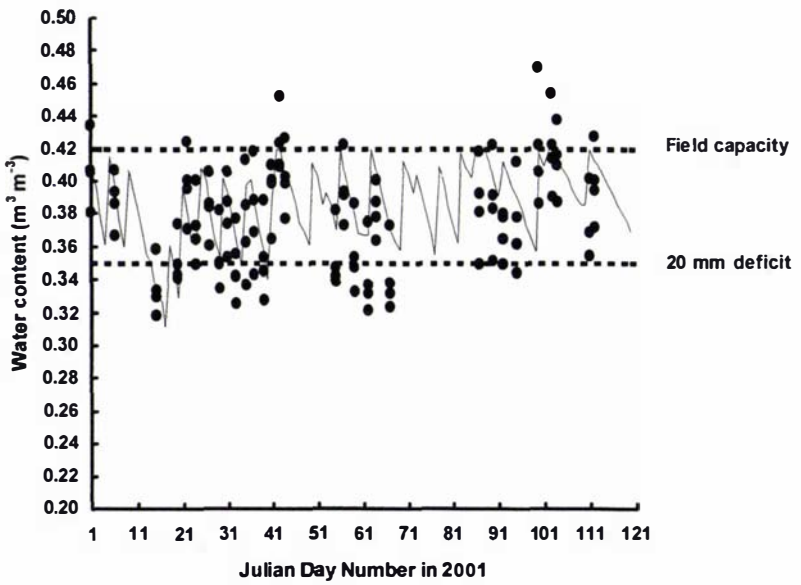


Figure 5.2 The measured (•) and predicted (—) volumetric water content values for the 0-300 mm depth for irrigation frequency I-20 during 1 January - 30 April 2001 (Julian day number 1-120), the volumetric water content values corresponding to field capacity and a deficit of 20 mm are shown as horizontal dashed line.

On occasions, the measured soil water content for the 0-300 mm and 0-450 mm depths was less than the 20 mm deficit. However, given the small differences between soil water contents at field capacity and 20 mm deficit (i.e. 0.07 and 0.04 $m^3 m^{-3}$ for 0-300 mm and 0-450, respectively) and the inherent variability associated with TDR measurements (Topp and Davis, 1985) this is hardly surprising. The model predicted

values were less than 20 mm deficit on day 17 due to a breakdown in irrigation equipment.

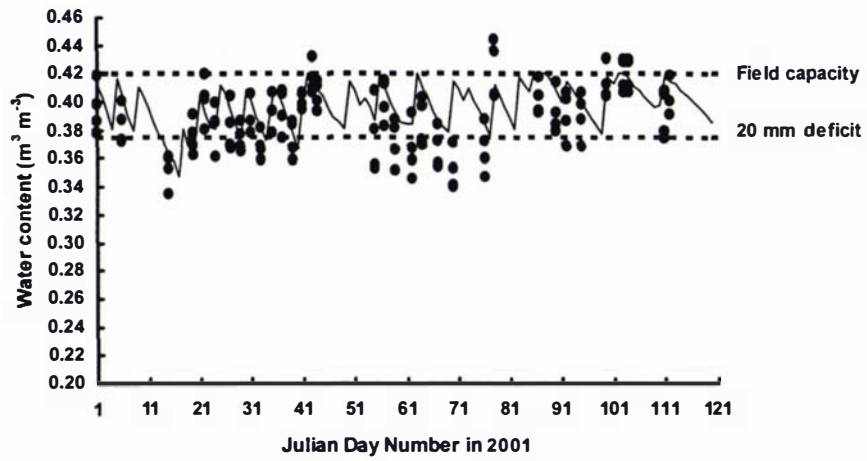


Figure 5.3 The measured(•) and predicted(—) volumetric water content values for the 0-450 mm depth for irrigation frequency I-20 during 1 January - 30 April 2001 (Julian day number 1-120), the volumetric water content values corresponding to field capacity and a deficit of 20 mm are shown as horizontal dashed line.

For I-40, the measured and predicted volumetric water content values for the 0-150 mm depth are in close agreement (Fig. 5.4). TDR measured soil water contents did not fall below 40 mm deficit. The measured and predicted volumetric water content values for the 0-300 mm depth for I-40 are also in reasonable agreement (Fig. 5.5). Actual observed TDR soil water contents figures never dropped below the 40 mm deficit line for I-40 (Fig. 5.5) and this indicates the success of implementation of irrigation frequency I-40 in the field experiment.

In contrast to irrigation treatment I-20, neither the rainfall of 41 mm on 11 February 2001 (day 43) nor the commencement of the autumn rains from 29 March 2001 onwards wet the 0-300 mm depth under I-40 beyond field capacity (Fig.5.5).

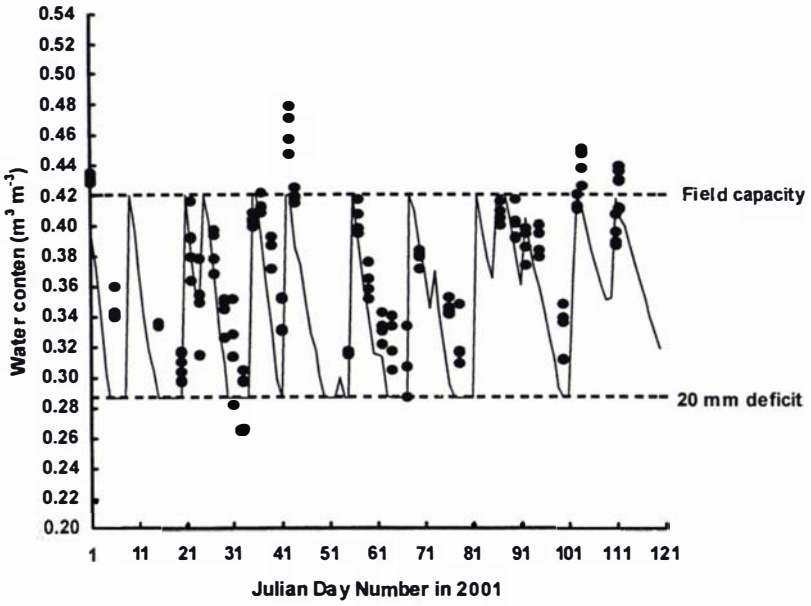


Figure 5.4 The measured(•) and predicted(—) volumetric water content values for the 0-150 mm depth for irrigation frequency I-40 during 1 January - 30 April 2001 (Julian day number 1-120), the volumetric water content values corresponding to field capacity and a deficit of 20 mm are shown as horizontal dashed line.

Measured and predicted volumetric water content values for the 0-450 mm depth for I-40 are shown in Fig. 5.6. Neither the 41 mm of rainfall on 11 February 2001 nor commencement of autumn rains from 29 March 2001 wetted the 0-450 mm profile under I-40 beyond field capacity. This may be attributed to the magnitude of the deficit (i.e. 40 mm) maintained by the I-40 irrigation trigger level.

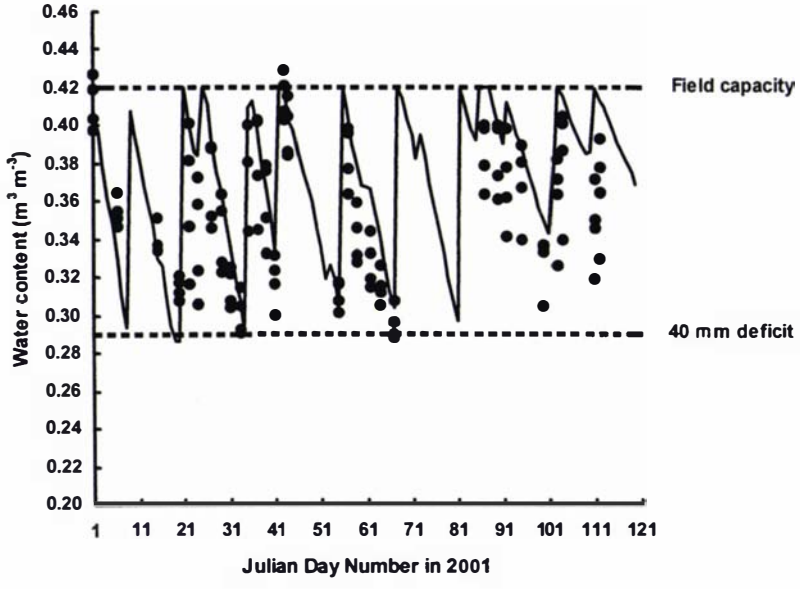


Figure 5.5 The measured(•) and predicted(—) volumetric water content values for the 0 - 300 mm depth for irrigation frequency I-40 during 1 January - 30 April 2001 (Julian day number 1-120), the volumetric water content values corresponding to field capacity and a deficit of 40 mm are shown as horizontal dashed line.

The measured and predicted volumetric water content values for 0-150 mm depth under I-60 are in close agreement (Fig. 5.7). This again indicates the ability of the model to simulate the topsoil water contents. Fig. 5.8 shows the measured and predicted volumetric water content values for 0-300 mm depth for I-60. Predicted values are in agreement with measured volumetric water contents for this profile depth too.

Similarly, Fig. 5.9 shows the measured and predicted volumetric water content values for the depth of 0-450 mm for I-60. In general, the modelled values again agree well with the measurements.

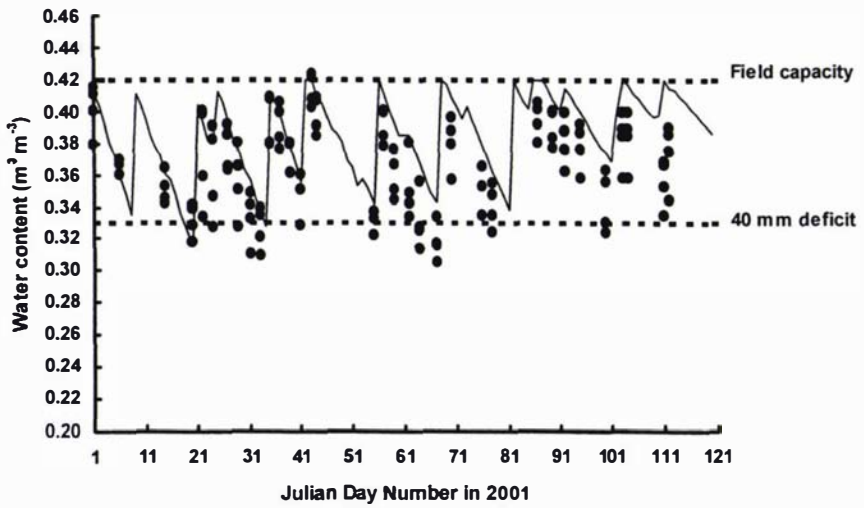


Figure 5.6 The measured(•) and predicted(—) volumetric water content values for the 0 - 450 mm depth for irrigation frequency I-40 during 1 January - 30 April 2001 (Julian day number 1-120), the volumetric water content values corresponding to field capacity and a deficit of 40 mm are shown as horizontal dashed line.

Overall, Fig. 5.7, Fig. 5.8 and Fig. 5.9 confirm that the model was capable of generating acceptable soil volumetric water contents for the 0-150 mm, 0-300 mm, as well as 0-450 mm depths for I-60.

The model is capable of producing soil water content values for the 0-150 mm, 0-300 mm and 0-450 mm depths for each of the irrigation frequencies. Similarly, the model will provide an opportunity to separate the soil water depletion into three respective soil water deficits ranges i.e. 0 to 20 mm, 21 to 40 mm, and 41 to 60 mm.

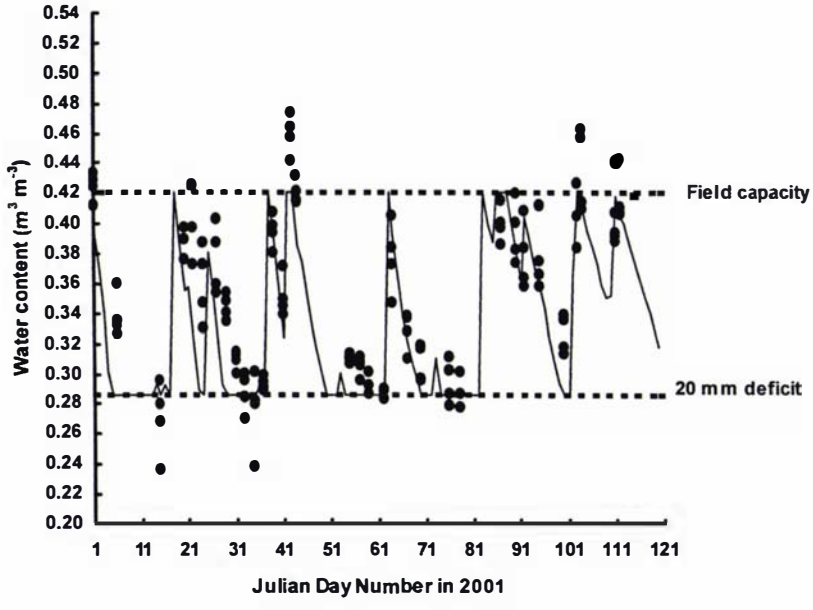


Figure 5.7 The measured(•) and predicted(—) volumetric water content values for the 0 - 150 mm depth (topsoil) for irrigation frequency I-60 during 1 January - 30 April 2001 (Julian day number 1-120), the volumetric water content values corresponding to field capacity and a deficit of 20 mm are shown as horizontal dashed line.

The number of days on which the soil water deficit was greater than stipulated deficit values (i.e. 20, 40, and 60 mm) for irrigation frequencies are given in Table 5.2. These values indicate the number of days on which pasture growth is limited by a water shortage in the surface soil (perhaps a new and more subtle definition of water 'stress' is hinted at here).

For I-40, there were 32 days when the deficit was greater than 20 mm i.e. when plants consumed soil water from deficit range 21 mm to 40 mm. In other words, 32 days when growth would be less than optimum because plants were extracting water from deeper down the profile (typically 150-300 mm) where there are fewer nutrients. Similarly, for I-60, the model predicted 69 days when pasture growth was compromised: this was made up of 46 and 23 days on which plants consumed soil water from deficit ranges 21

mm to 40 mm and 41 mm to 60 mm, respectively (Table 5.2). The implications of Table 5.2 for pasture production will be explored in Chapter 8.

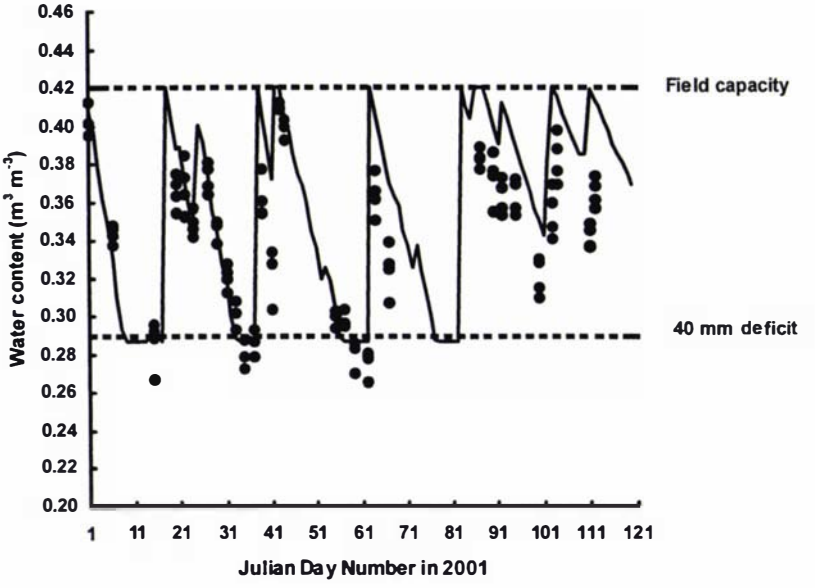


Figure 5.8 The measured(•) and predicted(—) volumetric water content values for the 0 - 300 mm depth (topsoil) for irrigation frequency I-60 during 1 January - 30 April 2001 (Julian day number 1-120), the volumetric water content values corresponding to field capacity and a deficit of 40 mm are shown as horizontal dashed line.

Table 5.2 Number of days between 1 January to 30 April 2001 on which soil water deficit was greater than stipulated deficit ranges for respective irrigation frequency treatments.

Treatments	I-20	I-40	I-60
Deficit range			
S' <-20 mm	0	32	46
S" <-40 mm	0	0	23
S <-60 mm	0	0	0

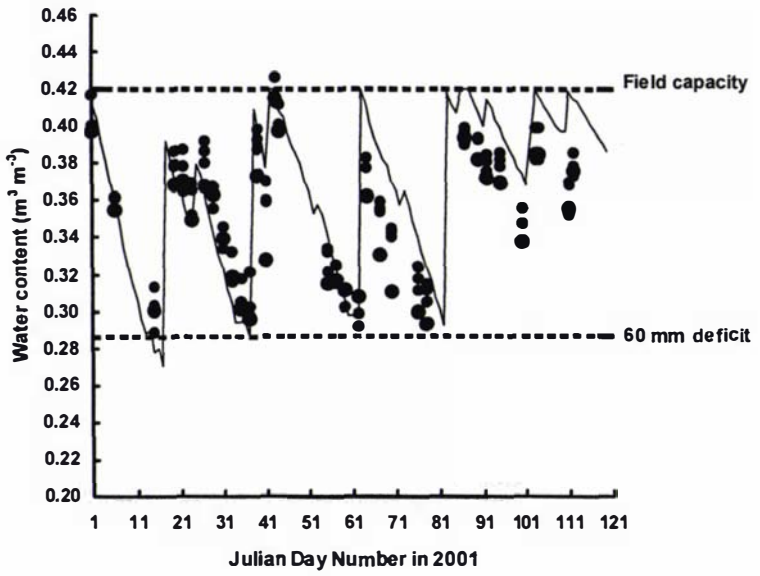


Figure 5.9 The measured(•) and predicted(—) volumetric water content values for the 0 - 450 mm depth for irrigation frequency I-60 during 1 January - 30 April 2001 (Julian day number 1-120), the volumetric water content values corresponding to field capacity and a deficit of 60 mm are shown as horizontal dashed line.

5.5. CONCLUSIONS

A simple water balance model was developed to simulate volumetric soil water contents at three layers in Manawatu fine sandy loam under three different irrigation regimes. The values generated using the model agreed well with field soil water contents measured using TDR. The model highlighted differences in soil moisture contents between the irrigation regimes particularly in the surface soil (0-150 mm).

Both the measured and simulated soil water content data reveal the water extraction patterns under ryegrass and clover under a range of irrigation frequencies. Initially, the great majority of the water requirement is met by extraction from the surface soil. When the surface soil is dry, readily available water is removed from deeper within the profile.

CHAPTER 6

ROOT GROWTH RESPONSES OF RYEGRASS AND WHITE CLOVER TO P FERTILISER AND IRRIGATION FREQUENCY

6.1. INTRODUCTION

Growth responses of root systems of pasture plants are less researched and understood than the dynamics of tiller and leaf turnover (Davidson, 1978; Matthew, 1992). To provide basic information for resource efficient agriculture, a reappraisal of existing knowledge of plant root systems is required (Atkinson, 1989).

In Chapter 4 and 5 it has been argued that more frequent irrigation is advantageous to pasture production because it keeps the surface soil, where the majority of nutrients are concentrated, constantly moist. In addition, it might be argued that the surface soil contains the majority of ryegrass and white clover roots. The major objective of this Chapter was to verify that this is indeed the case and to measure the effect of irrigation frequency and P fertility on plant root activity.

In order for this study to be carried out, there was a need for development of methodology for measuring root growth. Historically, studies of pasture root dynamics focussed on root mass, with a large number of cores taken to counter assumed spatial variability. For example, Deinum (1985) collected 40 samples, each of 40 cm^2 in surface area ha^{-1} paddock. However, it is now recognised that total root mass under pasture swards includes large quantities of dead roots and bears little relation to recent root production (Matthew *et al.*, 1986). To measure root growth more directly, Steen (1984, 1991) used buried mesh bags; a technique first developed in forest ecology

studies. Matthew *et al.* (1986) adapted Steen's technique, reducing installation time by dispensing with the mesh bag. This modified technique, using 75 mm diameter refilled cores was found to be effective for measuring defoliation-related differences in root production. Variations of this refilled core method have since been successfully used in three other New Zealand studies of pasture root dynamics. In one of these studies smaller refilled cores of approximately 25 mm diameter investigated root growth effects in a glasshouse experiment (Carvalho, 2002).

If smaller diameter refilled cores were effective in field experiments, and if a convenient method for assessing effect of depth in the soil profile could be found, this would facilitate future research on root growth.

An additional objective of the experiment described in this Chapter was to further develop the refilled core technique and associated statistical analyses, in order to reduce the sampling time and cost. It will be noted that the maximum depth attained in this study of root activity is 200 mm, well short of the depth of 450 mm that features in the arguments presented above. Unfortunately the refilled core technique is limited to a depth of 200 mm. Nevertheless, the results presented below make a convincing case for the decline in root activity with depth and the implications of this to the Thesis.

6.2. MATERIALS AND METHODS

6.2.1. Root sampling procedures and dates

The details of the field experiment and site are presented in Chapter 4. A modified version of the refilled core root sampling technique (Mathew *et al.*, 1986) was used. The use of smaller diameter cores required a system to relocate core holes some weeks after installation. The procedure developed, involved using a movable wooden core guide. To

insert a refilled core, the core guide was placed on the ground, and permanent wooden pegs driven through slots in the core guide. The slots were 300 mm distance from the core hole, so that the placing of pegs would not disturb root growth within the core. The permanent pegs allowed for the core guide to be precisely realigned to the original position for extracting the refilled core.

During the period 7-10 November 2000, two core holes for measuring root ingrowth (one for each of two intended sampling dates) were prepared in each plot. An additional refilled core hole was installed in each plot on 20 February 2001. Core holes were filled with fine river sand (< 2 mm size) to a depth of 225 mm. During core filling, sand was compacted with a 4.5 mm diameter steel rod. Sampling of the refilled cores was carried out with a smaller stainless steel soil corer (22.5 mm internal diameter). Each core was extracted in three segments, 0-50 mm depth, 50-100 mm depth and 100-200 mm depth.

Six weeks after installation (19 December 2000), one of the two refilled cores was harvested. There were only two I-20 irrigation events and one I-40 event between installation and the December root harvest of cores: data from this harvest reflects root responses to fertiliser treatments during this six week period. Fourteen weeks later, the second of the initial refilled cores was removed from each plot on 16 February 2001. Six weeks later (5 April 2001), the cores installed on 20 February 2001 were harvested.

After harvesting, root samples were stored for a maximum of 72 hrs at 4°C until washing to separate the roots from soil. Roots were extracted by thoroughly mixing each sample with approximately 2 L of water in a plastic container and then decanting the suspension through a sieve, leaving sand in the plastic container and roots retained on the sieve. Fine root fragments were further separated from adhering silt and sand particles by directing a gentle flow of water through the sieve. Samples were collected and stored in ethyl alcohol for later measurement of root length and mass.

Root length measurements were made by counting the number of observations of roots overlying intersections between 0.5 cm grid lines as described by Newman (1966), and refined by Tennant (1975). Root length data, are presented as root length densities (L_V, cm root cm^{-3} soil). The root length density of each depth was expressed as a percentage of the entire core value. Mean percentage values for each depth are also presented.

After the root lengths were measured, each root sample was transferred to a ceramic crucible, oven dried at 70^0C for 24 hours, and weighed. To account for any soil contamination, the ash free weight of each oven-dried sample was determined by subtracting the weight of ash remaining following burning in a Muffle furnace at 550^0C for 5 hours. Results are reported as root dry mass density for each sampling depth. The root mass density of each depth was expressed as a percentage of the entire core value. Mean percentage values for each depth are also presented.

Root mean diameter (RMD), an indicator of root branching (Matthew, 1992), was calculated assuming that; roots are perfect cylinders, have a fresh weight density of 1 g cm^{-3}, and that root DM is 8% of fresh weight (Matthew, 1992). Under these assumptions, RMD is given by the equation:

$$RMD\ (mm) = 10 \times [4 \times \text{root fresh weight (g cm}^{-3}) / \pi\ L_V, \text{ cm cm}^{-3}]^{1/2} \qquad (6.1)$$

The ratio of root length density (L_V) per unit of plant production (DM per $m^{2)}$ is used to identify those treatments exhibiting a shift of growth activity from shoot to root (Steingrobe *et al.*, 2001).

6.2.2. Statistical analysis

To avoid problems arising from heterogeneity of error, all data were converted to natural logarithm values before statistical analysis. After analysis, means were back-transformed to the original scale, and least significant differences for those means also back-transformed to give least significant ratios (LSR) (Steel and Torrie, 1982). The experimental design involved a factorial combination of 3 irrigation and 2 fertiliser treatments, 2 plant species, sampling at three different soil depths, different variables measured (e.g. root length, root mass), and three repeated measurements over time on the same plots. No existing statistical procedure provides for a design of this complexity to be treated in a single analysis. However, there are several options for analysing data, either as a single set, multiple variables from the same plots, or correlated observations such as those from different depths or repeat samplings over time in the same plots. In order to find the most satisfactory analytical method for this experiment, various exploratory statistical analyses were carried out, including principal component analysis of the correlation matrix (PCA), canonical discriminant analysis (CDA) (Matthew *et al.*, 1994) and general linear model (GLM) ANOVA procedures, with or without repeated measures analysis (SAS Institute, 1990).

The method eventually adopted was to first consider each of the three sampling dates and three depths independently in nine GLM factorial analyses, then combine data from soil depths, within each sampling date, in a PCA, to allow measurements from the three soil depths to be considered together as a single data set. For each sampling date, the PCA included three sets of 48 observations (2 species x 2 fertiliser regimes x 3 irrigation treatments x 4 replicates) from the three soil depths. Based on the sign and size of the principal component (PC) coefficients, the three sets of PC scores obtained could then be interpreted as representing variation in root growth response across the individual plots in the experiment and across the three soil depths sampled. In this way,

it was possible to categorise treatment effects as either being common to all three soil depths, or present predominantly in one particular depth, or manifesting as a contrast between particular depths. The PCA eigenvalue (reported as proportion of variation explained) gives a measure of the comparative importance of each effect. Finally, the PC scores for individual plots from PCA were subjected to separate GLM factorial analyses for each sampling date, to determine statistical significance of treatment effects described by each of the PC scores (Jolliffe, 1986). In presenting PCA structures in the results section, coefficients smaller than 0.30 have been suppressed.

6.3. RESULTS

6.3.1. General

Root length densities and root mass densities at all depths were significantly ($P<0.0001$) greater for ryegrass than clover (Tables 6.1, 6.3, 6.5, and 6.8). Aggregated across all fertiliser and irrigation treatments, 56% to 72% of the ryegrass root lengths recovered from the refilled cores and 56% to 63% of clover root growth was found in the 0 - 50 mm depth (Table 6.1). With the exception of root mass density for clover at the April harvest, L_V and root mass density were significantly ($P<0.05$) greater in the surface 0-50 mm depth than the other two depths. The percentage of root mass recovered from lower soil depths (50-100 mm and 100-200mm) tended to be greater than measurements of root length at corresponding depths (Table 6.1), especially for ryegrass. The root mean diameter (Table 6.2), in the 0-50 mm depth was significantly ($P<0.05$) smaller than for the other two depths for ryegrass at the February and April harvests and for clover at the April harvest, while clover had a significantly ($P<0.01$) greater mean diameter compared with ryegrass plants (Table 6.2).

L_V and root mass density values exhibited a positive, linear correlation ($R^2 = 0.598$), and on this basis it was decided to present only L_V values in subsequent Tables describing treatment effects. In general, L_V values were highest at the February harvest, and lowest at the April harvest following a dry period.

Table 6.1 Distribution of root length density L_V (cm root cm^{-3} soil) and dry mass density (mg root cm^{-3} soil) with soil depth, Values in parentheses are the mean percentage values.

Harvest dates	Sampling depth	Ryegrass		Clover	
		Length density	Dry mass density	Length density	Dry mass density
Dec. 19, 2000	0 - 50 mm	4.75 (60)	0.25 (53)	1.23 (63)	0.10 (57)
	50 - 100 mm	1.42 (20)	0.10 (23)	0.29 (16)	0.04 (19)
	100 - 200 mm	0.57 (20)	0.06 (24)	0.17 (21)	0.02 (24)
	LSD	1.61 (7)	0.04 (10)	0.28 (7)	0.03 (10)
Feb. 16, 2001	0 - 50 mm	18.62 (56)	0.58 (45)	2.34 (58)	0.26 (65)
	50 - 100 mm	7.73 (25)	0.37 (29)	0.65 (18)	0.06 (17)
	100 - 200 mm	3.00 (19)	0.16 (26)	0.40 (24)	0.04 (18)
	LSD	4.03 (8)	0.14 (8)	0.44 (8)	0.09 (8)
April 5, 2001	0 - 50 mm	5.26 (72)	0.14 (53)	0.51 (56)	0.04 (46)
	50 - 100 mm	0.68 (12)	0.05 (20)	0.17 (20)	0.05 (32)
	100 - 200 mm	0.43 (16)	0.04 (27)	0.10 (24)	0.03 (22)
	LSD	1.45 (8)	0.04 (13)	0.26 (8)	0.04 (13)

6.3.2. Irrigation and Fertiliser effects on L_V

6.3.2.1. December 2000 root harvest

The effect of fertiliser addition did not significantly increase L_v in the 0-50 mm depth, but was highly significant ($P<0.005$) in the 50-100 mm depth. There was no effect of irrigation on L_v at the first harvest. This P fertiliser effect and the difference in L_v

between clover and ryegrass mentioned above, dominated the December harvest (Table 6.3).

Table 6.2 Distribution of root mean diameter RMD (mm) with soil depth.

Harvest dates	Sampling depth	Ryegrass	Clover
Dec. 19, 2000	0 - 50 mm	0.27	0.37
	50 - 100 mm	0.32	0.46
	100 - 200 mm	0.35	0.43
	LSD	0.06	0.10
Feb. 16, 2001	0 - 50 mm	0.23	0.42
	50 - 100 mm	0.28	0.38
	100 - 200 mm	0.29	0.39
	LSD	0.04	0.10
April 5, 2001	0 - 50 mm	0.21	0.36
	50 - 100 mm	0.32	0.67
	100 - 200 mm	0.36	0.66
	LSD	0.08	0.15

PCA of the data from the three soil depths (Table 6.4) showed that 76% of the variation in the data set for this sampling date was explained by PC1. The coefficients for the contribution of each depth to the PC1 scores are positive and of similar size (0.571, 0.604, and 0.556, respectively, Table 6.4) indicating that the effects described by PC1 were common to all three depths. GLM analysis of scores for PC1 (Table 6.4) revealed that this PC described the plant species and fertiliser effects identified in Table 6.3.

PC2 and PC3 explained only 15.3% and 8.7% of the variation in the data set, respectively, and their scores did not display significant species or fertiliser differences (Table 6.4). Hence, these were considered biologically unimportant. However, these PCs do illustrate the capacity of the PCA to detect other patterns of response with soil depth. For example, the coefficients for PC2 describe an effect characterised by decreased root growth in the surface depth (strong negative coefficient) and increased

root growth in the lower soil depth (strongly positive coefficient), with no contribution from the middle depth (coefficient smaller than 0.30, and suppressed).

Table 6.3 Mean root length density, L_V (cm root cm^{-3} soil) for ryegrass and white clover without (P-0) or with P fertiliser (P-40), harvested in December 2000. I-20, I-40, I-60 are irrigation treatments as described in the text.

	Sampling depth intervals		
Treatments	0 - 50 mm	50 – 100 mm	100 – 200 mm
Ryegrass			
P-0, I-20	4.58	0.77	0.38
P-0, I-40	5.03	1.21	0.38
P-0, I-60	3.25	0.54	0.46
Adjusted Mean	4.22	0.80	0.40
P-40, I-20	6.91	2.24	0.66
P-40, I-40	4.34	1.91	0.39
P-40, I-60	4.94	2.01	1.51
Adjusted Mean	5.29	2.05	0.73
Clover			
P-0, I-20	0.93	0.17	0.20
P-0, I-40	1.09	0.29	0.11
P-0, I-60	1.18	0.16	0.14
Adjusted Mean	1.06	0.20	0.15
P-40, I-20	1.79	0.33	0.14
P-40, I-40	1.22	0.55	0.38
P-40, I-60	1.29	0.30	0.17
Adjusted Mean	1.41	0.38	0.21
LSR	2.85	3.71	3.35
Significance of main effects			
Species	0.0001	0.0001	0.0001
Fertiliser	NS	0.0051	0.0598
Irrigation	NS	NS	NS

6.3.2.2. *February 2001 root harvest*

Treatment effects observed in the February root harvest (Table 6.5) were similar to those seen in December. As in the December harvest, the PC analysis (Table 6.6) indicated that the species and fertiliser effects of Table 6.5 represented the majority of the variation in the data set (85%) and were common to all three soil depths.

Table 6.4 Principal component analysis (PCA) results to determine interaction between layers at the December 2000 harvest.

Description	PC1	PC2	PC3
Eigenvectors			
Layer 1	0.571	-0.642	0.512
Layer 2	0.604	-	-0.791
Layer 3	0.556	0.761	0.334
Proportion	0.760	0.153	0.087
*Significance			
Species	0.0001	NS	NS
Fertiliser	0.0136	NS	NS

*Obtained from ANOVA of principal component scores.

As for the December root harvest, the effect of irrigation frequency on root growth was not significant, and PC2 and PC3 (Table 6.6) were small and could not be related to the experimental treatments by ANOVA of PC scores, and are not interpreted.

6.3.2.3. *April 2001 root harvest*

At the final root harvest in April irrigation frequency affected L_V. Following a prolonged period without rain and the application of approximately 300 mm of irrigation, L_V values were lower for I-20 plots than for I-40 or I-60 plots (Table 6.7). As in the previous two harvests, L_V for ryegrass plots greatly exceeded that of clover plots, (GLM analysis Table 6.8; PCA Table 6.9), but at this harvest the fertiliser effect was

statistically significant only in the 0 - 50 mm depth for the GLM analysis (Table 6.8), and was not identified in the PCA analysis (Table 6.9).

Table 6.5 Mean root length density, L_V (cm root cm^{-3} soil) for ryegrass and white clover without (P-0) or with P fertiliser (P-40), harvested in February 2001. I-20, I-40, I-60 are irrigation treatments as described in the text.

	Sampling depth intervals		
Treatments	0 - 50 mm	50 - 100 mm	100 - 200mm
Ryegrass			
P-0, I-20	14.50	5.03	2.96
P-0, I-40	9.77	4.45	1.52
P-0, I-60	15.59	7.23	3.16
Adjusted Mean	13.02	5.45	2.42
P-40, I-20	33.95	9.20	3.65
P-40, I-40	18.63	9.23	3.23
P-40, I-60	22.47	11.83	3.85
Adjusted Mean	24.22	10.01	3.57
Clover			
P-0, I-20	2.16	0.47	0.43
P-0, I-40	1.58	0.57	0.41
P-0 I-60	2.2	2.42	0.22
Adjusted Mean	1.96	0.48	0.34
P-40, I-20	1.83	0.85	0.22
P-40, I-40	3.06	0.84	0.90
P-40, I-60	3.64	0.77	0.52
Adjusted Mean	2.73	0.82	0.47
LSR	2.10	2.95	3.33
Significance of main effects			
Species	0.0001	0.0001	0.0001
Fertiliser	0.0030	0.0127	NS
Irrigation	NS	NS	NS

PC1 of the PCA again had similar coefficients for all three depths (Table 6.9), indicating it arose from effects where growth in all depths was affected, and again accounted for a high proportion (78%) of the variation in the data set. For this harvest,

however, PC1 represents irrigation and species effects, with mean scores for PC1 being -0.62, 0.26 and 0.36 for treatments I-20, I-40 and I-60, respectively (data not presented, $P < 0.0012$, Table 6. 9).

Table 6.6 Principal component analysis (PCA) results to determine interaction between layers at the February 2001 harvest.

Description	PC1	PC2	PC3
Eigenvectors			
Layer 1	0.577	-0.585	0.570
Layer 2	0.587	-	-0.787
Layer 3	0.567	0.789	-
Proportion	0.854	0.088	0.057
*Significance			
Species	0.0001	NS	NS
Fertiliser	0.0014	NS	NS

* Obtained from ANOVA of principal component scores.

Table 6.7 Summary of the main effects of irrigation on L_V (cm root cm^{-3} soil) at the April 2001 harvest.

Treatments	Sampling depth intervals		
	0 - 50 mm	50 - 100 mm	100 - 200mm
Ryegrass			
I-20	4.437	0.409	0.206
I-40	6.005	0.842	0.565
I-60	4.703	0.903	0.670
Clover			
I-20	0.249	0.142	0.079
I-40	0.95	0.17	0.08
I-60	0.538	0.210	0.152
LSR for irrigation effect	1.662	1.620	1.732

Table 6.8 Mean root length density, L_V (cm root cm^{-3} soil) for ryegrass and white clover without (P-0) or with P fertiliser (P-40), harvested in April 2001. I-20, I-40, I-60 are irrigation treatments as described in the text.

	Sampling depth intervals		
Treatments	0 - 50 mm	50 - 100 mm	100 - 200mm
Ryegrass			
P-0, I-20	2.57	0.22	0.16
P-0, I-40	4.65	0.81	0.55
P-0, I-60	4.00	1.37	1.26
Adjusted Mean	3.63	0.63	0.48
P-40, I-20	7.66	0.75	0.27
P-40, I-40	7.76	0.87	0.58
P-40, I-60	5.52	0.59	0.36
Adjusted Mean	6.9	0.73	0.38
Clover			
P-0, I-20	0.28	0.14	0.09
P-0, I-40	0.71	0.15	0.08
P-0, I-60	0.51	0.19	0.11
Adjusted Mean	0.46	0.16	0.09
P-40, I-20	0.22	0.14	0.07
P-40, I-40	1.28	0.20	0.09
P-40, I-60	0.57	0.24	0.21
Adjusted Mean	0.55	0.19	0.11
LSR	2.76	2.63	3.00
Significance of main effects			
Species	0.0001	0.0001	0.0001
Fertiliser	0.0568	NS	NS
Irrigation	0.0093	0.0443	0.0068

The coefficients for PC2 shows a contrast between the 0-50 mm depth and 100-200 mm depth, which the ANOVA of PC scores shows, is also associated with a species by irrigation interaction (Table 6.9). Inspection of scores indicated that the data feature reflected by this PC is the comparatively greater L_V reduction in clover for the depth 0-50 mm (0.249 c.f. 0.538, Table 6.7), contrasting with the greater reduction in L_v for ryegrass in the depth 100-200 mm (0.206 c.f. 0.670, Table 6.7). Mean PC2 scores for

ryegrass I-20, I-40, and I-60 were 0.56, 0.09 and -0.15, respectively, while for clover I-20, I-40, and I-60 were -0.41, 0.28 and -0.37, respectively. As in earlier harvests, PC3 is not interpreted.

Table 6.9 Principal component analysis (PCA) results to determine interaction between layers at the April 2001 harvest.

Description	PC1	PC2	PC3
Eigenvectors			
0 - 50 mm	0.55	0.81	-
50 - 100 mm	0.60	-	-0.77
100 - 200mm	0.58	-0.54	0.61
Proportion	0.78	0.14	0.08
*Significance			
Species	0.0001	0.048	NS
Fertiliser	NS	NS	NS
Irrigation	0.0012	0.089	NS
Species x irrigation	NS	0.025	NS

• Obtained from ANOVA of principal component scores

6.3.3. Root mean Diameter (RMD)

There were two significant interactions in RMD data that did not emerge in the L_v data. The interaction of applied P fertiliser by irrigation frequency was significant ($P<0.027$) for RMD in the 50-100 mm depth for the February 2001 harvest. RMD decreased sharply from I-40 to I-60 in the absence of applied P fertiliser (P-0) while the opposite was seen with P fertilised (P-40) plots. The mean RMD values for I-40, P-0 and I-40, P-40 and I-60, P-0 and I-60, P-40 plots were 0.35, 0.29, 0.28 and 0.38 mm, respectively. The difference between I-60, P-0 and I-60, P-40 plots was significant. For the April harvest, there was a significant ($P<0.008$) interaction of species by applied P fertiliser for RMD in the 50-100 mm depth. The mean RMD values for ryegrass P-0, ryegrass P-40, clover P-0 and clover P-40 plots were 0.35 0.29, 0.58 and 0.79 mm, respectively.

Mean RMD of clover under P-40 plots was significantly greater than that P-0 clover plots, while mean RMD of ryegrass were almost equal for P-40 and P-0 plots for April.

6.3.4. Ratio of L_V per unit shoot production (L_V:shoot production DM)

As the effect of irrigation was significant only for the April 2001 root harvest, the ratio of L_V to shoot production is discussed only for this harvest. For perennial ryegrass plots, the ratio L_V:unit shoot production was very high at I-60, P-0 in soil depths 50-100 mm and 100-200 mm (Fig. 6.1). There was a marked reduction in mean ratio L_V:unit shoot production from 5.88 for P-0 to 2.72 for P-40 for ryegrass, while the corresponding change for clover was negligible for the 100-200 mm depth. There was a significant ($P<0.025$) interaction between species and fertiliser for the 100-200 mm depth. Similarly there was a possibility of an interaction ($P<0.06$) between species and irrigation frequency with an increased L_V:unit shoot production ratio for ryegrass from irrigation frequency I-20 to I-60 for depth 100-200 mm.

6.4. DISCUSSION

The development of the refilled core technique and its associated statistical analyses was an important objective of this work. However, this technique was a means to an end i.e. the measurement of root distribution pattern under irrigation and the effect of irrigation frequency on root activity. Accordingly, the development of the technique is discussed in Appendix 6.1; not because it is unimportant or secondary but by placing it there, the discussion that follows can focus on arguments that are more central to the Thesis.

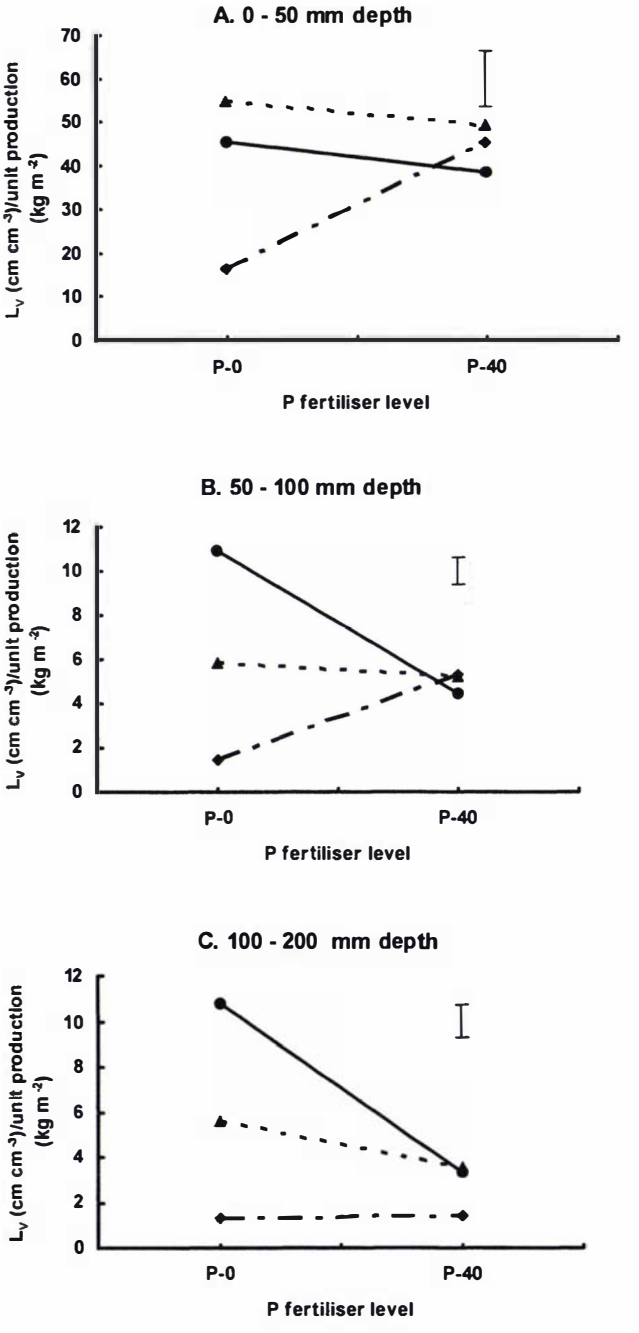


Figure 6.1 The Interaction between irrigation frequency and P fertiliser rate for ryegrass for the ratio of L_V (cm root cm^{-3} soil) per unit pasture production (kg DM m^{-2}) for the April root harvest. Symbols ♦, ▲, ● represent irrigation frequency treatments I-20, I-40, and I-60, respectively. Vertical bars are standard errors (P<0.05) for irrigation and fertiliser comparisons.

The greatest concentration of roots was observed in the 0- 50 mm depth irrespective of treatment combination. On occasions, root masses that were too small to weigh were observed in cores from the 100-200 mm depth. The root observations of the current study are consistent with other reported studies. For example, Deinum (1985) found 85% of the root biomass of a ryegrass dominant pasture in the 0 - 100 mm depth, another 10% within the 100-200 mm layer, and only 5% in the 200-300 mm depth. Likewise, Barker *et al.* (1988) observed 7 - 12 times greater pasture root length, surface area and biomass in the upper 50 mm of soil compared to the 150-200 mm depth. Using the refilled core technique, Mathew *et al.* (1991) harvested 90% of the total root mass of a ryegrass dominant pasture from the surface 250 mm of a 600 mm sampling core.

The decrease in L_V with increasing soil depth observed here is comparable with the observations of numerous studies including; Cullen *et al.* (1972), Campbell *et al.* (1977), Garwood and Sinclair (1979b), Newman *et al.* (1989), and Mathew *et al.* (1991). Likewise increased root branching in surface soil is well documented (Matthew, 1992; Wechsung *et al.*, 1999).

The decision to focus on one variable, L_V, was made because it gave the best information about the effect of the fertiliser and irrigation treatments on root growth, and because this particular measure of root distribution has been widely used in other studies (Atkinson, 1990; De Willigen and Van Noordwijk, 1987; Garwood and Sinclair, 1979b; Steingrobe, 2001; Steingrobe *et al.*, 2001).

The L_V of clover roots was significantly smaller than that for ryegrass roots in all depths at all three harvests. Similar observations have been made in several studies, even when different techniques were used (Cullen *et al.*, 1972; Evans, 1978; Mengel, 1983). L_V is low in many dicotyledonous species and there is very large variation (magnitude of 10^3) between species (Atkinson, 1990).

Clover root growth was less at the April harvest, while ryegrass root growth was relatively uniform between harvests. The effects of plant flowering on root growth can explain this difference. Root dry matter accumulates more rapidly than shoot dry matter during vegetative growth of shoots (September to November at the study site) and vice-versa during flowering (Fu *et al.*, 2001; Parsons and Robson, 1981). Fu *et al.* (2001) measured a root to shoot ratio of 2.52 in mid November and 0.78 by early February for Caucasian clover in New Zealand. In the present study, despite frequent mowing of the plots, clover flowered in February and March, the period of decreased clover root growth. In contrast, due to the frequent mowing of plots, ryegrass did not flower; therefore, all of the ryegrass root growth was associated with vegetative growth of shoots.

As I-20 and I-40 had been irrigated only twice and once, respectively, in early December, and I-60 had not been irrigated at all, the effect of irrigation was not expected to be significant for the December 2000 root harvest. But the differences between irrigation treatments were not statistically significant for the February 2001 harvest, either. This lack of an irrigation treatment effect could be attributed to the short duration of the irrigation period (41 days) and the relatively small quantity of water that was irrigated (approximately 120 mm) up to this point. This would suggest that, for the relatively short irrigation period at the beginning of the irrigation season, the irrigation treatments studied here had a similar impact on the root systems of clover and ryegrass. In other words, what periods of 'water stress' there had been in the soil surface on I-60 were not sufficiently prolonged to affect root activity.

Soil moisture availability was a key determinant of root growth at the April 2001 root harvest. The effect of irrigation frequency on L_V emerged at the April harvest and it was significant in all three sampling depths. Compared with I-20, the increase in L_V under I-

40 and I-60 across all three depths, irrespective of P fertiliser level, or species, was clear. The differences in L_V between I-40 and I-60 were generally not significant.

The sensitivity of root growth to moisture stress has been observed elsewhere, for example by Garwood and Sinclair (1979b) for ryegrass. Sindhøj *et al.* (2000) also observed increased root growth with increased seasonal dryness in a root dynamic study on semi-natural grassland. Similarly, Markus *et al.* (2000) observed the coincidence of minimum soil water storage, maximum leaf area, and maximum rooting density in the upper soil layers in one-year-old Maize (*Zea mays* L).

On occasions, there was a significant response in the growth of both ryegrass and clover roots to P fertiliser. The greater L_V measured in P fertilised plots compared to non-fertilised plots was consistent with observations of Power (1983) who found that frequently, plants grown with an adequate nutrient supply extend roots to greater depths than the same plants grown in soil that is deficient in one or more nutrient.

There was a general trend for ryegrass roots to be more responsive than clover roots to P fertiliser addition. Singh and Sale (1997) reported that the leaf fraction of clover was more responsive to increasing P than the root system.

PC analyses indicate that PC1 corresponds to each species effect as well as irrigation effect for the April harvest. These significant effects are common to all three layers as PC1 was almost equal and positive across all the depths. PC2 scores at the April harvest identified a significant interaction between species and irrigation. The magnitude of this interaction was not significantly reflected in the GLM analysis performed on the individual depths. This interaction may be associated with greater stress-stimulated clover root growth in the 0-50 mm depth.

The minimum root mean diameter (RMD) of 0.28 mm for I-60, P-0 plots with the significant (P<0.027) interaction between irrigation and P fertiliser at 50-100 mm depth at the February harvest was an indication of root branching associated with stimulation by stress. This may be an indication of root branching to access more P or water or both of them in an environment where there is less available P and increased water stress. Davidson (1978) concluded that pasture root growth is stimulated by decreased soil moisture. Significantly (P < 0.008) smaller RMD of clover at P-0 associated with the significant interaction of species and fertiliser for 50 - 100 mm depth for April harvest may be an indication of the greater sensitivity of clover than ryegrass to P stress.

The maximum ratio of L_V per unit shoot dry matter for ryegrass P-0 plots associated with significant (P<0.025) interaction of species into fertiliser for depth of 100-200 mm as well as other trends in L_V: unit production ratio values for the April harvest also provide some complementary evidence of root growth stimulation as a result of fertiliser as well as water stress.

Since PC1 strongly suggested that the variations in root L_V parameters are distributed equally across all the three soil depths in this study, it can be deduced that stress stimulation effects of root growth seem to be common for all soil depths from 0 to 200 mm in this study. This appears to be in line with the general principle that reduction in resource availability promotes increased allocation to the affected organs (Wilson, 1988).

6.5. CONCLUSIONS

Measurement of root growth into refilled cores is an effective technique for comparing root growth response of perennial ryegrass and white clover to different irrigation

frequencies and fertiliser levels. Principal component analysis can be employed to explore variation in treatment effects with soil depth.

Root growth was invariably greatest in the surface soil (0 - 50 mm depth). The root growth of ryegrass was always greater than clover during the irrigation season. At all three root harvests, the application of 40 kg P significantly improved the root growth of both species. The effect of irrigation on root growth emerged towards the end of the summer irrigation season where root growth stimulation due to water stress (i.e. less frequently irrigated plots) and P shortage was observed.

In contrast to the view often espoused by irrigation designers, the advantages of frequent irrigation of pasture cannot be attributed to the stimulation of extra root production in the surface soil. It is suggested that an additional benefit of frequent irrigation is that a moist surface soil means that plants need to produce fewer roots, resulting in the allocation of more resources to shoot growth.

CHAPTER 7

NITROGEN AND PHOSPHORUS LEACHING UNDER THREE IRRIGATION FREQUENCIES

7.1. INTRODUCTION

Leaching and/or runoff of nutrients such as nitrate-N and phosphorus can impact negatively on the wider environment. It is often argued that irrigation will result in an increased downward soil water flux and, as a consequence, greater nutrient loss to the ground water (Nguyen *et al.*, 1996; Schneekloth *et al.*, 1996). However, it is also possible that, as a result of improved water and nitrogen uptake by crops, efficient irrigation will reduce nutrient leaching (Hack-ten Broeke, 2001; Burgess *et al.*, 2002). While there has been some speculation on increased leaching under irrigated pasture, references to relevant research are rare.

The amount of nitrogen (N) leaching is influenced by the quantity of excess N in the soil profile and the volume of water draining through the soil. While there is a substantial body of New Zealand research describing the dynamics of N cycling in soils (Ledgard *et al.*, 1996), there are very few studies of N dynamics under irrigated pasture.

The objective of the study described in this Chapter was to monitor the effect of irrigation frequency on soil water N and P concentrations at a depth of 300 mm throughout the summer irrigation period and the subsequent early winter drainage season. The field research site described in Chapter 4 was used. Having stated this objective, two important qualifying comments are in order. Firstly, there was no grazing at the experimental site and therefore the role of dung and urine deposits in leaching is

excluded here. Secondly, and relatedly this is a partial and tentative investigation of the impacts of irrigation frequency on leaching. A more substantive study would have required a different sort of field experiment which time did not allow.

7.2. MATERIALS AND METHODS

7.2.1. Field sampling

Soil water samples were collected from plots at the field trial. All the details about experimental treatments and irrigation strategies have been described in detail in Chapter 4 and 5. The exact quantities of N applications during the irrigation season are shown in Table 4.1.

Ceramic suction cup samplers (Grossmann and Udluft, 1991) were adopted as the most suitable technique for capturing soil water samples for use in estimating nitrate-N leaching from the ryegrass and clover plots in this study. Samplers were constructed using high flow round bottom straight wall ceramic cups; they were 75 mm long and 22 mm in outer diameter (652x10, Soil-moisture Equipment Corp. PO Box 30025, Santa Barbara, California 93105). The ceramic cup was cemented onto a 22 mm outer diameter PVC pipe of about 60 cm length. A PVC connector was placed between the ceramic cup neck (outer diameter 12 mm) and the PVC tubing before cementing with araldite glue. One such soil water sampler was installed near the centre of each plot. For easy installation of the suction cup, a hole was drilled by means of a soil auger. Soil material from the upper horizons was prevented from falling into the hole. To ensure good hydraulic contact between the suction cup and the soil *in situ*, slurry of the material from the soil auger column was made and put back into the hole before the suction probe was inserted. The outer end of the sampler PVC tube was kept closed with a PVC cap. The installation of the suction cup probe was followed by a stabilizing

phase. A rubber stopper connected with neoprene tubing and a valve was used to hold vacuum when the soil water sampler was in operation. At the start of a sampling period, a tension of about 50 kPa was applied to each sampler using a Soil Moisture Equipment hand pump and the units were left to draw soil water for 24 hours. The accumulated soil water sample was then drawn off with the help of polythene tubing connected to a 50 ml disposable syringe. Each soil water sample was transferred to a dispensing bottle, tagged and frozen for later analysis.

One ceramic cup was placed in each plot in first week of December 2000. The centre of the ceramic cup was placed at 300 mm depth. A number of workers have placed suction cup samplers at this depth. For example, Field *et al.* (1985) adopted 300 mm depth as the sampling depth for evaluation of leaching losses for Manawatu silt loam soil, while Burgess *et al.* (2002) assumed 350 mm to be the bottom of the rooting zone for barrel lysimeters in their pasture irrigation study.

Soil water sampling was conducted on 2 occasions during the irrigation season, and on 6 occasions between April 14 and July 31 2001 when heavy rain occurred. The concentrations of nitrate-N and ammonium-N in each water sample were measured using a Technicon II auto-analyser (Technicon, 1976; Downes, 1978).

Soil water nitrate-N concentration values were compared with KCl extracted soil nitrate-N concentrations. The values of KCl extracted soil nitrate-N concentrations, measured in mg kg^{-1} of moist soil, for soil samples collected on 24 April 2001 (Chapter 4) were converted to mg nitrate-N L^{-1} of soil water using the gravimetric moisture content of the soil at the time of sampling.

7.2.2. Estimation of nitrate-N leaching losses

The amount of nitrate-N leached per hectare per day was calculated for each treatment as the product of the mean nitrate-N concentration of soil water samples and the drainage volume estimated using the soil water balance (Chapter 5). Between 23 November 2000 and 31 July 2001 there were nine major rainfall events which recharged the soil profile to field capacity (i.e. soil water storage (*S*) became 0), and generated some drainage on at least one of the irrigation frequency treatments.

As the experimental site is flat and the Manawatu fine sandy loam is a free draining soil, all the excess water was assumed to drain through the profile. Similarly, all the major assumptions associated with simple piston flow were assumed to hold for nitrate-N movement beyond the root zone. It was assumed that all the nitrate-N found in soil water solution at 300 mm depth would be leached to the ground water at this site. Field *et al.* (1985) adopted a similar assumption for Manawatu silt loam soil when estimating nitrate-N leaching.

7.2.3. Measurement of dissolved reactive P in soil water

Heckrath *et al.* (1995) reported that dissolved reactive P is the largest phosphorus fraction in drainage water in permeable soils. Dissolved reactive phosphorus (DRP), i.e. mainly soluble inorganic P, was measured using the acid ammonium molybdate method (Murphy and Riley, 1962). A 20 ml sample of the water extracted from the suction cups was measured into a test tube and 10 ml of Murphy and Riley solution was added. This mixture was kept for about 2 hours to develop the colour and then an aliquot was taken to measure the absorbance at a wavelength of 720 nm through a 4 cm cell using a PU 8620 UV/VIS/NIR Spectrophotometer having the precision of 0.001 mg L^{-1}.

Even though 384 soil water samples were collected, only 180 samples were of adequate volume to allow sub-sampling for measurement of DRP. Therefore, standard statistical analyses were not carried out on values of DRP concentration of soil water samples.

7.3. RESULTS

7.3.1. Drainage

According to the soil water balance model developed above (Chapter 5), irrigation frequency affected the quantity of drainage between November 2000 and July 2001 (Fig. 7.1). The main drainage period was from mid May (Day 171) to July 31 2001 (Day 251). The cumulative drainage until May was 140, 60, and 80 mm for irrigation frequency I-20, I-40, and I-60 plots, respectively. Total drainage estimates to 31 July 2001, were 20, 240, and 260 mm for these plots, respectively.

In contrast to the irrigated plots, substantial deep drainage was not predicted until 16 June 2001 (Day 206) for non-irrigated plots and total drainage was 0 on 12 May and it was only 93 mm by 31 July 2001.

7.3.2. Nitrate-N in soil water samples

Soil water nitrate-N concentration data was variable (Fig 7.2 and Fig 7.3). This data was not normally distributed and log transformation did not change the results of statistical analysis.

The overall mean of nitrate-N concentration of soil water samples taken from ryegrass plots were significantly ($P<0.05$) smaller than those from clover plots (Fig. 7.4). The concentration of nitrate-N in soil water in ryegrass plots approached a plateau (at approximately 4 mg nitrate-N L^{-1}) from 14 April onwards. In comparison, the nitrate-N

concentrations of soil water in the clover plots increased rapidly until the end of May and approached a plateau (at approximately 17 mg nitrate-N L^{-1}) from mid June onwards.

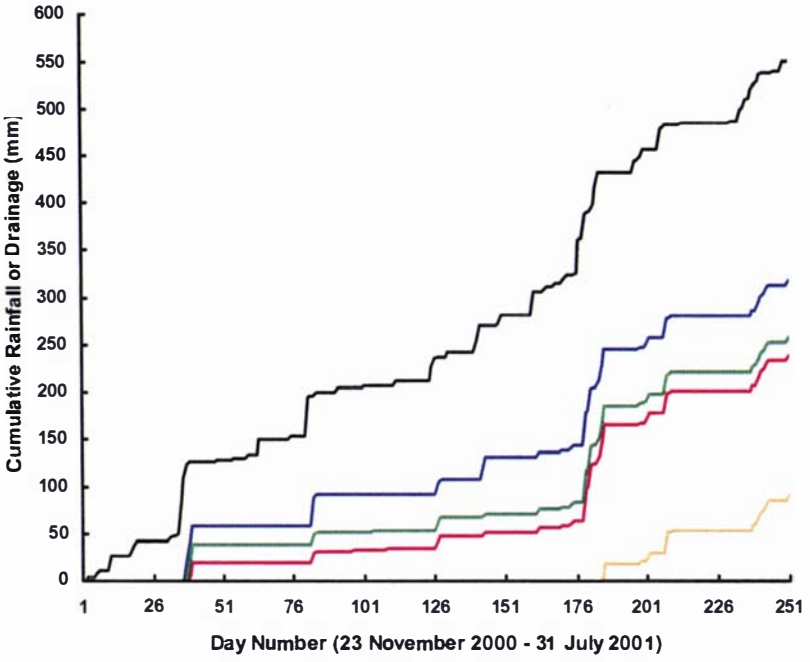


Figure 7.1 Cumulative rainfall and simulated cumulative drainage (from a soil water balance) for the irrigation season and early winter. The colour black represents rainfall while colours; blue, green, red and yellow represent cumulative drainage from I-20, I-40, I-60 and non-irrigated plots, respectively.

There were some intimations of an irrigation effect on nitrate-N concentrations in soil water samples (Fig. 7.5). Greater nitrate-N concentrations were observed in soil water samples for I-20 plots until 12 June 2001. Nitrate-N concentrations in soil water samples under I-60 tended to be smaller than those measured under the other irrigation frequencies.

P fertiliser application did not have a significant or consistent effect on the overall mean nitrate-N concentrations in soil water samples. However, for ryegrass, there was a

tendency for P-0 plots to have greater nitrate-N concentrations in the soil water samples than P-40 plots (Fig.7.2).

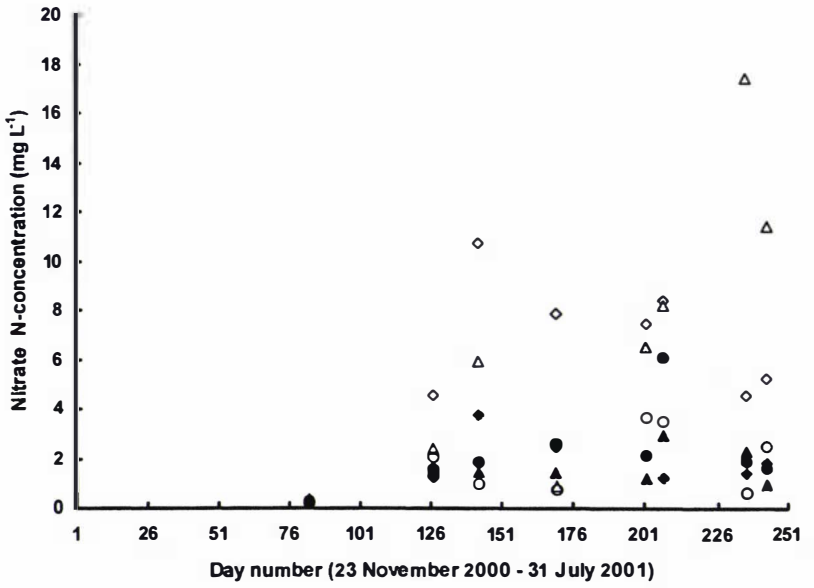


Figure 7.2 Nitrate-N concentrations of soil water at 300 mm depth following heavy rain for ryegrass plots. Symbols; ♦, ▲, ●, represent I-20, I-40, and I-60, respectively. Open symbols represent P-0 plots while closed symbols represent P-40 plots.

7.3.3. Correlation between nitrate-N in soil water and soil samples

The correlation coefficients between mean KCl extracted soil nitrate-N concentrations on 24 April and the nitrate-N concentrations of soil water samples collected at 300 mm depth on both the 14 April and 12 May 2001 were obtained. Very strong positive correlations were observed between the nitrate-N concentrations of soil and soil water in the 75-150 mm and 150-225 mm depths of ryegrass plots for April 14 and 12 May (Appendix 7.1a). The nitrate-N concentrations of soil water collected from suction cup samplers were always smaller than the KCl extracted soil nitrate-N values for ryegrass plots (Appendix 7.1b).

In contrast, the nitrate-N concentrations of soil water collected from suction cup samplers from I-20 plots on 12 May 2001 were almost equal to the KCl extracted soil nitrate-N values for clover plots for both P-40 and P-0 (Appendix 7.1b).

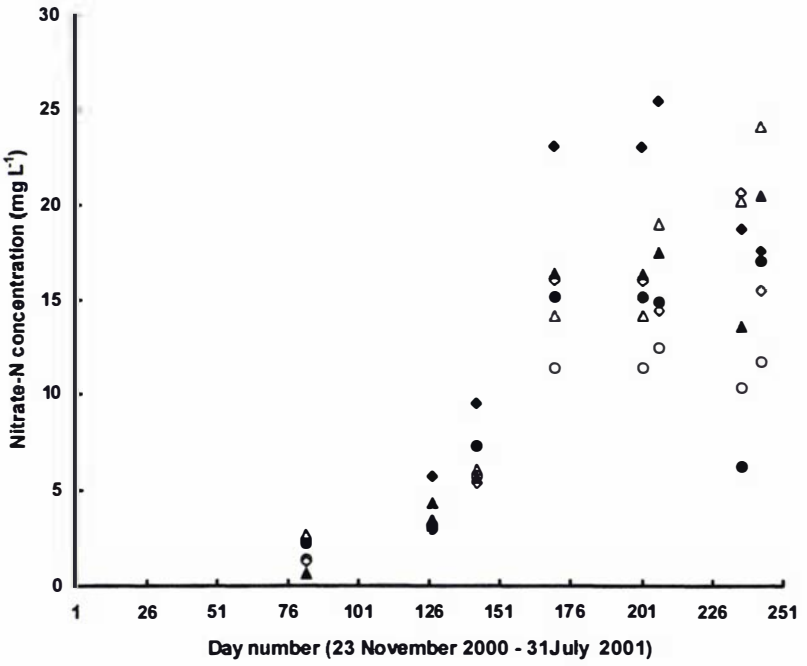


Figure 7.3 Nitrate-N concentrations of soil water at 300 mm depth following heavy rain for clover plots. Symbols ♦, ▲, ●, represent I-20, I-40, and I-60, respectively. Open symbols represent P-0 plots while close symbols represent P-40 plots

7.3.4. Estimated nitrate-N leaching losses

For the period November 2000 to July 2001, the greatest losses of nitrate-N estimated for ryegrass treatments were 17 and 10 kg nitrate-N ha^{-1} for I-20, P-0 and I-40, P-0 plots (Table 7.1). These losses equate to 12% and 8% of the N applied in fertiliser. The cumulative nitrate-N losses of all the other ryegrass plots were very similar and within the range of 3 to 6 kg ha^{-1} nitrate-N (2-4% of applied N) (Table 7. 1). Total nitrate-N losses under I-60 tended to be smaller than for the other two irrigation frequencies.

A comparison between cumulative losses up to mid May with cumulative losses up to the end of July reveals that most of the N leaching losses occurred in the period May to July. This was the period with high drainage (Fig. 7.1) and nitrate-N concentrations in soil water.

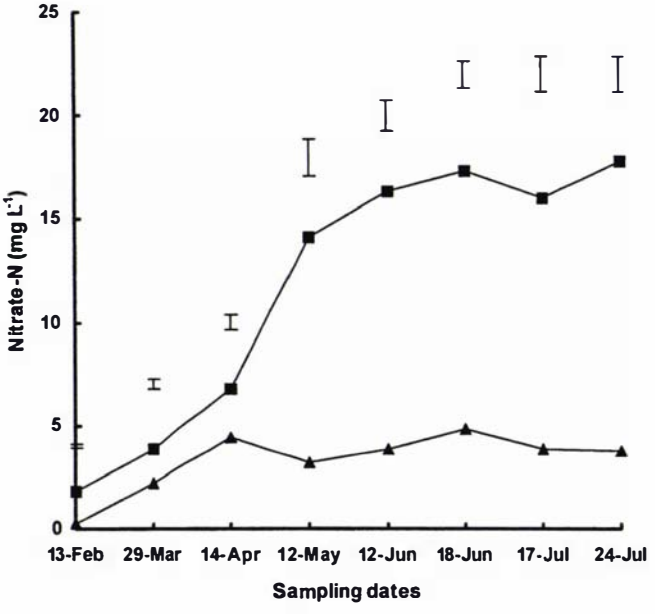


Figure 7.4 The effect of species on nitrate-N concentrations of soil water at 300 mm depth following heavy rain. Symbols ■ and ▲, represent clover and ryegrass, respectively. Vertical bars represent the standard error of means at P<0.05.

Cumulative nitrate-N losses estimated for clover plots until 31 July 2001 were at least two fold greater than those estimated for ryegrass plots (Table 7.2). Nitrate-N losses increased to a marked extent (8 to 15 times) under all clover treatments between May and July

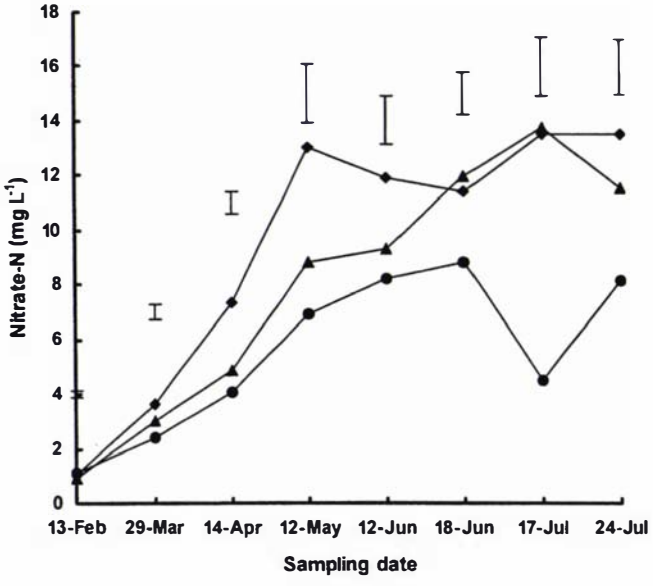


Figure 7.5 The effect of irrigation frequency on nitrate-N concentrations of soil water at 300 mm depth following heavy rain. Symbol; ♦, ▲, and ● represent irrigation frequency I-20, I-40, and I-60, respectively. Vertical bars represent the standard error of means at $P<0.05$.

7.3.5. Dissolved reactive P in free draining soil water samples

There was no visible treatment effect for dissolved reactive P concentrations of soil water samples. Therefore, only the mean dissolved reactive P concentrations with time are shown in Fig 7.6. The range of P concentrations was very narrow, and decreased gradually towards mid winter with increased drainage volumes.

7.4. DISCUSSION

According to Magesan *et al.* (1994), some caution is required when interpreting leaching data obtained using suction cup samplers: not all the solute present in the soil participates in solute transport, nitrate is dynamic and the biological transformations to

which nitrate is subject in soil are spatially variable. Likewise, Wild and Cameron (1980) and Litaor (1988) have reported that suction cup samplers have limitations for measuring leaching losses because of the variations in soil solution concentrations and water flow through the soil that can occur over relatively short distances.

Table 7.1 Summary of the nitrogen that was; added as fertiliser, removed in harvested material, and leached (kg ha $^{-1}$) for ryegrass plots for the periods 23 November 2000 to 14 May 2001 and 23 November 2000 to 31 July 2001. Values in parentheses denote the nitrate-N loss as a percentage of applied fertiliser N.

Treatment	Fertiliser N Input	N removal as pasture	Leaching loss until 14 May 2001 as nitrate-N	Leaching loss until 31July 2001 as nitrate-N
I-20 P-0	140	177	5 (4)	17 (12)
I-20 P-40	140	206	2 (2)	5 (4)
I-40 P-0	140	172	1 (1)	10 (8)
I-40 P-40	140	198	1 (1)	4 (3)
I-60 P-0	140	161	1 (1)	3 (2)
I-60 P-40	140	184	1 (1)	6(4)

The range of values reported here for soil water nitrate-N concentrations are comparable with the values given by Cuttle *et al.* (1992) for ryegrass/white clover plots which were sampled using suction cups.

As ammonium-N was not detectable in almost all of the samples, the concentration of ammonium-N in soil water was considered to be zero. Heng *et al.* (1991) also failed to detect ammonium-N in drainage water samples. This is again comparable with observations of Cuttle *et al.* (1992).

Table 7.2 Summary of the nitrogen that was; removed in harvested material, and leached (kg ha $^{-1}$) for clover plots for the periods 23 November 2000 to 14 May 2001 and 23 November 2000 to 31 July 2001.

Treatment	Fertiliser N Input	N removal as pasture	Leaching loss until 14 May 2001 as nitrate-N	Leaching loss until 31 July 2001as nitrate-N
I-20 P-0	0	351	4	33
I-20 P-40	0	367	7	41
I-40 P-0	0	291	3	44
I-40 P-40	0	345	2	22
I-60 P-0	0	273	2	19
I-60 P-40	0	314	3	24

The variability in the measurement of nitrate-N concentrations increased between late autumn and early winter i.e. 12 May to 24 July 2001: this is a common phenomenon that has been observed by several other authors (e.g. White *et al.*, 1987; Cuttle *et al.*, 1992; Magesan *et al.*, 1996). According to these workers, the increased variability in measured nitrate-N concentration is attributable to the changes in water movement patterns as the profile nears saturation. Earlier saturation of the root zone and greater cumulative drainage was observed for I-20 (Fig 7.1).

A tendency for P-0 plots to have greater nitrate-N concentration in soil water samples than P-40 plots were seen for the ryegrass plots (Fig 7.2). This may be an indication of more efficient utilization of N fertiliser by ryegrass in the presence of P fertiliser. This trend was not observed for I-60, P-0 plots at the peak of the drainage season.

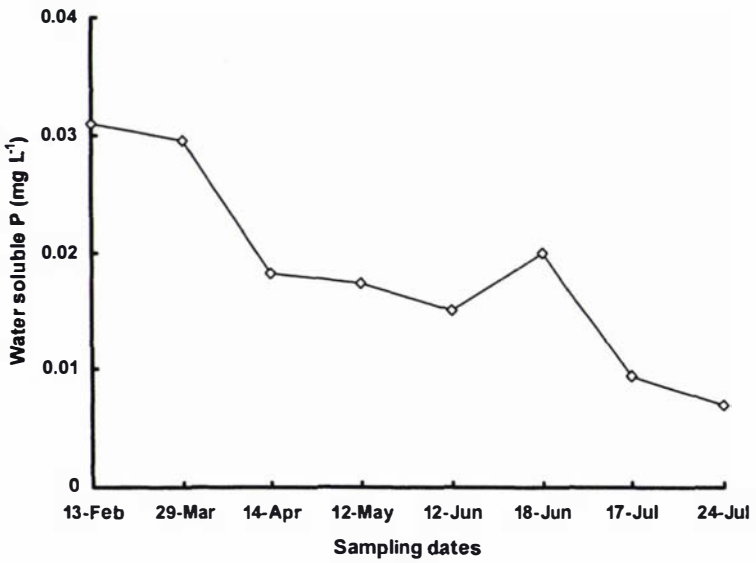


Figure 7.6 The mean dissolved reactive P concentrations of free draining soil water at 300 mm depth following heavy rains in 2001.

The cumulative losses of nitrate-N from clover plots by July 31 2001 were at least two fold greater than losses form corresponding ryegrass plots. A flush in the mineralization of soil organic N upon the rewetting of the soil profile (White *et al.*, 1983) may have resulted in the greater leaching losses under clover plots (Table 7.2) as no N fertiliser was added to the clover plots. In part, the greater concentration of nitrate-N in soil water under clover may explain the trend of lower concentration (and losses) of nitrate-N under I-60. As I-60 plots produced less clover than I-20 then presumably there was less N_2 fixation and ultimately less nitrate-N at risk to leaching.

Major quantities of nitrate-N were lost from the irrigated plots in May. Workers like Heng *et al.* (1991) and Field *et al.* (1985) have reported similar trends with the commencement of autumn drainage events for the same locality. Heng *et al.* (1991) reported that most of the nitrate-N lost from Tokomaru silt loam was in the first 70 - 80

mm of drainage during late autumn/early winter, and concluded that the drainage during the rest of the winter had a relatively small effect on the total amount of nitrate-N leached.

Overall, nitrate-N leaching losses from ryegrass plots were only 2 to 12% of the N applied as fertiliser. A substantial loss of nitrate-N was measured only for I-20, P-0 ryegrass plots: losses from other plots appeared to be negligible. Comparably, Hack-ten Broeke (2001) reported that different irrigation strategies had no significant effect on nitrate-N concentrations in the leachate from two 'dry' fields in pasture land in the Netherlands. Moreover, for the relatively 'wet' field in his study, an increase in irrigation water use improved pasture production and reduced nitrate concentrations at 1 m depth. In a recent lysimeter study in Waikato in New Zealand, Burgess *et al.* (2002) observed excess nitrate-N leaching below the pasture root zone under non-irrigated treatments when the autumn drainage flush occurred and they attributed this to the accumulation of nitrate-N in the root zone during the dry season.

The maximum total cumulative nitrate-N loss under ryegrass (I-20, P-40) of 17 kg ha^{-1} is almost half of the value of 37 kg ha^{-1} for a pure sward of ryegrass on Manawatu silt loam estimated by Field *et al.* (1985). However, the study site used by Field *et al.* (1985) was grazed by sheep while the current experiment involved cut swards. The value reported here is closer to estimates reported by Heng *et al.* (1991) on Tokomaru silt loam soil at Palmerston North which was also grazed by sheep.

In general, dissolved reactive P concentrations in soil water samples were in the range of 0 - 0.166 mg L^{-1}. The observations of this experiment are within the range of values reported in the literature (Culley *et al.*, 1983; Sharpley and Menzel, 1987; Heckrath *et al.*, 1995). The concentration of P decreased from autumn onwards with increased volumes of drainage. This is most likely attributable to dilution of dissolved reactive P

with saturation of the profile. The dissolved reactive P measured at 300 mm depth may not be a potential source of environmental pollutant, as this soluble P may be adsorbed onto P-deficient subsoil in the 300- 450 mm depth. Sharpley *et al.* (2001) noted that the concentration of P in water percolating through the soil profile is small due to fixation of P by P- deficient subsoil. Overall, the small dissolved reactive P concentrations recorded under the different irrigation regimes indicate that it is unlikely that there will be a major increase in P leaching as a result of increasing irrigation frequency under pasture in the summer period.

7.5. CONCLUSION

Nitrate-N concentrations in soil water under irrigated swards of clover were large in early winter drainage events: this was the case irrespective of irrigation frequency. This resulted in relatively large leaching losses of N under clover. Nitrate-N concentrations in soil water were not as great under irrigated ryegrass swards. Nitrate-N leaching losses as a percentage of N fertiliser applied to ryegrass were very small (2-12%).

Estimated total nitrate-N losses until 31 July 2001 indicated that irrigation frequency of ryegrass during the previous summer did not have a major effect on the overall nitrate-N leaching pattern during the late autumn/early winter period following the irrigation season. However, there was some indication that irrigation frequency may have affected nitrate-N leaching loss under clover.

CHAPTER 8

SIMULATION OF PASTURE PRODUCTION UNDER THREE IRRIGATION AND TWO PHOSPHORUS FERTILITY REGIMES

8.1. INTRODUCTION

Models can be built to increase our understanding of the system under study, and of the nature of the functional relationships between parts of that system. In turn, this catalyses and informs future research which translates into improved models. Models are useful for extrapolating the understanding gained in a limited context to a wider range of circumstances.

Many of the models developed to simulate processes such as evaporation, crop yield, and leaching, are based on algorithms that describe the dynamic nature of soil water at different temporal and spatial scales with varying degrees of complexity. There appears to be a dichotomy in the choice of soil water models available for use in the prediction of crop yield. On the one hand, there are simple water balance models which require few inputs. However, they involve empirically determined parameters – which often depend on variables such as the nutrient status of the topsoil, or root density - and so these models have to be calibrated for each new soil, plant and perhaps climatic condition. On the other hand, detailed process-oriented models do not, in theory, require calibration as such but the input variables are many and are often not readily obtainable. A recent approach is to employ a hybrid of the two approaches, using models which incorporate some aspects of the process-oriented models into a simple soil water balance (De Jong, 1988).

Recently workers like Faulalo (1997), Moir *et al.* (2000a, 2000b), Scotter *et al.* (2000) and Blennerhassett (2002), have used a simple soil water balance to help predict pasture yield. They suggested that actual evaporation (*E)* might be a useful way of combining climatic and soil parameters (soil water availability and energy inputs) into a single factor. All these studies investigated pasture growth and fertiliser responses relative to *E,* and identified the relationship between pasture growth per mm of *E* and soil fertility. If one of these models could be expanded to predict responses in pasture production to different irrigation frequencies, there would be substantial benefits to irrigation science and management.

Increasing P fertility significantly improved ryegrass and clover production in both the pot (Chapter 3) and field experiments (Chapter 4). Frequent irrigation, in comparison to less frequent irrigation, significantly improved ryegrass and clover production in the field trial. If a model capable of simulating the significant effects of irrigation frequency and fertiliser application can be developed then the benefits of more frequent irrigation and P fertiliser application can be quantified for other years. The pasture prediction model proposed by Moir *et al.* (2000a, 2000b) is a useful starting point.

The soil water balance model developed in Chapter 5 can be used to simulate water depletion in the root zone. This three layer model was used successfully to simulate volumetric soil water contents in Manawatu fine sandy loam under three different irrigation regimes during the summer of 2000/2001. The model highlighted differences in soil water content between the irrigation frequencies particularly in the surface soil (0 - 150 mm).

The objectives of this chapter are twofold: firstly, to develop a simple model, based on the results from Chapter 4, to predict pasture production under irrigation, and secondly, to use this model to quantify the benefits of more frequent irrigation and P fertiliser application for a range of summer climatic conditions i.e. as experienced in the past 26 years (1975–2000).

8.2. THE PASTURE GROWTH MODEL

8.2.1. The concept

Moir *et al* (2000a and 2000b) and Moir (2000) proposed an approximately linear relationship between pasture production and E. The proportionality constant linking these two parameters was defined as k with units of kg of DM per ha per mm of E (kg DM ha^{-1} mm^{-1}). The good correlation between measured pasture production and cumulative E at the experimental site described in Chapter 4 encouraged exploration of the possibility of further developing the model of Moir *et al*. (2000a and 2000b). The accumulated production of all the cuts up to 29 March 2001 was taken as the irrigation season yield for calculations of k.

The following two major assumptions were adopted throughout the modelling procedure.

- To an acceptable first approximation, pasture production is proportional to transpiration (McAneney and Judd, 1983).

- For full cover pasture (LAI> 3), nearly all of the evaporation is transpiration (Kerr *et al.*, 1986; Allen *et al.*, 1998).

Thus, pasture growth (G) is calculated daily as

$$G = kE \qquad (8.1)$$

As argued above, the significant yield reduction measured for the least frequent irrigation treatment (I-60) is primarily due to nutrient shortage during periods of soil water extraction from deeper, P deficient soil layers. Therefore, the following calculation procedure was developed to derive different k values associated with different soil water deficit ranges. So, whereas Moir *et al.* (2000a and 2000b) and the other workers cited above, used only one k value, the model developed below will use four k values, each pertaining to a specific soil water deficit range.

Equation 8.2 is used to calculate cumulative evaporation. The soil water available for evaporation is assumed to be the totally available water.

$$\Sigma E = \Sigma E_1 + \Sigma E_2 + \ldots + \Sigma E_n \qquad (8.2)$$

Where

ΣE = cumulative evaporation for the period (mm)

ΣE_i = cumulative evaporation when soil moisture is in the i^{th} soil water deficit range (mm)

Daily E values are calculated using the soil water balance model developed in Chapter 5.

Equation 8.3 is used to calculate pasture production

$$G = k_1\Sigma E_1 + k_2\Sigma E_2 + \ldots + k_n\Sigma E_n \qquad (8.3)$$

Where

$k_i \Sigma E_i$ = pasture production when soil moisture is in the i^{th} soil water deficit, k_i - the proportionality constant when soil water is in the i^{th} soil water deficit

Total soil water depletion in the plots to a depth of 450 mm, the assumed root depth, was measured as 120 mm (Chapter 4). Four soil water deficit ranges were selected for this 120 mm of totally available water. The deficit ranges selected here were based on the irrigation regimes studied i.e. deficit range I (0 to 20 mm), deficit range II (21 mm to 40 mm), deficit range III (41 to 60 mm). The fourth range was for soil water deficits between 61 and 120 mm. The model does not allow further evaporation or growth after a soil water deficit of 120 mm is attained (see section 5.4 for elaboration on selection of these ranges)

Measured pasture production data from the field experiment (Chapter 4) was used to derive k_1 k_2, k_3, and k_4 as follows.

$$k_1 = MG_{20}/\Sigma E_1 \quad (8.4)$$

$$k_2 = (MG_{40} - k_1\Sigma E_1) / \Sigma E_2 \quad (8.5)$$

$$k_3 = (MG_{60} - (k_1\Sigma E_1 + k_2\Sigma E_2))/ \Sigma E_3 \quad (8.6)$$

$$k_4 = (MG_{120} - (k_1\Sigma E_1 + k_2\Sigma E_2 + k_3\Sigma E_3))/ \Sigma E_4 \quad (8.7)$$

Where

$\Sigma E_1, \Sigma E_2, \Sigma E_3, and \Sigma E_4$ = ΣE evaporation when soil water is in deficit ranges I, II III and IV, respectively

MG_{20}, MG_{40}, MG_{60} and MG_{120} = Measured cumulative pasture production for I-20, I-40 and I-60 and non-irrigated plots, respectively

The k values are given in Table 8.1. A sample calculation for k_3 is given below. For the example, P fertilised plots of ryegrass are considered (i.e. I-60, P-40). As there was no irrigation of either the I-40 or I-60 plots during the month of April 2001, the accumulated pasture production of all the cuts up to 29 March, 2001 was taken as the MG value. Prior to the calculation of k_3 as outlined below, similar computations were required to yield k_1 and k_2 values.

ΣE = 472 mm

ΣE_1 = 233 mm

ΣE_2 = 348 mm -233 mm

= 115 mm

Expected production when soil water is in deficit range I = 233 x 12.1

= 2819 kg DM ha^{-1}

Expected production when soil water is in deficit range II = 115 x 7.5

= 863 kg DM ha^{-1}

So estimated production when soil water is in deficit range III =

Measured production - [Expected production for deficit range I and deficit range II]

$= 4057 - (2819 + 863)$ kg DM ha^{-1}

$= 375$ k kg DM ha^{-1}

k_3= Production when soil water is in deficit range III/ ΣE_3

$k_3 = 375$ kg DM ha^{-1}/ (472 - 348)

$= 3.0$ kg DM ha^{-1} mm^{-1}

A cautionary note about a limitation of the above method used to calculate the k values is necessary. Variability in the pasture production data measured at the experimental site means that there is a great deal of uncertainty in the k_3 value. This is nicely illustrated by considering the consequences of a 10% increase in the value of MG_{60}. If a value of 4463 kg DM ha^{-1} is inserted for MG_{60} in the above example calculation then k_3 becomes 6.3 kg DM ha^{-1} mm^{-1} i.e. twice the value presented in Table 8.1.

Values calculated for k_4 are even more sensitive to small perturbations in pasture production measured on the non-irrigated plots. An attempt was made to calculate k_4 following the procedure outlined above. The k_4 value derived for ryegrass was close to the k_3 ryegrass value. However, the k_4 value for clover was substantially greater than the k_3 clover value.

In acknowledgement of this limitation in methodology, and in the light of Olsen P values (see next section), no attempt was made to discriminate between k values for P-0 and P-40 for the deficit ranges 21 to 40 mm (k_2) or 41 to 60 mm (k_3). In addition, for the

purposes of the model developed here, the mean k_4 values for ryegrass and clover are assumed to be equal to the corresponding mean k_3 value (Table 8.1).

Table 8.1 Proportionality constant (k) values for different soil water deficit ranges and P treatments. The units of k are kg DM ha^{-1} mm^{-1}.

Treatment	P-0	P-40	Mean values
Ryegrass			
Deficit range I (k_1)	10.4	12.1	-
Deficit range II (k_2)	6.6	7.5	7.1
Deficit range III (k_3)	6.9	3.0	5.0
Deficit range IV (k_4)	-	-	5.0
Clover			
Deficit range I (k_1)	14.8	15.8	-
Deficit range II (k_2)	10.5	10.3	10.4
Deficit range III (k_3)	7.9	10.2	9.0
Deficit range IV (k_4)	-	-	9.0

The k values for ryegrass and clover depend on the soil water deficit range, and the P status when the soil water deficit is in the 0 to 20 mm range (Table 8.1). Mean soil Olsen P levels for samples removed on 24 April, 2001 are shown in Table 8.2. (This table has been generated by aggregating data in Table 4.6 to determine Olsen P values for the soil depths of interest here i.e. 0-150 mm, 150-300 mm and 300-450 mm). In the 0-150 mm depth, the values are significantly greater for the P-40 plots than for P-0 plots. The dependence of k_1 on the P treatment is in keeping with the finding of Moir *et al.* (2000a and 2000b). The difference in Olsen P at the 150-300 mm depth between P-0 and P-40 is small for both ryegrass and clover plots. This is, in part, why mean values for P-0 and P-40 are used for k_2 and k_3 in the model.

Table 8.2 Mean soil Olsen P (mg kg^{-1}) values measured for samples taken on 24 April 2001 from experimental plots.

Treatment	I-20		I-60	
	P-0	P-40	P-0	P-40
Soil depths (mm)				
Ryegrass				
0- 150	9	15	10	20
150-300	7	9	8	9
300-450	5	5	6	5
Clover				
0-150	10	16	12	16
150-300	6	8	7	10
300-450	5	5	5	7

8.2.2. Use of *k* values to predict pasture production in 2000/2001

The predicted cumulative ryegrass and clover productions for the summer irrigation season (23 November 2000 - 30 April 2001) are compared with measured cumulative productions for irrigation frequency I-20 in Fig. 8.1. The standard deviation for measured production is also shown. Throughout the irrigation season, harvested and modelled yields agree almost exactly for ryegrass. The model underestimates clover production at the January harvest date (day number 55) for both P-0 and P-40 (Fig 8.1). This may be attributable to clover being in a reproductive phase and therefore growing at a faster rate than the model predicts.

The predicted cumulative productions for ryegrass and clover for irrigation frequency I-40 is compared with measured cumulative yields in Fig. 8.2. In general, predicted values are in agreement with measured values throughout the season. There is no

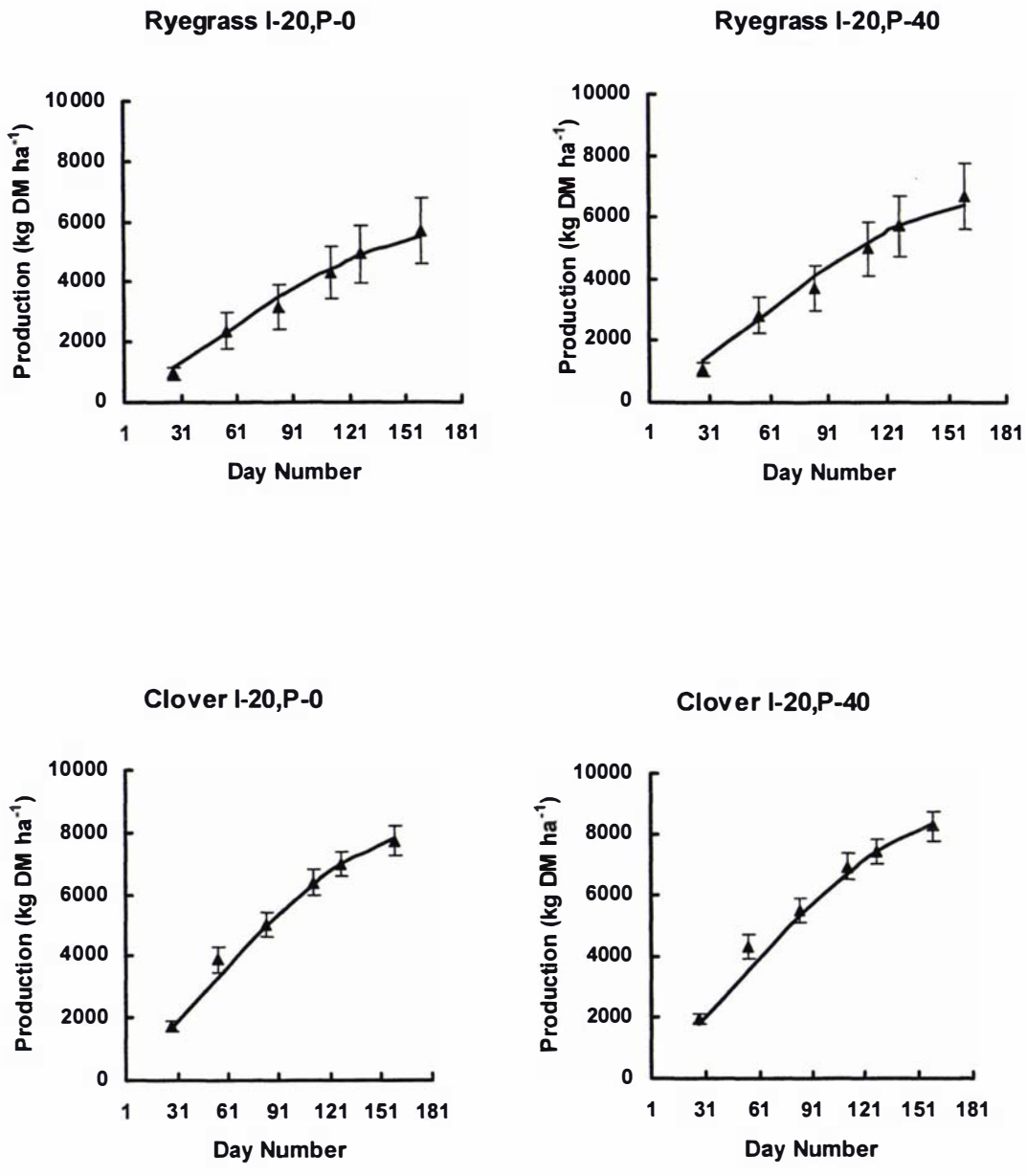


Figure 8.1 Cumulative predicted (–) and measured pasture production (▲) during the summer irrigation season (23 November 2000–30 April 2001) for irrigation frequency I-20. Error bars indicate ± one standard deviation.

substantial difference between the productions predicted using unique k_2 values for P-0 and P-40, and the mean k_2 value (Table 8.2). This is true for both ryegrass and clover (Fig. 8.2). Again, as for the I-20 case, there is a discrepancy between predicted and measured clover yields in January. The predicted cumulative production for I-60 is compared with measured cumulative yield in Fig. 8.3. In general, predicted values are within plus or minus one standard deviation for ryegrass irrespective of P fertility for the whole irrigation season. Again there was little difference between predictions of production made using mean k_2 and k_3 values and those made using individual k_2 and k_3 values for P-0 and P-40. Production of ryegrass was overestimated at the February harvest (day number 84), but this over-estimation did not exceed one standard deviation from the mean. Also there was again a discrepancy between the predicted and measured clover production at the January harvest (day number 55).

There was reasonable agreement between predicted and measured ryegrass and white clover production on non-irrigated, non-P fertilised plots (graphs not presented).

Although the model is constrained to accurately predict the final cumulative yield, the very close agreement between predicted and measured production throughout the season is cause for some confidence in the model, including the derived k values.

8.3. PREDICTION OF LONG TERM YIELD VARIATION, IRRIGATION WATER REQUIREMENTS, AND DRAINAGE

In order to quantify the effects of irrigation frequency for a range of climate scenarios, the model developed above along with the water balance model developed in Chapter 5 was used to simulate pasture production for the irrigation seasons (i.e. from 1 November to 30 April) of the past 26 years using historical weather data (DSIR Palmerston North).

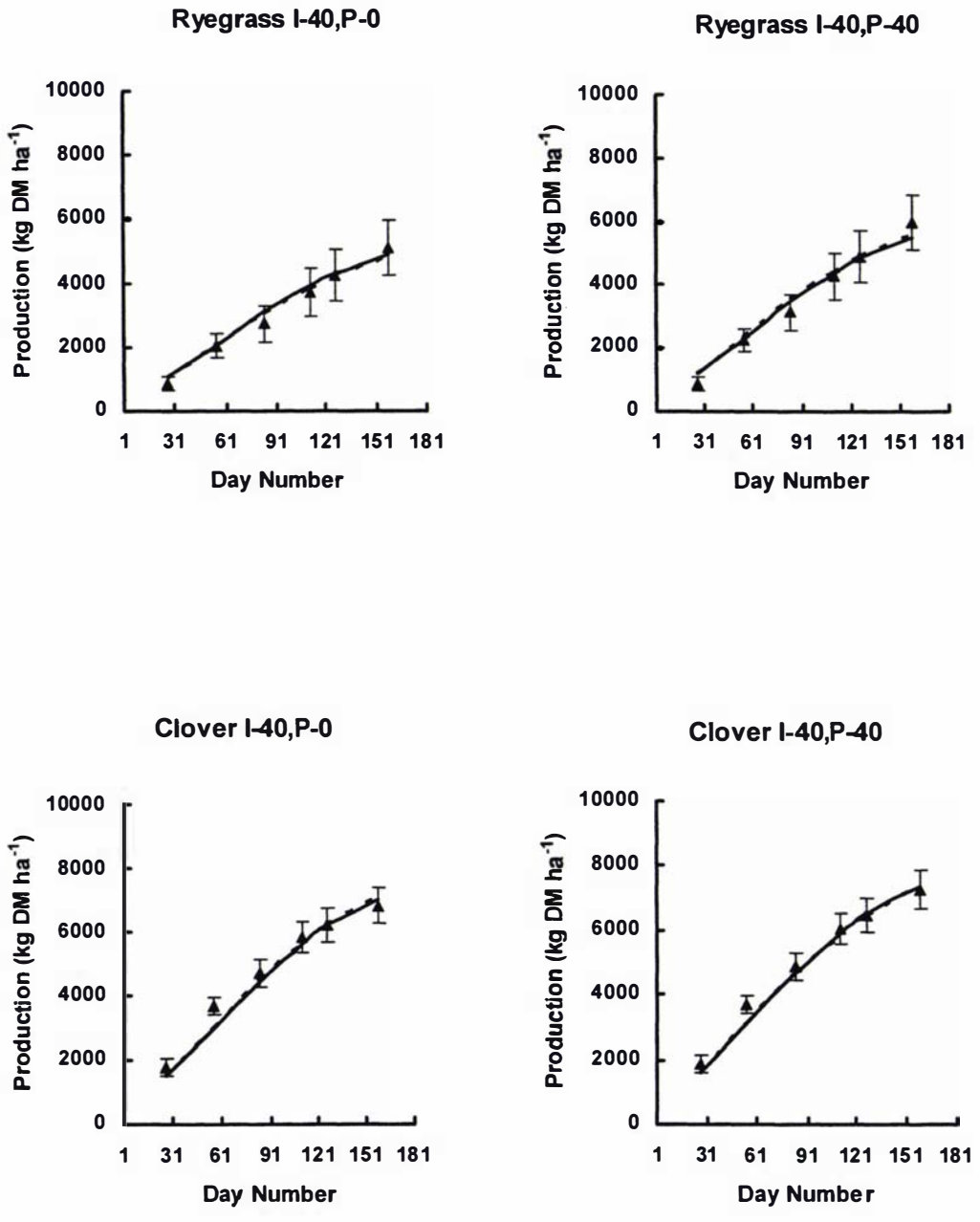


Figure 8.2 Cumulative predicted mean k_2 (—), P dependant k_2 (---) and measured pasture production (▲) during the summer irrigation season (23 November 2000–30 April 2001) for irrigation frequency I-40. Error bars indicate ± one standard deviation.

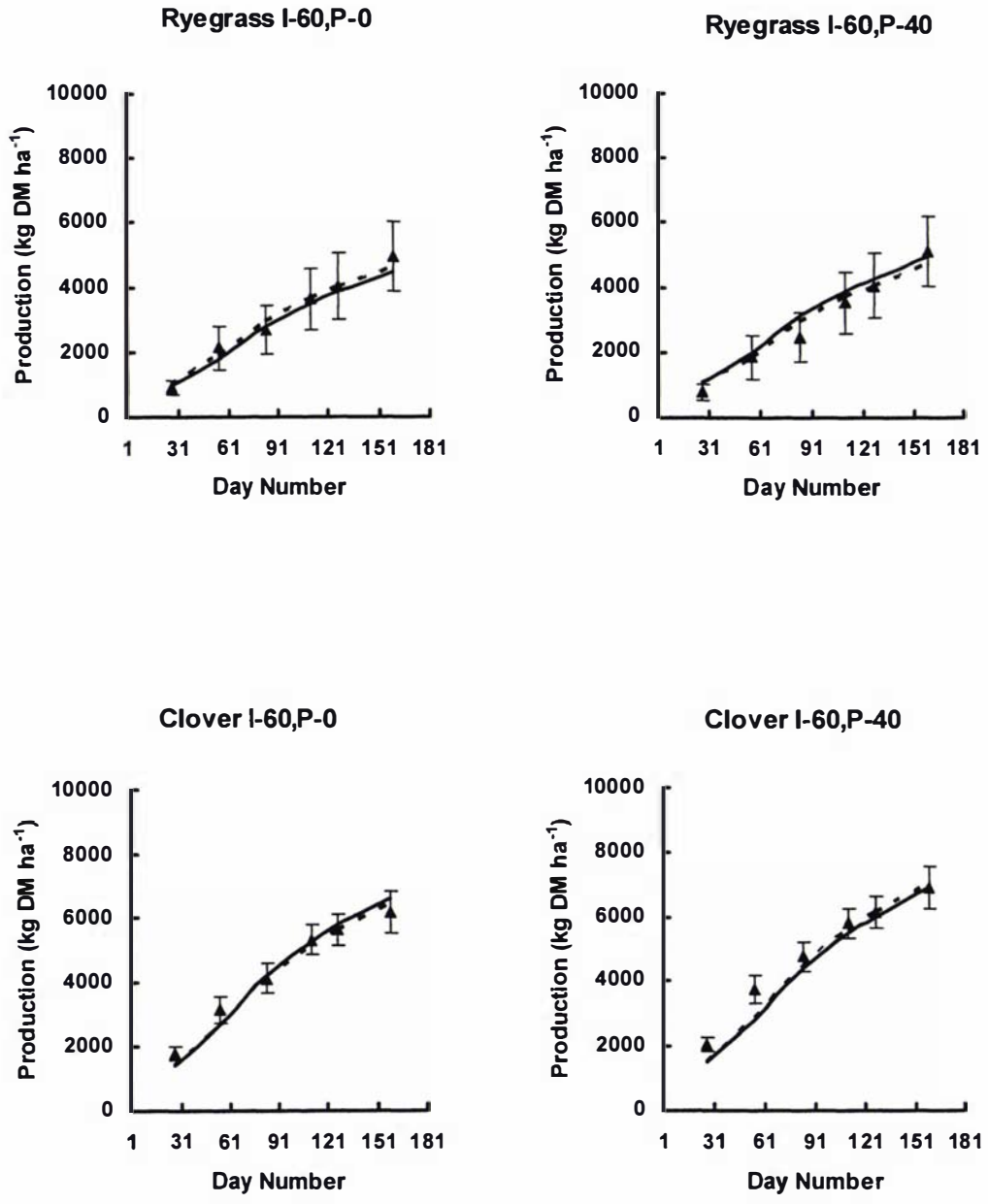


Figure 8.3 Cumulative predicted mean k_2, k_3 (—), P dependant k_2, k_3 (---) and measured pasture production (▲) during the summer irrigation season (23 November 2000–30 April 2001) for irrigation frequency I-60. Error bars indicate ± one standard deviation.

The irrigation frequencies I-20, I-40 and I-60 will be studied. As stated above these are representative of the range of pastoral irrigation practices. However, the actual details of scheduling on farms may be quite different (e.g. delaying of irrigation in anticipation of rainfall) and so the results presented below should be applied with some caution.

The model predicts the production of ryegrass and clover independently. Seasonal pasture production is estimated by combining these simulations. Two ryegrass:white clover compositions are considered: 70:30 and 85:15. These two ratios were selected on the grounds that they are typical of the range of ryegrass to clover mixes found on New Zealand dairy farms. McAneney *et al.* (1982) reported that the botanical composition changed seasonally from approximately 70 - 80% ryegrass and 5 - 10 % white clover in mid winter to 30 - 50 % ryegrass and 30 - 50 % white clover for an irrigated sward in mid summer in the Waikato region. Likewise, Harris *et al.* (1997) claims that the current clover content of pasture is 10 - 20% on average.

Any potential synergistic or antagonistic interactions between ryegrass and clover growing together in the same sward were not considered here.

Seasonal pasture production was plotted as cumulative probability distributions. Pasture production, irrigation requirements, or drainage quantities from the 26 year simulation were sorted in ascending order and plotted assuming each year's value to have an occurrence probability of 1/26.

8.4. RESULTS AND DISCUSSION

8.4.1. Pasture yield

The cumulative probability distribution for simulated pasture production for the summer-autumn irrigation season for the ryegrass:clover ratio of 0.7:0.3 is shown in

Fig. 8.4. The y-axis value is the probability that pasture production will be less than the corresponding x-axis value. Thus one minus the y-axis value is the probability of the production being greater than the x-axis value.

Relative to non-irrigated pasture, significantly greater pasture production was predicted under all of the irrigation-P fertility combinations. The year-to-year variability in production was narrowed to 5 - 6 % CV by all of the irrigation frequencies. The expected pasture production for each treatment combination at 50% probability is given in Table 8.3. The pasture production increases associated with irrigation and P fertiliser application given in this Table have been calculated for each treatment combination with reference to the I-60, P-0 case. The mean pasture productions under irrigation ranged from 5898 to 7893 kg DM ha^{-1} compared with mean yields of 4396 (P-0) and 4725 (P-40) kg DM ha^{-1} for non-irrigated pasture.

For the farmer contemplating the adoption of irrigation, the purchase of a system that allows more frequent irrigation is as significant a consideration as the decision to adopt irrigation itself. Increasing irrigation frequency substantially increased pasture production. Relative to the non-irrigated, P-40 production, application of I-60 (at P-40) increased production by 36% (1695 kg DM ha^{-1}), while increasing frequency to I-20 increased production by a further 31% (of the non-irrigated value).

For a farmer already enjoying the benefits of less frequent irrigation, there are substantial production increases to be realised by altering scheduling criteria in order to increase irrigation frequency. Increasing irrigation frequency form I-60 to I-20 increased pasture production, on average, by 1473 kg DM ha^{-1} (i.e. 23%) and 1105 kg DM ha^{-1} (i.e. 19%) for the P-40 and P-0 situations, respectively.

These estimated pasture responses to irrigation are comparable with those predicted for Canterbury and Manawatu by Kerr *et al.* (1986).

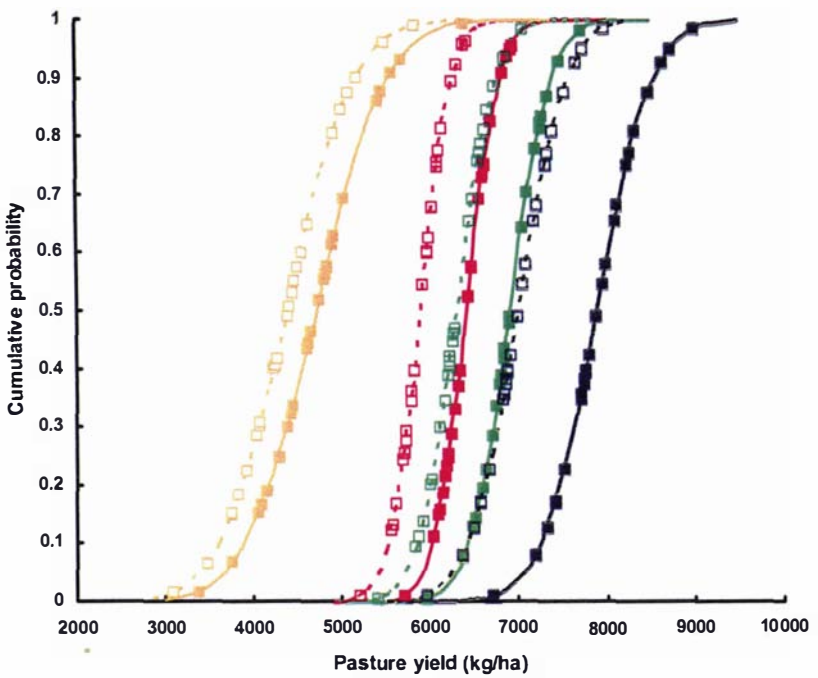


Figure 8.4 The cumulative probability distribution of pasture yield for the ryegrass:clover ratio of 0.7:0.3 in the sward under different irrigation and P fertility regimes. The colours; blue, green, red and yellow represent irrigation frequencies; I-20, I-40, I-60, and non-irrigated conditions, respectively. Dashed and solid lines represent P-0 and P-40 plots, respectively.

If 40 kg P ha^{-1} was applied to a sward with a ryegrass:clover ratio of 0.7:0.3 on I-20 irrigated soil with an Olsen P value of approximately 10 in the surface 150 mm, an additional 890 kg DM (i.e. 13%) would be produced on average. However, the predicted yield improvement following application of 40 kg of P ha^{-1} decreases with a decrease in irrigation frequency: on average, an extra 610 kg DM ha^{-1} (i.e. 10%) and

522 kg DM ha^{-1} (i.e. 9%) is produced for the irrigation season at irrigation frequencies of I-40 and I-60, respectively (Table 8.3).

Table 8.3 Summary of mean predicted seasonal pasture production (kg DM ha^{-1}) for the last 26 years for ryegrass:clover ratio of 0.7:0.3 in the sward. Irrigation season is 1 November to 30 April of following year.

Treatment	Pasture production		Pasture production range	
	Mean	Increase %	Minimum	Maximum
I-20 P-0	7003	19	5953	7995
I-20 P-40	7893	34	6710	9012
I-40 P-0	6318	7	5442	7093
I-40 P-40	6928	17	5989	7739
I-60 P-0	5898	0	5219	6438
I-60 P-40	6420	9	5721	6948
Non irrigated P-0	4396	NA	3091	5847
Non irrigated P-40	4725	NA	3377	6408

LSD =188 kg ha^{-1} for means at P <0.05, NA= not applicable.

The cumulative probability distribution for simulated pasture production for the summer/autumn irrigation season for a ryegrass:clover ratio of 0.85:0.15 is shown in Fig. 8.5 and mean seasonal production is given in Table 8.4. In general, these cumulative probability distribution patterns are very similar to those generated for a ryegrass:clover ratio of 0.7:0.3. There is a systematic reduction in pasture production of 300 to 600 kg ha^{-1} (on average) for the ryegrass:clover ratio of 0.85:0.15 relative to ryegrass:clover ratio of 0.7:0.3. This may be attributed to the smaller clover contribution to production in the to ryegrass:clover ratio of 0.85:0.15.

Again, increasing irrigation frequency substantially increased pasture production. Increasing irrigation frequency from I-60 to I-20 increased pasture production, on

average, by 1472 kg DM ha^{-1} (i.e. 24%) and 1078 kg DM ha^{-1} (i.e. 19%) for the P-40 and P-0 situations, respectively. In summary, important further production gains are realised under irrigation by increasing the frequency of application: application of I-60 irrigation at P-40 increased production by 36%, increasing frequency to I-20 increased production by a further 33% (of the non-irrigated production).

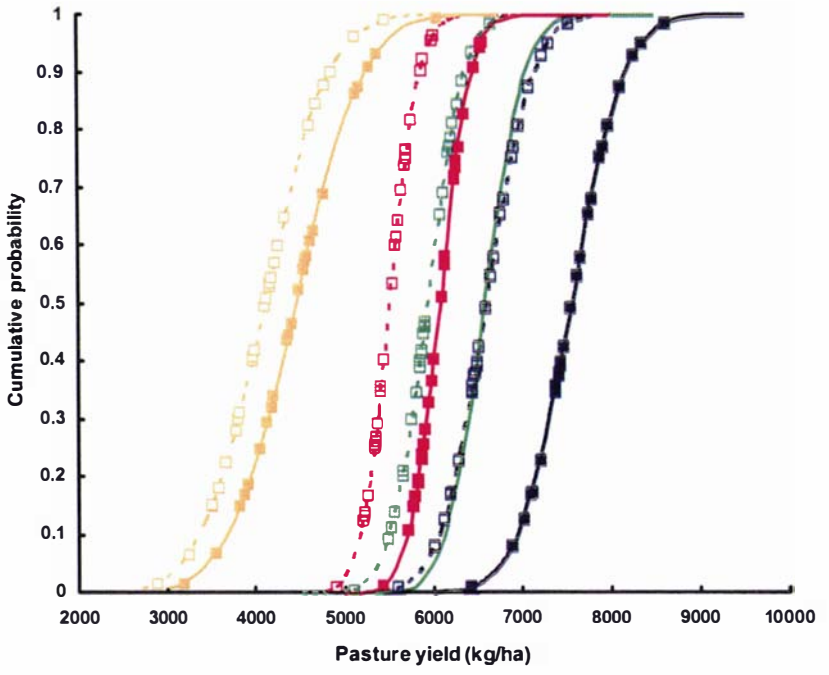


Figure 8.5 The cumulative probability distribution of pasture yield for the ryegrass clover ratio of 0.85:0.15 in the sward under different treatments. The colours; blue, green, red and yellow represent irrigation frequencies; I-20, I-40, I-60, and non-irrigated conditions, respectively. Dashed and solid lines represent non-P fertilised and P fertilised plots, respectively.

If 40 kg P ha^{-1} was applied to a sward with an 85% ryegrass, 15% clover mix on I-20 irrigated soil with an Olsen P value of approximately 10 in the surface 150 mm, an additional 953 kg DM (i.e. 14%) would be produced on average. However, the

predicted yield improvement following application of 40 kg of P ha^{-1} decreases with a decrease in irrigation frequency: on average, an extra 652 kg DM ha^{-1} (i.e. 11%) and 522 kg DM ha^{-1} (i.e. 10%) is produced for the irrigation season at irrigation frequencies of I-40 and I-60, respectively. The greater response to P fertiliser by a sward with a ryegrass:clover ratio of 0.7:0.3 than for a 0.85:0.15 ratio can be accounted by reference to the relative difference in *k* values for P-0 and P-40 for ryegrass and clover (Table 8.1)

Table 8.4 Summary of mean predicted seasonal pasture production (kg DM ha^{-1}) over last 26 years for ryegrass:clover ratio of 0.85:0.15 in the sward. Irrigation season is 1 November to 30 April of following year.

Treatment	Pasture production		Pasture production range	
	Mean	Increase %	Minimum	Maximum
I-20 P-0	6608	16	5618	7543
I-20 P-40	7561	37	6428	8633
I-40 P-0	5955	8	5130	6684
I-40 P-40	6607	19	5716	7376
I-60 P-0	5530	0	4904	6026
I-60 P-40	6089	10	5442	6582
Non irrigated P-0	4113	NA	2890	5479
Non irrigated P-40	4462	NA	3189	6064

LSD =170 kg ha^{-1} for means at P <0.05, NA= not applicable.

8.4.2. Irrigation water requirements

The annual irrigation requirement depends on the weather patterns i.e. rainfall and cumulative *E*. The probability distributions of seasonal total rainfall, seasonal *Ew* and *E* for the non-irrigated scenario (lower boundary of -120 mm soil water deficit) are shown in Fig. 8.6. The variability of total rainfall (CV = 19 %) is greater than the variability of E_w (CV = 6 %) for the season. The variability of total *E* for the non-irrigated scenario is a function of E_w, rainfall, and the site specific lower boundary of soil water storage, and

therefore it has intermediate variability (CV = 13%). The difference between E_w and E is greatest in the driest year.

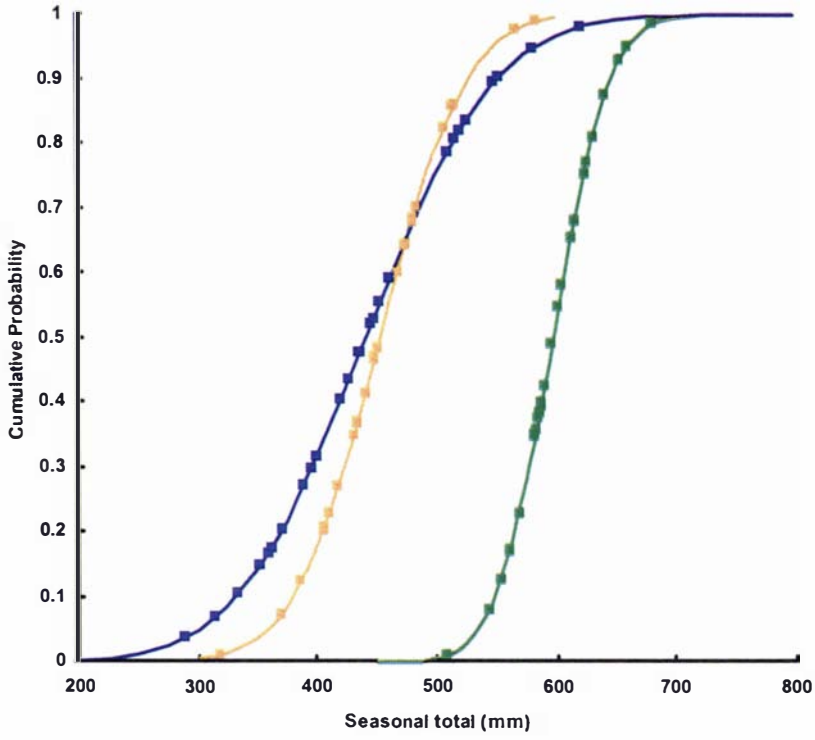


Figure 8.6 The cumulative probability distribution of seasonal rainfall and evaporation. The colours; blue, green and yellow colours represent rainfall, potential evaporation, and actual evaporation under non-irrigated conditions, respectively, for the summer irrigation season (1 November to 30 April 30).

The seasonal quantity of irrigation needed under the different irrigation frequencies is one of the model's outputs. The cumulative probability distribution of irrigation requirements for each irrigation frequency is shown in Fig. 8.7. The number of applications varied substantially from year to year. For I-20, the quantity of irrigation required varied from 220 mm for an extremely wet year to 440 mm for an extremely dry year (i.e. a range of 10 to 22 applications). For irrigation frequencies I-40 and I-60, the quantities of irrigation varied from 160 mm to 440 mm (4 to 11 applications) and from

120 mm to 420 mm (2 to 7 applications), respectively. The most common seasonal irrigation requirements were 320 mm, 320 mm, and 300mm, for irrigation frequencies I-20, I-40, and I-60, respectively. The similarity in irrigation water requirements for the three frequencies in average and drier years is noteworthy. The values for irrigation water requirements reported here are similar to those predicted by Scotter *et al.* (2000) using 1000 years of 'synthetic' weather data for the Manawatu region with small differences between the two studies being attributable to the differences in scheduling criteria.

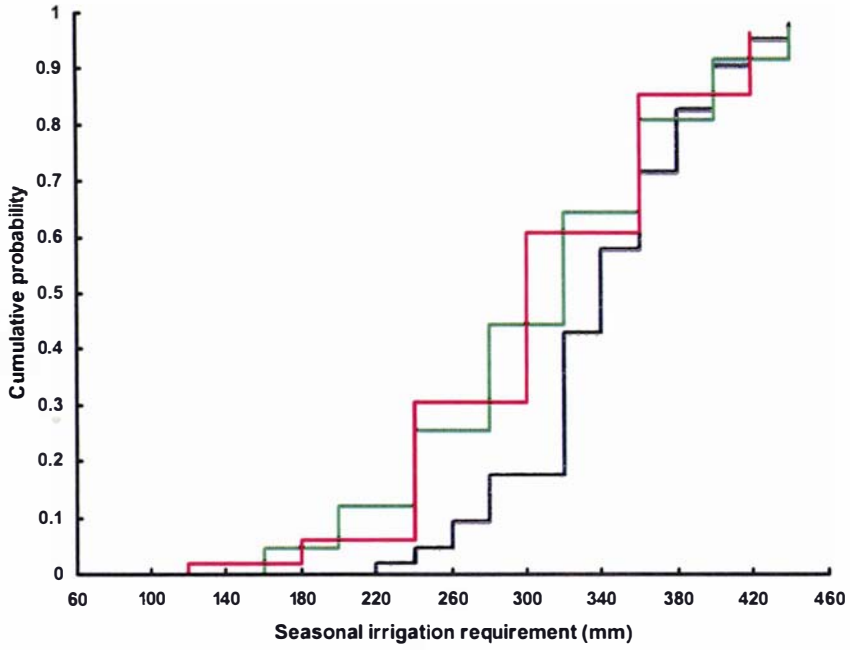


Figure 8.7 Cumulative probability distribution of total seasonal irrigation requirement for each irrigation frequency. The colours; blue, green, and red represent irrigation frequencies I-20, I-40, and I-60, respectively.

According to Ritchie (1994), some of the information generated in simulation exercises for irrigation in a humid region can be useful to consideration of policy issues related to irrigation. For example, the model indicates that pastoral farmers who request a water

permit for irrigation in the Manawatu region should apply for 420 to 440 mm yr^{-1} (4200 - 4400 m^3 ha^{-1} yr^{-1}) if they are to have sufficient water for the driest of summers. Conversely, if the Regional Council wanted to distribute scarce water most equitably amongst farmers, and other users, they might consider limiting water permits to an 'average' quantity i.e. approximately 300 to 320 mm which would allow adequate irrigation in half the number of years.

8.4.3. Deep drainage losses

The cumulative deep drainage losses beyond the root zone (taken as 450 mm deep) for the irrigation season are shown in Fig. 8.8. Relative to the non-irrigated case, I-40 and I-60 increase drainage by about 95 mm on average. I-20 irrigation, typically, increases drainage losses by a further 40 mm (compared to I-60 irrigation). Drainage is more likely under I-20 irrigation than I-60 because the soil water deficits will be, on average, smaller under I-20. Drainage losses under I-60 and I-40 are very similar in drier years. These deep drainage events indicate the potential for leaching losses of solutes such as nitrate-N from the root zone.

Some farmers are currently applying irrigation at 10 mm deficit or smaller. Drainage for this scenario was estimated. Under this irrigation frequency there would be 220 mm of drainage on average. The environmental consequences of this require further consideration.

It was argued above that water use efficiency was greatest under I-20 as this was where E in the 0-20 mm deficit range, with the greatest k value, was maximised. The drainage losses predicted here provide something of a corrective to this view. This is to say that there is a certain tension between the ability of I-20 to produce more pasture while encouraging greater drainage. A more detailed consideration of the overall irrigation

efficiency which would quantify the relative importance of these two attributes (water used for production verse water that drains) for the three irrigation systems was beyond the scope of this study.

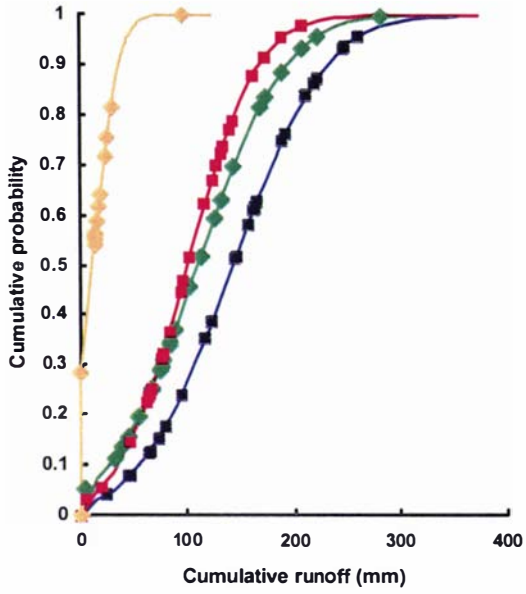


Figure 8.8 Cumulative probability distribution of drainage from the root zone for the summer irrigation season (1 November to 30 April 30). The colours; blue, green, red and yellow represents irrigation frequency I-20, I-40, I-60, and non-irrigated conditions, respectively.

8.5. CONCLUSIONS

The performance of the irrigation and fertiliser strategy found in the field trial (Chapter 4) was able to be extrapolated for other years by running the model for ryegrass: clover ratios of either 0.70:0.30 or 0.85:0.15.

The simulation predicted a wide range of pasture production values depending on the; weather patterns, irrigation frequency, nutrient status and reyegrass:clover ratio.

Increasing irrigation frequency substantially increased pasture production. For a ryegrass:clover ratio of 0.70:0.30, increasing irrigation frequency form I-60 to I-20 increased pasture production, on average, by 1473 kg DM ha^{-1} (i.e. 23%) and 1105 kg DM ha^{-1} (i.e. 19%) for the P-40 and P-0 situations, respectively.

For the farmer contemplating the adoption of irrigation, the purchase of a system that allows more frequent irrigation is as significant a consideration as the decision to adopt irrigation itself. For a farmer with an existing irrigation system that lends itself to an increase in irrigation frequency, there are significant pasture production gains to be made from more frequent irrigation.

For a ryegrass:clover ratio of 0.70:0.30, applying P fertiliser (40 kg P ha^{-1}) to I-20 irrigated soil with an Olsen P value of approximately 10 in the surface 150 mm, produced an additional 890 kg DM (i.e. 13%) on average. However, the predicted yield improvement following application of 40 kg of P ha^{-1} decreased with a decrease in irrigation frequency.

There is a systematic reduction in pasture production of 300 to 600 kg ha^{-1} (on average) for the ryegrass:clover ratio of 0.85:0.15 relative to ryegrass:clover ratio of 0.70:0.30.

The most common quantities of irrigation water required were 320 mm, 320 mm, and 300 mm for irrigation frequencies I-20, I-40, and I-60, respectively. Most frequent irrigation typically increases drainage losses by about 40 mm compared to less frequent irrigation.

The simulation results generate valuable information which could be of potential use to both farmers contemplating irrigation or a change in irrigation management, and policy analysts grappling with water use issues.

CHAPTER 9

SUMMARY AND SUGGESTIONS FOR FUTURE RESEARCH

9.1. SUMMARY

It has been suggested by the manufacturers of irrigation equipment, some farmers and a few scientists that more frequent irrigation enhances pasture production. There is a trend amongst pastoral farmers purchasing irrigation hardware to favour irrigation systems that afford greater flexibility in scheduling, in particular those that allow for more frequent irrigation. However, there is limited research into the quantity of the benefits of more frequent irrigation or the mechanisms responsible for any such increase in pasture production. Most of the literature on irrigation of pasture is of limited use in this changing view of irrigation management. In most irrigation studies conducted to date, irrigation was scheduled so as to recharge the whole root zone when all the readily available water had been depleted. In these studies, if irrigation frequency was a variable, there was little attention given to the consequences of increasing irrigation frequency within the readily available water range.

The overall objective of this Thesis was to investigate the combined effect of increased irrigation frequency and P fertiliser application on pasture production during the summer season in New Zealand. The key hypothesis that underwent testing and modification was that more frequent irrigation (in the readily available water range) would increase pasture production because it would enhance water uptake from the surface soil where there are more plant roots and greater quantities of nutrients.

Initially, a large scale pot experiment was conducted to investigate the response to irrigation frequency (within the readily available water range) where the key variables of water, fertiliser, and roots were as uniformly distributed throughout the soil or as homogenous as possible. In this experiment, fertiliser addition (three rates of N, P, K and S) to pots of Ramiha silt loam had a significant and consistent effect on a number of indicators of ryegrass and white clover performance including total yield. In contrast, the range of irrigation frequencies adopted here did not significantly or consistently affect indicators of ryegrass and white clover performance. In this pot study, where nutrients and plants roots were uniformly distributed through the soil, more frequent watering was not significantly advantageous to plant growth. This suggests that as far as ryegrass and white clover yield is concerned, there is no distinction between increments of readily available water.

On the basis of the significant effect of fertiliser application on pasture production in the pot trial, it was hypothesised that, in the field, irrigation frequency would affect pasture yield. Increased pasture production was anticipated under more frequent irrigation as it would keep the surface soil moist and maximise water uptake from this zone of greatest fertility. In contrast, production of less frequently irrigated pasture is expected to be reduced because plants would often be extracting water from depths (the bottom of the root zone) where soil nutrients are often scarce. To test this hypothesis, a large scale field experiment was conducted with three different irrigation regimes within the readily available soil water range (60 mm); irrigation at 20 mm deficit (I-20), irrigation at 40 mm deficit (I-40), and irrigation at 60 mm deficit (I-60). For simplicity, in the field Olsen P and P fertiliser application were used as surrogate indicators of nutrient status. Two P treatments were combined with irrigation treatments; no P fertiliser, and application of the recommended quantity of P fertiliser (40 kg ha^{-1}) for the site (Manawatu fine sandy loam soil). As for the pot trial above, species were introduced as another treatment as ryegrass and white clover have different root systems and responses to P fertiliser.

Irrigation of ryegrass and white clover at 20 mm (33%) depletion of readily available water, I-20, over the summer period resulted in maximum seasonal pasture production (6185 kg DM ha^{-1} and 7995 kg DM ha^{-1} for ryegrass and white clover, respectively) and the water use per unit pasture production (15 and 20 kg DM ha^{-1} mm^{-1} for ryegrass and white clover, respectively) for irrigated pasture (proportionality constant *k* value). Least frequent irrigation i.e. applications of 60 mm of water at the total depletion of readily available water, I-60, resulted in substantial yield loss and reduction in water use efficiency. Application of the recommended quantity of P fertiliser significantly enhanced total pasture production and hence water use efficiency.

It is difficult to accurately quantify the responses of ryegrass and white clover root systems to changes in soil management. Measurement of root growth into refilled cores was found to be an effective technique for comparing root growth response of ryegrass and white clover to different irrigation frequencies and fertiliser levels. However, this technique works best at depths up to 200 mm. While a technique that would have facilitated the monitoring of root activity over the entire root depth (assumed to be 450 mm) would have been preferable, the data obtained using the re-filled core procedure is very suggestive and lends important support to the thesis developed above.

Root activity of both ryegrass and white clover was significantly greater in shallow soil, and it declined markedly with depth. The root growth of ryegrass was always greater than white clover during the irrigation season. At all three root harvests, the application of 40 kg P significantly improved the root growth of both species. The effect of irrigation on root growth emerged towards the end of the summer irrigation season. Root growth stimulation due to water stress and P shortage (i.e. less frequently irrigated plots) was observed at the April root harvest. It is suggested that frequent irrigation is beneficial because a moist surface soil means that plants need to produce fewer roots, resulting in the allocation of more resources to shoot growth.

It is often claimed that irrigation impacts adversely on water quality. This claim was investigated at the experimental site using suction cup samplers. Nitrate-N concentrations in soil water under irrigated swards of white clover were large in early winter drainage events: this was the case irrespective of irrigation frequency. This resulted in relatively large leaching losses of N under white clover. Nitrate-N concentrations in soil water were not as great under irrigated ryegrass swards. Nitrate-N leaching losses as a percentage of the N applied as fertiliser to the ryegrass plots were small (2-12%).

Estimated total nitrate-N losses until 31 July 2001 indicated that irrigation frequency of ryegrass during the previous summer did not have a major effect on the overall nitrate-N leaching pattern during the late autumn/early winter period following the irrigation season. In comparison, there was some indication that nitrate-N losses under clover were less under less frequent irrigation.

A simple water balance model was developed and used successfully to simulate volumetric soil water contents for the field experimental site under three different irrigation regimes. The values generated using the model agreed reasonably well with field soil water contents measured using a TDR moisture meter. The field data and the model highlighted differences in soil water contents between the irrigation regimes. The model was constructed to simulate changes in soil water content over three deficit ranges that emerge from, or are related to, the irrigation treatments i.e. 0 to 20 mm, 20 to 40 mm and 40 to 60 mm. In turn, soil water retentivity analysis suggests that these deficits correspond to water removal from soil depths; 0 - 150 mm, 150-300 mm and 300-450 mm, respectively. Therefore, the soil water balance model was further developed to predict pasture production and study the effect of irrigation management on pasture yield.

A simple model was developed to predict pasture production under irrigation. The simulation suggests that the findings of the field trial are representative. In other words, pasture production under irrigation varies markedly with irrigation frequency, P fertility status and the ryegrass:clover ratio of the sward. Increasing irrigation frequency from I-60 to I-20 to a sward with a ryegrass:clover ratio of 0.70:0.30 increased pasture production, on average, by 1473 kg DM ha^{-1} (i.e. 23%) and 1105 kg DM ha^{-1} (i.e. 19%) for the P-0 and P-40 situations, respectively. The simulations illustrate the significant production increases that can be realised by improved management of irrigation frequency, nutrient status and species ratio.

The model also produces information that is useful to considerations of sustainable resource management. The model predicts that on average 320 mm, 320 mm, and 300 mm of irrigation water was required for frequencies I-20, I-40, and I-60, respectively. High frequency irrigation (I-20) typically increases drainage losses by about 40 mm compared to lower frequency irrigation (I-60).

9.2. SUGGESTIONS FOR FUTURE RESEARCH

Field experimentation on the effects of irrigation frequency on pasture production at a number of other locations with different climate regimes and soil types would be interesting. In particular, future studies might like to incorporate a wider range of P fertility treatments, and study the effect of the uptake of other nutrients on the responsiveness of pasture production to irrigation frequency. The response of pasture production to irrigation frequency on a soil with horizons of contrasting texture would be an interesting comparison with the results reported above for the Manawatu fine sandy loam with its relatively uniform profile.

One obvious research initiative would be to study irrigation frequencies greater than those used here: indeed some farmers are already irrigating at deficits of 5 and 10 mm. The argument developed above might be extended to say that if there were advantages to keeping the surface 150 mm moist then there would be additional benefits in preventing shallower depths, where the nutrients and plant roots are more concentrated, from drying. Indeed, the values presented above showing the concentration of P and roots in soil depth shallower than 150 mm would be impetus to such research.

There were intimations in the results presented above that while the response of white clover to irrigation was greater than for ryegrass it was sometimes less consistent. A more nuanced understanding of the water use efficiency pattern of white clover during summer is required. It might also be argued that there was some indication that under very frequent irrigation there may be the risk that the surface soil will be too moist for optimum white clover growth.

The production data generated in the model could be used for full economic analyses of the benefits of a number of irrigation frequencies and fertiliser application.

The extension of experimental research of irrigation frequency to other sites could be accompanied by an extension of the model. Perhaps there are existing pasture production data sets that could provide the opportunity to trial the model for other soils, fertility status, and climates.

One of the acknowledged weaknesses of the model developed above was the imprecision associated with the derivation of some of the k values, in particular those related to uptake of readily available water from depth (k_3) and the extraction of water between stress point and permanent wilt point (k_4). Improved experimental procedures for more accurately determining these k values warrant attention

A 'user friendly' version of the model could be developed to help farmers who currently irrigate to explore the ramifications of changing irrigation frequency and fertiliser application rates. Such a model would also allow farmers contemplating the adoption of irrigation to calculate the range of responses in pasture production and provide supportive information for their application for resource consent.

Another potential issue associated with frequent irrigation is the long term consequences for soil structure. Treading is commonplace on many pastoral farms, and maximum compaction under the hoof of the grazing animal occurs at soil water contents at and slightly drier than field capacity. By maintaining surface soil in a moist condition, more frequent irrigation may result in deterioration in soil structure. The increased stocking rates that often accompany irrigation will exacerbate this degradation.

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APPENDICES

Appendix 3.1 Determination of fertiliser application rates for pot experiment using equilibrium phosphorus isotherm

A3.1.1 General

Phosphorus (P) is one of the most important elements in plant metabolism and consumption. The effect of P on plant growth is through many aspects of its function in the plant metabolism and as a structural element. Phosphorus fertiliser is usually taken up as $H_2PO_4^-$ by plants, and then it either remains as inorganic P or is esterfied. Phosphorus concentration of a plant is related to application regime (Wang, 1991). Usually, low concentration and low solubility of P in soils make it commonly the key growth-limiting nutrient in soils and waters. The use of N fertilisers to boost yields has meant that even on very fertile soils, yields are often P limited. Adequate P fertilization requires large amounts of P because more than 80% of the P fertilisers may be strongly absorbed or precipitated by the soil and not be immediately available to the crop (Hedley *et al.* 1995). The possibility of using P sorption characteristics and critical soil solution P concentrations to estimate initial P requirements has been widely reviewed (Hedley *et al.* 1995). Therefore, this preliminary experiment was carried out to find P sorption isotherm for Ramiha silt loam (*Andic haplumbrept*) prior to selecting P application rates to pots.

A3.1.2 Procedure

Topsoil (0 - 150 mm depth) collected from mid slope of Tuapaka farm was used for this analysis. The soils were air-dried and material passing through a 2mm sieve was used

for all analyses. Sorption of inorganic phosphorus (P) was evaluated as follows. Samples of one-gram of soil were put into a series of 40 ml polypropylene tubes and KH_2PO_4 solution was added to generate 0, 50, 100, 200, 400, 1000, 1500, 2000 and 2500 μg P added per 1 g of soil. Then each tube was filled to 30 ml volume support medium by adding distilled water. These polypropylene tubes were shaken overnight at room temperature. After shaking, the suspensions were centrifuged at 9000 rpm at 23° C for 5 minutes and the supernatant solutions were passed through a 0.45 μm Millipore filter. An aliquot was taken for the determination of dissolved inorganic P. The method of Murphy and Riley (1962) was used for the determination of P in all extracts and absorbency was measured at 712 nm using PU8620, Philips UV/Visible spectrophotometer. The amount of P sorbed was calculated as the difference between P added and P in solution after shaking.

Then 25 ml of 0.01M $CaCl_2$ was added to each residual soil sample and shaken for one hour and poured out following centrifuging for one minute. This process was repeated. Olsen P content of the washed soil sample was determined by adding 20 ml of 0.5M $NaHCO_3$ solution (adjusted to a pH of 8.5) to each sample and shaken for 30 minutes. Then supernatant solution was filtered following 1 minute of centrifuging at 9000 rpm. An aliquot was taken for colour development and measurement of P were made with the PU8620, Philips UV/Visible spectrophotometer.

On the trend of the P isotherm obtained for above wide range of added P levels, the same procedure was repeated to find the final P isotherm for the lower range of final P

solutions. The P addition levels of 0, 25, 50, 100, 200, 300, 400 and 500 μg P g^{-1} of soil were used for a second set of samples.

A3.1.3 Selection of fertiliser rates

The best-fit equation for logarithmic relationship is Y=130.49 ln (x)+480.06 with r^2 of 0.9678 for final equilibrium P in solution over a final P concentration of range of 0 - 0.8 μgml^{-1} versus added P sorbed onto one gram of soil (μg g^{-1} of soil) (Fig. 1). The curve resembles the isotherms obtained for some other New Zealand soils (Ryden and Syers 1975). Olsen P values of soil samples following the attainment of equilibrium with the solution are shown in Fig. 2. The relationship is exponential ($Y=0.0114e^{0.0364x}$ with r^2 of 0.9842) for Olsen P values of soil samples following the attainment of equilibrium with the supernatant solution (Fig. 2). The final equilibrium P content in the supernatant solution increased exponentially beyond the level of 0.2 μg ml^{-1} (Fig.2). Correspondingly, P sorption isotherm also approached its plateau at solution P level of 0.2 μg ml^{-1}. Hedley et al. (1995) extensively reviewed the P isotherms for a number of major agricultural soils and found that most of them followed the exponential relationship and approached the plateau value at approximately 0.2 mg L^{-1} (0.2 μg ml^{-1}). Subsequently, the mean P requirement to attain solution P levels of 0.02 and 0.2 mg L^{-1} were worked out and estimated initial phosphate requirements to attain solution P levels to 0.02 and 0.2 mg L^{-1} (μgml^{-1}) are taken as medium and high P testing levels, respectively (Hedley *et al.*, 1995).

Therefore, a proposed maximum addition level (300 μg of P g soil^{-1} (300 mg kg^{-1})) seems to be justifiable. The medium rate of 50 μg of P g soil^{-1} was located at the beginning of the exponential trend of the isotherm. A low testing level of 5μg of P g soil^{-1} is proposed to avoid soil P deficiency in this experiment.

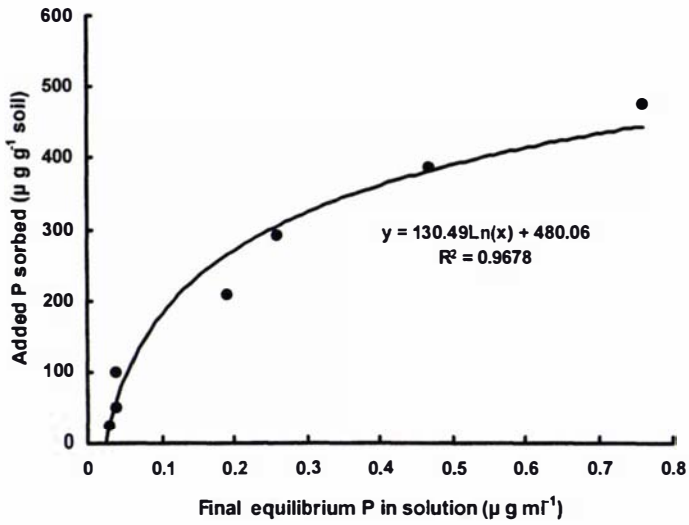

Figure A3.1 Phosphorus (P) isotherm for Ramiha silt loam soil (0 - 150mm).

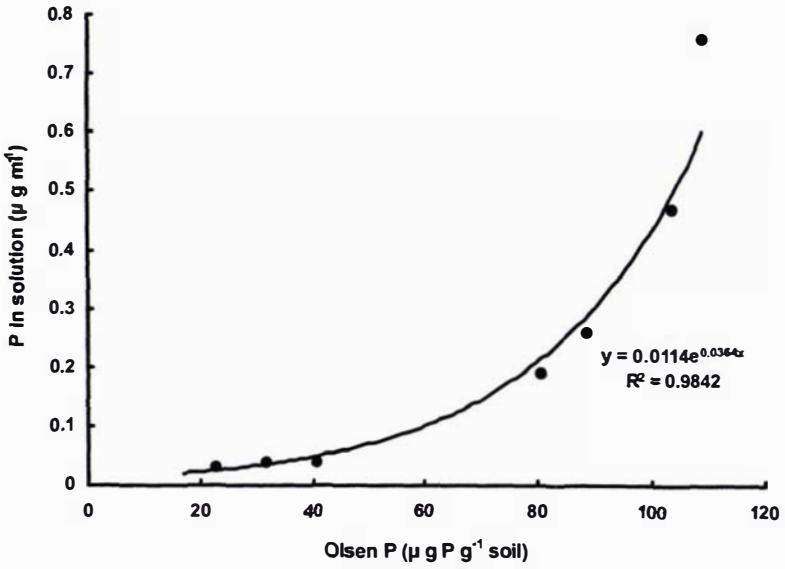

Figure A3.2 Soil Olsen P found following equilibrium.

Appendix 3.2 Mean values of production (g DM/pot) for each harvest date for ryegrass and clover.

Harvest dates	14/10/1999	30/10/1999	14/10/1999	14/11/1999	20/12/1999
Treatments					
Ryegrass					
I-15					
Low	1.12	1.8	1.13	1.19	2.04
Medium	4.48	3.77	1.77	1.68	2.57
High	4.73	5.39	3.38	3.28	4.17
I-30					
Low	1.33	1.98	1.03	0.7	1.03
Medium	2.71	3.43	1.76	1.73	1.8
High	4.16	4.06	2.84	3.06	3.43
I-45					
Low	1.22	1.87	1.02	0.80	1.26
Medium	2.74	2.61	1.19	1.26	1.85
High	3.97	4.31	2.68	2.52	5.49
Clover					
I-15					
Low	0.02	0.39	1.73	2.28	4.12
Medium	0.13	1.03	2.53	3.2	4.74
High	0.32	1.72	2.9	3.57	4.99
I-30					
Low	0.11	0.87	2	2.39	3.84
Medium	0.32	1.61	3.13	3.27	3.37
High	0.68	2.39	3.97	4.86	4.86
I-45					
Low	0	0.09	0.49	1.02	3.04
Medium	0.21	1.63	2.8	4.14	4.16
High	0.88	2.86	5.14	5.71	5.61

Each I-15, I-30, I-45 represents respective irrigation frequencies and Low, Medium and High represent respective fertiliser rates.

Appendix 4.1 Working water balance sheet up to 450 mm assumed root zone for the field trial site from December 2000 to April 2001.

December 2000 — Different items (in mm) of water balance for assumed root zone depth of 450 mm.

Date	I-20 (W_R)	S	D	I-40(W_R)	S	D	I-60(W_R)	S	D	E	P(local)	P(AGR)	Irrigation
1	49.8	-10.2		49.8	-10.2		49.8	-10.2		5.1			
2	45.4	-14.6		45.4	-14.6		45.4	-14.6		5.4			
3	60	0		60	0		60	0		0.7		16	
4	54.1	-5.9		54.1	-5.9		54.1	-5.9		5.9			
5	47.9	-12.1		47.9	-12.1		47.9	-12.1		6.2			
6	42.1	-17.9		42.1	-17.9		42.1	-17.9		5.8			
7	36.9	-23.1		36.9	-23.1		36.9	-23.1		5.2			
8	52.6	-7.4		32.6	-27.4		32.6	-27.4		4.3			I=20
9	48.5	-11.5		28.5	-31.5		28.5	-31.5		4.1			
10	51.2	-8.8		31.2	-28.8		31.2	-28.8		4.3	7	2.2	
11	60	0		41.1	-18.9		41.1	-18.9		2.6	12.5	8	
12	60	0	3.1	44.2	-15.8		44.2	-15.8		3.4	6.5	5.4	
13	53.9	-6.1		38.1	-21.9		38.1	-21.9		6.1			
14	51.4	-8.6		35.4	-24.6		35.4	-24.6		2.7			
15	49.2	-10.8		33.2	-26.8		33.2	-26.8		2.2			
16	44.2	-15.8		28.2	-31.8		28.2	-31.8		5			
17	59.1	-0.9		23.1	-36.9		23.1	-36.9		5.1			I=20
18	53.2	-6.8		57.2	-2.8		17.2	-42.8		5.9			I2=40
19	47.8	-12.2		51.8	-8.2		11.8	-48.2		5.4			harvested
20	42	-18		46	-14		6	-54		5.8			
21	37.7	-22.3		41.7	-18.3		1.7	-58.3		4.3			
22	53.2	-6.8		37.2	-22.8		-2.8	-62.8		4.5			I=20
23	51	-9		35	-25		55	-5		2.7	0.5	1.4	I3=60
24	53.3	-6.7		37.3	-22.7		57.3	-2.7		1.7	4	2.2	
25	50.1	-9.9		34.1	-25.9		54.1	-5.9		3.2	0	2	
26	46.7	-13.3		60	0		50.7	-9.3		3.4	0	0	I2=40
27	45.8	-14.2		59.1	-0.9		49.8	-10.2		3.9	3	2.1	
28	60	0	38.6	60	0	31.9	60	0	22.6	3.4	36.2	36.2	I=20
29	60	0	19.4	60	0	19.4	60	0	19.4	1.4	20.8	22.5	
30	60	0	12.9	60	0	12.9	60	0	12.9	1.1	14	14.8	
31	60	0	1.4	60	0	1.4	60	0	1.4	2.6	4	2.5	

AGR=AgResearch Palmerston North; Local= Experimental site.

January 2001 Different items (mm) of water balance for assumed root zone depth of 450 mm.

Date	1-20 (W_R)	S	D	1-40(W_R)	S	D	1-60(W_R)	S	D	E	P(local)	P(AGR)	Irrigation
1	55.5	-4.5		55.5	-4.5		55.5	-4.5		4.5	3	1	
2	55.3	-4.7		55.3	-4.7		55.3	-4.7		3.7	0.5	0.2	
3	50.4	-9.6		50.4	-9.6		50.4	-9.6		4.9	0	0	
4	44.9	-15.1		44.9	-15.1		44.9	-15.1		5.5	0	0	
5	60	0	1.1	41.1	-18.9		41.1	-18.9		3.8	0	0	I=20
6	54.5	-5.5		35.6	-24.4		35.6	-24.4		5.5	0	0	
7	48.7	-11.3		29.8	-30.2		29.8	-30.2		5.8	0	0	
8	43.4	-16.6		24.5	-35.5		24.5	-35.5		5.3	0	0	
9	57.6	-2.4		58.7	-1.3		18.7	-41.3		5.8	0	0	I1=20,I2=40)
10	60	0	3	60	0	4.1	24.1	-35.9		4.1	9.5	0.8	
11	56	-4		56	-4		20.1	-39.9		4	0	0	
12	51.5	-8.5		51.5	-8.5		15.6	-44.4		4.5	0	0	
13	47.9	-12.1		47.9	-12.1		12	-48		3.6	0	0	
14	45.8	-14.2		45.8	-14.2		9.9	-50.1		3.1	1	1.1	
15	40.2	-19.8		40.2	-19.8		4.3	-55.7		5.6	0	0	
16	40.2	-19.8		40.2	-19.8		4.3	-55.7		2	2	0.9	harvested
17	35.7	-24.3		35.7	-24.3		-0.2	-60.2		4.5	0	0	
18	50.5	-9.5		30.5	-29.5		54.6	-5.4		5.2	0	0	I=20,I3=60
19	46	-14		26	-34		50.1	-9.9		5.1	0.6	0	
20	41.5	-18.5		21.5	-38.5		45.6	-14.4		4.5	0	0	
21	60	0	2	60	0		46.1	-13.9		2.7	3.2	3	I1=20,I2=40
22	54.5	-5.5		54.5	-5.5		40.6	-19.4		5.5	0	0	
23	49.4	-10.6		49.4	-10.6		35.5	-24.5		5.1	0	0.4	
24	50	-10		50	-10		36.1	-23.9		0.6	1.2	0.1	
25	60	0	5.9	60	0	5.9	52	-8		2.6	18.5	16.8	
26	57.4	-2.6		57.4	-2.6		49.4	-10.6		2.6	0	0	
27	52.1	-7.9		52.1	-7.9		44.1	-15.9		5.3	0	0	
28	46.8	-13.2		46.8	-13.2		38.8	-21.2		5.3	0	0	
29	43.5	-16.5		43.5	-16.5		35.5	-24.5		3.3	0	0	
30	58.2	-1.8		38.2	-21.8		30.2	-29.8		5.3	0		I=20
31	55.4	-4.6		35.4	-24.6		27.4	-32.6		3.3	0	0	

February 2001 Different items (mm) of water balance for assumed root zone depth of 450 mm.

Date	1-20 (W_R)	S	D	1-40(W_R)	S	D	1-60(W_R)	S	D	E	P(local)	P(AGR)	Irrigation
1	50.2	-9.8		30.2	-29.8		22.2	-37.8		5.2	0	0	
2	46.8	-13.2		26.8	-33.2		18.8	-41.2		3.4	0	0	
3	42.3	-17.7		22.3	-37.7		14.3	-45.7		4.5	0	0	
4	57.5	-2.5		57.5	-2.5		9.5	-50.5		5	0.2	0	I1=20,I2=40
5	60	0	0.8	60	0	0.8	12.8	-47.2		1.2	4.5	2.1	
6	55.7	-4.3		55.7	-4.3		8.5	-51.5		4.3	0	0	
7	50.9	-9.1		50.9	-9.1		60	0	3.7	4.8	0	0	I3=60
8	46.9	-13.1		46.9	-13.1		56	-4		4	0	0	
9	41.8	-18.2		41.8	-18.2		50.9	-9.1		5.1	0	0	
10	56.6	-3.4		36.6	-23.4		45.7	-14.3		5.2	0	0	I1=20
11	60	0	36.8	60	0	16.8	60	0	25.9	0.8	41	41	
12	60	0	2.9	60	0	2.9	60	0	2.9	0.6	3.5	3.1	
13	54.8	-5.2		54.8	-5.2		54.8	-5.2		5.2	0	0	
14	53.1	-6.9		53.1	-6.9		53.1	-6.9		4.7	3	3.1	harvested
15	49.5	-10.5		49.5	-10.5		49.5	-10.5		3.6	0	0	
16	46.2	-13.8		46.2	-13.8		46.2	-13.8		3.3	0	0	
17	44.5	-15.5		44.5	-15.5		44.5	-15.5		1.7	0	0	
18	42.1	-17.9		42.1	-17.9		42.1	-17.9		2.4	0	0	
19	57.2	-2.8		37.2	-22.8		37.2	-22.8		4.9	0	0	I1=20
20	55	-5		35	-25		35	-25		2.2	0	0	
21	49.7	-10.3		29.7	-30.3		29.7	-30.3		5.3	0	0	
22	52.7	-7.3		32.7	-27.3		32.7	-27.3		2.5	5.5	4.6	
23	50.4	-9.6		30.4	-29.6		30.4	-29.6		2.3	0	0	
24	45.8	-14.2		25.8	-34.2		25.8	-34.2		4.6	0	0	
25	60	0	1.7	60	0	1.7	21.7	-38.3		4.1	0	0	I1=20,I2=40
26	55.4	-4.6		55.4	-4.6		17.1	-42.9		4.6	0	0	
27	51.1	-8.9		51.1	-8.9		12.8	-47.2		4.3	0	0	
28	47.9	-12.1		47.9	-12.1		9.6	-50.4		3.2	0	0	

March 2001 Different items (mm) of water balance for assumed root zone depth of 450 mm.

Date	1-20 (W_R)	S	D	1-40(W_R)	S	D	1-60(W_R)	S	D	E	P(local)	P(AGR)	Irrigation
1	44.6	-15.4		44.6	-15.4		6.3	-53.7		3.8	0.5		
2	45.6	-14.4		45.6	-14.4		7.3	-52.7		1.2	2.2		
3	46.6	-13.4		46.6	-13.4		8.3	-51.7		1.2	2.2		
4	60	0	2.7	42.7	-17.3		60	0	4.4	3.9	0		I=20,I3=60
5	56	-4		38.7	-21.3		56	-4		4	0		
6	52	-8		34.7	-25.3		52	-8		4	0		
7	47.9	-12.1		30.6	-29.4		47.9	-12.1		4.1	0		
8	45.2	-14.8		27.9	-32.1		45.2	-14.8		2.7	0		
9	43.1	-16.9		60	0	5.8	43.1	-16.9		2.3	0.2		I2=40
10	41.7	-18.3		58.6	-1.4		41.7	-18.3		1.6	0.2		
11	58.1	-1.9		55	-5		38.1	-21.9		3.6	0		I1=20
12	55.7	-4.3		52.6	-7.4		35.7	-24.3		2.4	0		
13	52.2	-7.8		49.1	-10.9		32.2	-27.8		3.5	0		harvested
14	57.5	-2.5		54.4	-5.6		37.5	-22.5		1.2	6.5		
15	53.8	-6.2		50.7	-9.3		33.8	-26.2		3.7	0		
16	50.1	-9.9		47	-13		30.1	-29.9		3.7	0		
17	46.5	-13.5		43.4	-16.6		26.5	-33.5		3.6	0		
18	42.7	-17.3		39.6	-20.4		22.7	-37.3		3.8	0		
19	59	-I		35.9	-24.1		19	-41		3.7	0		I1=20
20	55.3	-4.7		32.2	-27.8		15.3	-44.7		3.7	0		
21	51.8	-8.2		28.7	-31.3		11.8	-48.2		3.5	0		
22	48.4	-11.6		25.3	-34.7		8.4	-51.6		3.4	0		
23	44.9	-15.1		60	0	1.8	4.9	-55.1		3.5	0		I2=40
24	60	0		56.7	-3.3		60	0	1.6	3.3	0		I=20,I3=60
25	57.1	-2.9		53.8	-6.2		57.1	-2.9		2.9	0		
26	55.5	-4.5		52.2	-7.8		55.5	-4.5		1.9	0.3		
27	60	0	10.7	60	0	7.4	60	0	10.7	0.8	16		
28	60	0	3.5	60	0	3.5	60	0	3.5	3	6.5		
29	60	0	1.3	60	0	1.3	60	0	1.3	0.7	2		harvested
30	57.3	-2.7		57.3	-2.7		57.3	-2.7		2.7	0		
31	54.3	-5.7		54.3	-5.7		54.3	-5.7		3	0		

April 2001 Different items (mm) of water balance for assumed root zone depth of 450 mm.

Date	1-20 (W_R)	S	D	1-40(W_R)	S	D	1-60(W_R)	S	D	E_r	P(local)	P(AGR)	Irrigation
1	51.2	-8.8		51.2	-8.8		51.2	-8.8		3.1	0		
2	58.6	-1.4		58.6	-1.4		58.6	-1.4		0.3	6.7	7.7	
3	56.6	-3.4		56.6	-3.4		56.6	-3.4		2.2	0	0.2	
4	53.8	-6.2		53.8	-6.2		53.8	-6.2		2.8	0		
5	52	-8		52	-8		52	-8		1.8	0		
6	49.6	-10.4		49.6	-10.4		49.6	-10.4		2.4	0		
7	47	-13		47	-13		47	-13		2.6	0		
8	44.6	-15.4		44.6	-15.4		44.6	-15.4		2.4	0		
9	42.1	-17.9		42.1	-17.9		42.1	-17.9		2.5	0		
10	60	0	0.3	40.3	-19.7		40.3	-19.7		1.8	0		I1=20
11	57.6	-2.4		37.9	-22.1		37.9	-22.1		2.4	0		
12	60	0	9.7	50	-10		50	-10		0.6	12.2	12.7	
13	60	0	8.7	58.7	-1.3		58.7	-1.3		0.8	15.3	9.5	
14	58.6	-1.4		57.3	-2.7		57.3	-2.7		1.4	0	0	
15	56.2	-3.8		54.9	-5.1		54.9	-5.1		2.4	0	0	
16	54.8	-5.2		53.5	-6.5		53.5	-6.5		1.4	0	0	
17	52.9	-7.1		51.6	-8.4		51.6	-8.4		1.9	0	0	
18	51.1	-8.9		49.8	-10.2		49.8	-10.2		1.8	0	0	
19	49.8	-10.2		48.5	-11.5		48.5	-11.5		1.3	0	0	
20	51.9	-8.1		50.6	-9.4		50.6	-9.4		1.4	0	0	
21	60	0	1.2	59.9	-0.1		59.9	-0.1		0.2	3.5	1.5	
22	58	-2		57.9	-2.1		57.9	-2.1		2	9.5	10.2	
23	57.3	-2.7		57.2	-2.8		57.2	-2.8		0.7	0	0	
24	55.3	-4.7		55.2	-4.8		55.2	-4.8		2	0	0	
25	53.3	-6.7		53.2	-6.8		53.2	-6.8		2	0	0	
26	51.5	-8.5		51.4	-8.6		51.4	-8.6		1.8	0	0	
27	49.9	-10.1		49.8	-10.2		49.8	-10.2		1.6	0	0	
28	48.4	-11.6		48.3	-11.7		48.3	-11.7		1.5	0	0	
29	46.7	-13.3		46.6	-13.4		46.6	-13.4		1.7	0	0	
30	45	-15		44.9	-15.1		44.9	-15.1		1.7	0	0	harvested

Appendix 4.2 Soil volumetric water contents for non-irrigated non-P fertilised plots during January to April 2001.

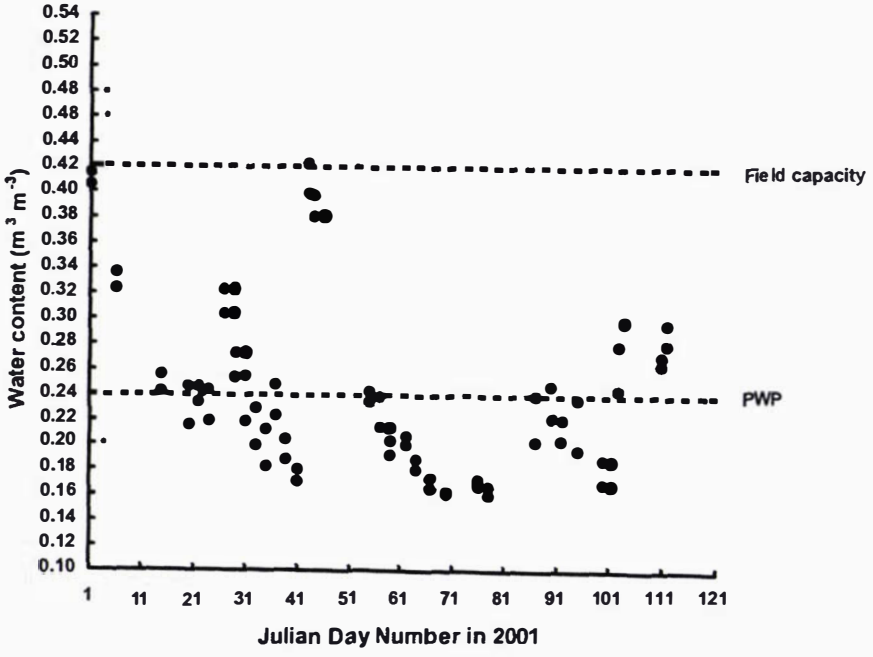

Figure A4.2.1 For depth 0-150 mm of the profile, PWP represents permanent wilting point.

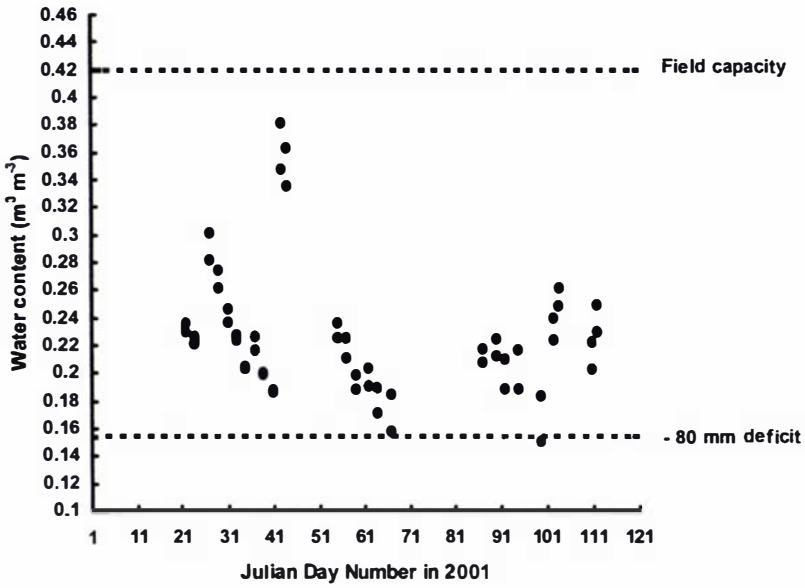

Figure A 4.2.2 For depth 0-300 mm of the profile, PWP represents -80 mm deficit.

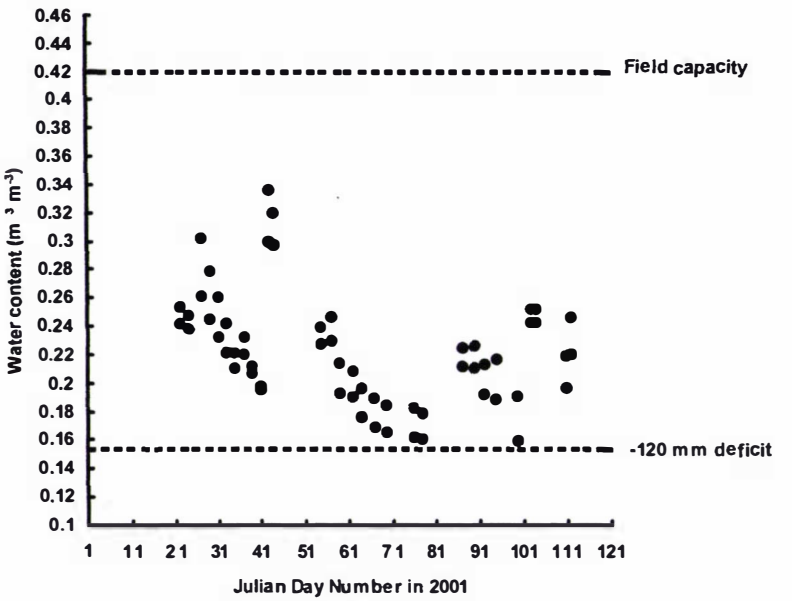

Figure A 4.2.3 For depth 0-450 mm of the profile, PWP represents -120 mm deficit.

Appendix 4.3 Soil test Olsen P (mg kg^{-1} soil), nitrate-N (mg kg^{-1} soil), ammonium-N (mgkg^{-1} soil) in non-irrigated non-P fertilised plots at different sampling depth on 24 April 2001.

Soil tests	0-75 mm	75-150 mm	150-225 mm	225-300 mm	300-450 mm
Ryegrass					
Olsen P	11.0	9.0	8.0	7.0	7.0
nitrate-N	5.7	4.9	5.6	4.6	3.8
ammonium-N	2.3	1.1	1.2	0.9	0.9
Clover					
Olsen P	10.0	10.0	6.0	5.0	6.0
nitrate-N	9.3	10.3	8.1	5.9	5.6
ammonium-N	4.1	3.0	2.3	1.5	1.8

Appendix 4.4 Mean values for soil ammonium-N (mg kg^{-1} soil) at different sampling depths for the experimental site on 24 April 2001.

Treatments	Sampling depths (mm)				
	0-75 mm	75-150 mm	150-225 mm	225-300 mm	300-450 mm
Ryegrass					
I-20, P-0	1.6	0.8	0.8	0.3	0.4
I-60, P-0	1.3	1.1	0.2	2.5	0.3
Mean (n=8)	1.5	0.9	0.5	1.4	0.3
I-20, P-40	1.2	1.2	0.7	0.3	0.1
I-60, P-40	2.4	1.2	0.6	0.6	0.2
Mean (n=8)	1.8	1.2	0.6	0.5	0.2
Mean (n=16)	1.6	1.0	0.6	0.9	0.3
Clover					
I-20, P-0	0.8	0.7	0.8	0.3	0.4
I-60, P-0	2.1	0.8	1.2	0.5	0.2
Mean (n=8)	1.4	0.7	1.0	0.4	0.3
I-20, P-40	1.9	0.7	0.8	0.6	0.8
I-60, P-40	2.8	1.0	1.3	0.6	0.5
Mean (n=8)	2.4	0.9	1.1	0.6	0.7
Mean (n=16)	1.9	0.8	1.0	0.5	0.5
LSR $_{\text{at P<0.05 (n=4)}}$	1.8	1.5	1.6	2.0	1.4
Significance					
Species*irrigation	-	-	P<0.02	-	-
Species*P fertiliser	-	-	-	-	P<0.04

LSR=Least significant ratio

Appendix 5.1 Calculating potential evapotranspiration.

A number of methods are available for estimating, from meteorological data, the evapotranspiration from an extensive area of well-watered, full cover pasture (designated E_w, often referred to as the "potential evapotranspiration"). Authors like, Blennerhassett (2002), Moir *et al.* (2000a and 2000b,), Scotter *et al.* (1979), and Scotter *et al.* (2000) use the Priestly & Taylor (1972) method for New Zealand pasture. The Priestly & Taylor model has been shown to work well in humid regions provided the aerodynamic effect is small relative to that of radiation (Smith *et al.* 1996). On the other hand, Woodward *et al.* (2001) reported that, this requirement is not met for some areas in New Zealand, where the relative contribution of the aerodynamic effect is frequently large enough to require a Priestly & Taylor factor considerably greater than the 1.26 commonly used. Priestly & Taylor (1972) suggested the following equation for daily potential evapotranspiration.

$$E_w = \alpha \; R_n \, s/[(s+\gamma)\, \rho_w L \,] \qquad \text{(A5.1)}$$

Where s is the rate of change of saturation vapour pressure with temperature (kPa C^{0-1}), γ is the psychrometric constant (kPa C^{0-1}), R_n is the net radiation expressed in MJ m^{-2}, ρ_w is the density of water (10^3 kg m^{-3}), L is the latent heat of vaporization (2.46 MJ kg^{-1}), and α is a dimensionless empirical parameter.

Fitting a quadratic equation to tabulate values for the dimensionless ratio $s/(s + \gamma)$ by Scotter *et al.* (1979) at an air pressure of 100 kPa over the temperature range 5 to 20^0 C gave

$$s/((s+\gamma) = 0.403 + 0.0164T_{av} - 0.00012T_{av}^2 \quad \text{(A5.2)}$$

where T_{av} (^{0}C) is the average daily screen air temperature, approximated as the mean of the daily maximum and minimum.

Priestly & Taylor (1972) used data from the literature to show α to be approximately 1.26. Scotter et al. (1979) experimentally obtained a value of 1.3 for α with a regression coefficient of 0.94 for a site near Massey University, Palmerston North. Moreover, the accuracy of both Penman, and Priestly & Taylor ET estimates were found similar, with errors of 15 to 20 % for daily ET estimates for the Manawatu region (Clothier *et al.* 1982). The following empirical site-specific relationship between R_n and R_s was found through regression analyses of 9 months net radiation data collected over winter oat or paspalum pasture at Palmerston North

$$R_n = 0.62R_s - 1.47 \quad \text{(A5.3)}$$

Where the units of R_n and R_s are MJ m^{-2}. Alternatively, R_n can be calculated using in FAO guidelines (Allen *et al.* 1998).

If R_s data are not available, daily values may be estimated from sunshine hour measurements. Scotter *et al.* (1979) adopted the following procedure.

$$R_s = R_a\,(a + b\,n/N) \quad \text{(A5.4)}$$

Where R_a is the daily radiation outside the earth's atmosphere, n is the number of sunshine hours, N is the maximum number of hours measurable with a sunshine hour recorder (equals actual maximum less half an hour), and a and b are locally determined constants. The half an hour deduction from N was adopted to compensate for the inability of the sunshine recorder to register at low solar elevations.

De Lisle (1966) established that a = 0.25, and b=0.54 for New Zealand. Comparison of such estimates with Epply pyranometer measurements over a 4-month period showed the error in weekly values to be only 4% for Palmerston North (Scotter *et al.* 1979).

The maximum number of sunshine hours, N depends on the position of the earth relative to the sun, and is hence a function of latitude (λ) and Julian day. To find N the equation

$$H = \cos^{-1}(-\tan \lambda \tan \delta) \qquad \text{(A5.5)}$$

is used, where H is the half-day length in degrees (H= 90^0 at the equinox) (Sellers, 1965), λ is the latitude in degrees (negative in the southern hemisphere), and δ is the angle of declination for the sun (range -23.5^0 to $+23.5^0$) (Rosenberg, 1983) given by

$$\delta = 23.5 \sin [(M - 79)\ 360/365] \qquad \text{(A5.6)}$$

where M is the Julian day number (i.e. day of year from 1 to 365 or 366 for a leap year). N is then found using

$$N = (2)\ (24)\ H/360 - 0.5 \qquad \text{(A5.7)}$$

The extra-terrestrial solar radiation normal to the earth's surface (R_a, J m^{-2}) can be calculated as follows (Sellers, 1965):

$$R_a = (1.4x\ 10^3/\pi)\ (60 \times 60 \times 24)\ ((2\pi H/360) \sin\lambda \sin\delta + \cos\lambda \cos\delta \sin H)\ (d'/d)^2 \qquad \text{(A5.8)}$$

Where $(d'/d)^2$ is equal to $1+0.0334 \sin [0.986(M-274)]$ and d and d' are the instantaneous and mean distances of the earth from the sun, respectively.

The Priestly-Taylor method as proposed by Scotter *et al.* (2000) is adopted in this study for two reasons. Firstly because it has been calibrated extensively for the locality (Scotter *et al.* 1979). Secondly because the Priestly-Taylor model requires, fewer independent weather observations, which is a good feature for a decision support model. A numerical example of the use of the above equations for calculating E_w may help the reader. Consider 1 January 2001 in Palmerston North. At Agresearch near Massey University the maximum screen temperature was 17.8 ^{0}C, and the minimum was 6.6 ^{0}C. A few kilometres away at Palmerston North Airport, the measured incoming solar radiation was 26.7 MJ m^{-2}. Putting the average daily air temperature of 12.2 ^{0}C into equation (A2) gives $s/(s + \gamma)$ as 0.59. Putting R_s of 26.7 MJ m^{-2} into equation (A3) gives R_n as 15.1 MJ m^{-2}. From equation (A1) we then find E_w for the day as 0.0045 m or 4.5 mm.

Appendix 6.1 Discussion of development on refilled core technique and associated statistical analyses

A6.1.1 Root sampling technique

Arnone III *et al.* (2000) cites a number of recent grassland studies where the refilled core technique was used with only a 0 - 200 mm sampling depth. In recent root growth studies of arable crops such as winter barley and sugar beat, a 300 mm sampling depth was employed (Steingrobe, 2001; Steingrobe *et al.*, 2001). Given the inability of the refilled core technique to measure root activity at depth, the sampling depth of 0 - 200 mm used in this present study appears to be justifiable.

Mathew *et al.* (1986) used an 80 mm diameter corer when sampling plots of pasture; this comparatively large core diameter allowed easier relocation of core holes. Disadvantages of using an 80 mm corer include the large volume of sand collected, and the large degree of disturbance, which is of particular concern where the aim is to measure root production near the soil surface. Values for root growth into refilled cores 25 mm in diameter compare well with entire root system measurements in a glasshouse pot experiment (Carvalho, 2002). Steingrobe (2001) and Steingrobe *et al.* (2001) used refilled cores (ingrowth cores) of 40 mm diameter and suggest that deeper roots are more likely to grow into relatively narrow cores. In light of these results, a 30 mm diameter refilled core was used in this experiment.

The greatest advantage of the refilled core technique is that it can be readily used in field. Other advantages are simplicity, and low cost. Many studies carried out on root systems of pasture plants have used young seedlings, potted plants, or hydroponic cultures to avoid the difficulties associated with sampling roots in the field, including the determination of live: dead ratios in root samples (Matthew *et al.*, 1991). The data from such studies (Evans, 1977; Cullen *et al.*, 1972; Hunt and Thomas, 1985) are specific to the respective study environments and conditions, and the relevance of these

studies to field swards is not obvious. Alternatively, a variety of approaches that rely on measurements of the fate of the radioisotope ^{14}C have been devised to estimate fine root production and turnover but the efficacy of this technique in the complex soils that characterize most natural ecosystems has been questioned (Milchunas and Lauenroth, 1992).

Although the placement and sampling of multiple cores within plots would have lowered the coefficient of variation, associated increases in workload would have created a logistical difficulty. In addition, a number of arguments can be advanced in support of the use of one core per plot. First, in comparison with fruit trees, or crops such as vegetables or maize, grass tillers and clover shoots are small in size and their root systems are comprised of fine roots with a comparatively homogeneous distribution within any soil layer. Secondly, in this particular experiment, the number of replicates and the factorial design meant that species or fertiliser comparisons were based on the means of 24 individual cores, and irrigation treatment comparisons on means of 16 individual cores. In comparison, the experiment of Steingrobe *et al.* (2001) comprised 4 replicates of two treatments, with 4 sampling cores per plot per harvest, making a total of 32 refilled cores used at each harvest, compared with 48 cores per harvest in the current experiment. Thirdly, in a recent glasshouse experiment with Guinea grass (*Panicum maximum*), Carvalho (2002) found that results from a single 25 mm refilled core inserted in a pot showed treatment effects and coefficients of variation closely similar to those obtained by recovering the entire root system. Finally, the fact that significant treatment effects were detected and showed patterns amenable to biological interpretation, also confirms the technique was effective.

A6.1.2 Statistical techniques

Existing multivariate analysis techniques cope with multiple correlated measurements in one 'dimension' of the data set e.g. multiple variables measured or multiple harvest

dates. The data set from this experiment had multiple measures in three dimensions, namely three soil depths, three harvest dates, and multiple measures of root characteristics (root mass, root length, RMD, and L_V). A multivariate analysis in two dimensions was achieved by Roberts and Raison (1983). These authors fitted polynomial regressions of root density with depth, and then performed multivariate analyses on the regression coefficients. That approach is conceptually similar to the PCA approach used here to review the interaction between treatment effects and soil depth, except that the PCA analysis is arguably simpler to execute, and the results are easier to interpret. Also, Roberts and Raison (1983) separated cores into 10 depth segments, giving more degrees of freedom (not available with only three soil depths in the current experiment) for fitting polynomial curves for root distribution with depth.

As mentioned in the methods section, exploratory analyses were carried out using PCA, CDA, and GLM repeat measures techniques. The main reason for not including the three harvest dates as repeat measures in a single statistical analysis was that the three harvests were felt to be sufficiently different in character to warrant independent analysis. For example, at the December harvest there had been insufficient time for irrigation effects to be expressed, while for the cores harvested in February irrigation effects would have been masked by unseasonably high rainfall. CDA was discarded when it was realised that with only two species and two fertiliser regimes in the experiment, only one discriminant function was available in these analyses. In discriminant functions with this constraint, coefficients are necessarily +1 or −1, and so are uninformative as to the strength of association between effects. PCA followed by ANOVA of PC scores, however, provided a convenient way to identify relationships between data for the three soil depths.

Appendix 7.1 Correlation between nitrate-N in soil water samples and KCl extracted nitrate-N in profile soil samples

Table A7.1.1 The correlation coefficients between mean nitrate-N concentrations of water samples collected at 30 cm depth and KCl extracted soil nitrate-N concentrations at each soil depth. Water sampling dates were 14 April and 12 May 2001, and the soil sampling date was 24 April 2001.

	Ryegrass		White clover	
Soil depth	14 April 2001	12 May 2001	14 April 2001	12 May 2001
0- 75mm	- 0.21	- 0.24	0.14	- 0.32
75-150mm	0.80	0.77	- 0.45	- 0.81
150-225mm	0.96	0.87	- 0.79	- 0.68
225-300mm	- 0.14	- 0.14	0.50	0.12
300-450mm	0.31	0.51	0.17	- 0.81

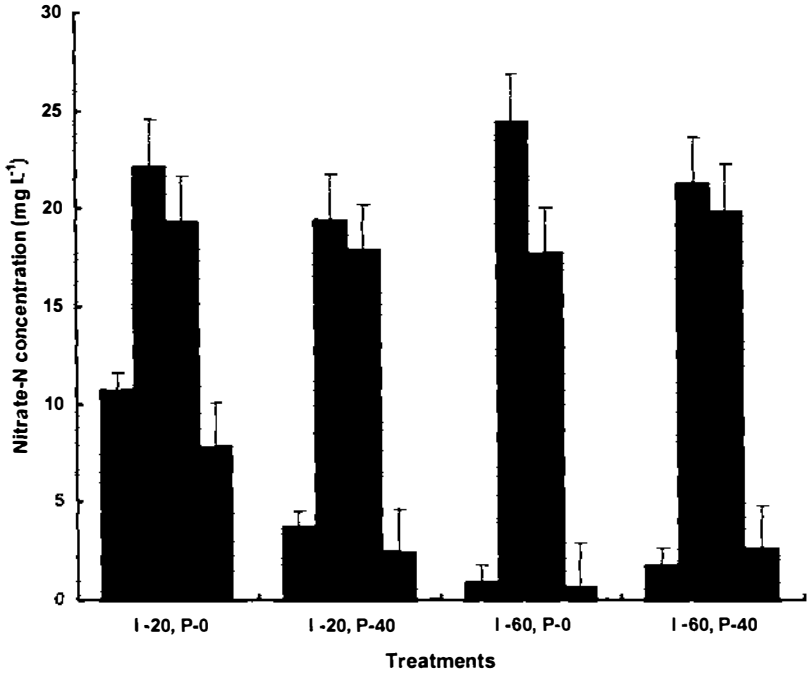

Figure A7.1.1 Soil nitrate-N on 24 April at two depths and soil water nitrate-N concentration at 300 mm depth for ryegrass. Colours blue and green represent soil water nitrate-N for 14 April and 12 May 12 2001, respectively. Colours black and dark brown represent KCl extracted soil nitrate-N for depth interval 225-300mm and 300-450mm, respectively. Standard errors ($P<0.5$) are on the top of bars.

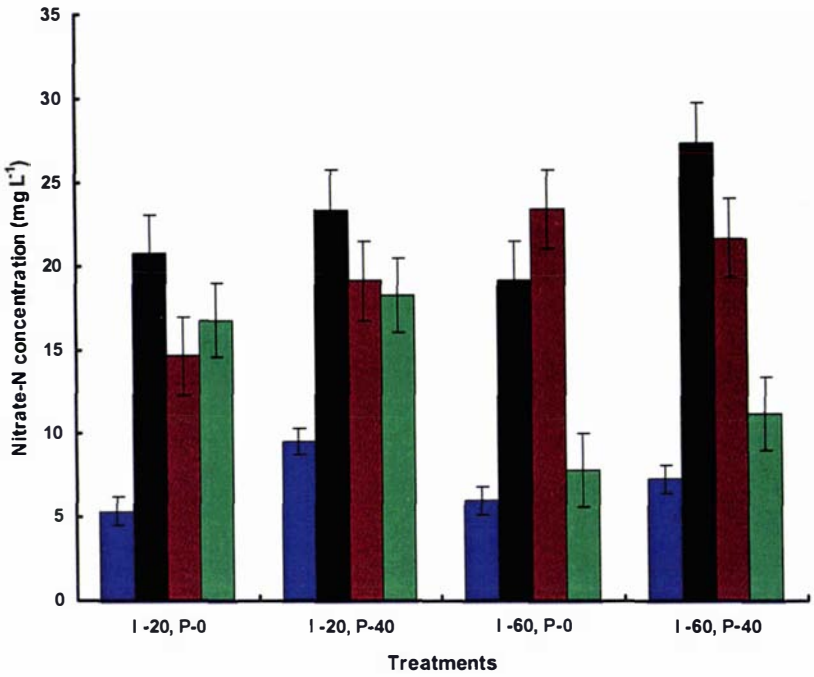

Figure A7.1.2 Soil nitrate-N on 24 April at two depths and soil water nitrate-N concentration at 300 mm depth for clover. Colours blue and green represent soil water nitrate-N for 14 April and 12 May 12 2001, respectively. Colours black and dark brown represent KCl extracted soil nitrate-N for depth interval 225-300mm and 300-450mm, respectively. Standard errors ($P<0.5$) are on the top of bars.