Quantifying lucerne (*Medicago sativa*) growth in response to temperature and soil moisture

A dissertation

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by

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DECLARATION

The data collected from the 'Maxclover' Grazing experiment (2002-2010) used in this dissertation was collected by and provided for use by the Dryland Pastures Research Team. All data analysis, and its subsequent interpretation, is my own work.

Abstract of a Thesis submitted in partial fulfillment of the requirement for the Degree of Bachelor of Agricultural Science

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The success of lucerne based farm systems has led to an increased interest in its use in different regions of New Zealand. Annual yields (kg DM/ha^{-1}) and daily growth rates (kg DM/ha/d) have been collated as a reference library for lucerne grown in the Waikato, Taupo, Manawatu, Marlborough, Canterbury and Otago regions. The main aim of this dissertation was to determine whether lucerne yields at Lincoln could be predicted from local weather data. Data from the 'Maxclover' long term grazing experiment at Lincoln University was used as a pilot dataset to examine seasonal and annual yield variations of dryland lucerne in response to environmental drivers. Analysis involved quantification of the relationships between dry matter production and weather factors, soil moisture and temperature, that might then be useful for predicting lucerne yield in other areas of New Zealand. The average annual yield in the 'Maxclover' experiment was 15 ± 1.1 t DM/ha^{-1} over the eight years. The analysis of dry matter yield over six harvests per season identified two phases of growth, each influenced by mean air temperature, soil moisture or both. Lucerne dry matter production was ~9.2 ± 0.29 kg DM/°Cd in the spring period until the onset of moisture stress, after which it decreased to ~2.2 ± 0.24 kg DM/°Cd. The breakpoint in dry matter production occurred at ~1410 ± 46°Cd. Dry matter production after the breakpoint was influenced mainly by amount (mm) and frequency of rainfall events. Potential evapotranspiration alone was not an accurate measure of lucerne production therefore potential soil moisture deficit and rainfall were analysed. Potential soil moisture deficit was 250 ± 10.6 mm at the breakpoint x (°Cd) in Years 2-8, which indicates a critical limiting deficit for this soil. The quantification of these relationships will allow farmers to predict the potential yield of their lucerne stand with the use of specific climatic data for their region and soil type. Based on this analysis, accumulated thermal time (°Cd) and potential soil moisture deficit (mm) and rainfall (mm) were able to be used to estimate lucerne production.

Keywords: Alfalfa, annual yield, daily growth rates, potential evapotranspiration, soil moisture deficit, thermal time, *Medicago sativa*

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LIST OF ABBREVIATIONS

Abbreviations	Description	Units
DM	Dry matter	kg DM/ha^{-1}
PET	Potential evapotranspiration	mm
PSMD	Potential soil moisture deficit	mm
R^2	Coefficient of determination	%
SEM	Standard error or the mean	
T_b	Base temperature	°C
T_{max}	Maximum temperature	°C
T_{min}	Minimum temperature	°C
T_{opt}	Optimum temperature	°C
T_t	Thermal time	°Cd
Y	Yield	kg DM/ha

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1 INTRODUCTION

Lucerne (*Medicago sativa*) is a valuable perennial pasture legume due to its persistence in summer dry environments, ability to fix atmospheric nitrogen and production of high quality feed. Animal productivity from grazing lucerne is maximised because of its high digestibility, nutrient content and dry matter intake. It has traditionally been sown as a monoculture and is suitable for both sheep and cattle grazing. Lucerne fixes atmospheric N_2 via its symbiotic relationship with rhizobia located in root nodules. It produces a deep taproot, which enables it to extract water deeper in the soil profile than most pasture species, and therefore grow for longer into summer dry periods (Brown, 2004). Because of this it is well adapted to dryland (rain fed) farming conditions, which have 3-4 months of little growth in summer. Typically the life of a stand is 7-9 years, however stands of up to 20 years old were reported by Langer (1973), with correct management of a suitable cultivar in the right environmental conditions.

Successful lucerne management was updated by Moot *et al.,* (2003) to balance animal and plant requirements with demand for high quality and yield. Lucerne yields in excess of 20 t DM/ha^{-1} have been recorded around New Zealand (Brown *et al*., 2000). It produces high yields in the spring due to the remobilisation of assimilates from the roots to shoots and rapid expansion of leaf area from nodes that accumulated over winter. The spring growth rates are often linear and usually associated with temperature when moisture is non-limiting (Moot *et al*., 2003). This spring period is extended beyond that of most other pasture species, because more soil moisture is available to lucerne due to its tap root (Moot, 2010). Time of defoliation within this period should be based on the trade-off between crop yield and stock requirements (Moot *et al*., 2016). The highest annual daily lucerne growth rates are achieved during spring. Rotational grazing is recommended through the spring and summer months to maximise available feed. There is a plateau of summer dry matter production as evapotranspiration exceeds rainfall at the time of low to zero growth. Daily growth rates therefore vary due to the amount and frequency of these rainfall events. Summer grazing is recommended when herbage is 30-35 cm tall or earlier if there is a terminal drought (Moot *et al*., 2016). During autumn, lucerne should have one extended period of flowering to ensure the priority of assimilate storage in the roots for the following spring (Moot *et al.,* 2003). Into the autumn/winter growth period growth rates decline further as mean daily temperatures decrease. A challenge to dryland farming systems is maintaining profitability through periods of moisture stress, which are typical of many east coast areas of New Zealand. Meeting stock feed requirements is dependent on the ability to produce and allocate high quality feed to meet target sale weights. Annual yield (t DM/ha^{-1}) is greatly influenced by spring production and is important from an animal perspective due to the time of lambing and lactation. Therefore, stock demands are high during this period so accurate prediction of feed available is important for making farm management decisions.

The success of lucerne based farm systems (Avery *et al*., 2008; Anderson *et al*., 2014) has led to an increase in interest to use lucerne in different regions of New Zealand. The first step in using lucerne is having some idea of how much can be grown in a region. Therefore, this dissertation begins with a summary of published annual lucerne yields and growth rates from different regions of New Zealand. This serves as a library of measured yields across New Zealand and provide a basis for extrapolating yields into new regions. However, the main aim of this dissertation is to determine whether yields can be predicted from weather data. Specifically a data set from one location at Lincoln University is used as a pilot investigation to examine seasonal and annual yield variation in response to environmental drivers. Data from this experiment are analysed to identify relationships that might be useful for predicting lucerne yield in other areas of New Zealand, based on the main environmental drivers of temperature and moisture. The importance of these drivers are considered in the literature review, which focuses on accumulated thermal time and accumulated potential evapotranspiration as potential predictors of lucerne yield.

1.1 Aims and Objectives

The aim of this dissertation is to quantify the relationship between lucerne growth in response to temperature and soil moisture. Objective 1 of this dissertation is to summarise lucerne annual yield and growth rate data reported in literature from different regions of New Zealand. Objective 2 is to review previous experiments analysing relationships between lucerne growth and weather variables to identify any potential methods for analysis. Objective 3 is to analyse the lucerne yield data from the 'Maxclover' long term grazing experiment from 2002-2010 to establish any relationships between yield and environmental factors. Environmental factors selected will be ranked by their ability to be used to predict lucerne yield or growth rates.

To meet the objectives this dissertation is divided into six chapters. Chapter 2 reviews the literature to meet objectives 2 and 3. Chapter 3 outlines the 'Maxclover' experiment from which the data were collected for analysis in Chapter 4 and discussion in Chapters 5 and 6.

2 REVIEW OF THE LITERATURE

This literature review provides an introductory context behind the growth of lucerne in different regions of New Zealand. Initially it summarises lucerne yield data from experiments carried out in Waikato, Taupo, Manawatu, Marlborough, Canterbury and Otago to meet Objective 1 of this dissertation. The data summarised also outline the differences in yields achieved on various soil types, indicating the influence of soil water holding capacity on lucerne growth. Also included are relevant temperature and soil fertility data, which are relevant when considering extrapolation of yields to other regions. Previous attempts to predict lucerne yield based on environmental drivers are then outlined to meet Objective 2 and 3 as a basis for the analysis undertaken in the remainder of this dissertation.

2.1 Annual yields and growth rate data for lucerne in New Zealand

2.1.1 Waikato

McGowan *et al.,* (2003) carried out lucerne growth analysis of six cultivars on two north-facing plots at Whatawhata research center, 26 km east of Hamilton. The plots were on a 20° slope on a Dunmore silt loam soil which was free draining volcanic ash. Over the five years of study, 1982-1987, the mean rainfall was 1413 mm. The mean monthly maximum and minimum temperatures were 19.7°C and 7.5°C, respectively. The plots were rotationally grazed by sheep, except for in early spring (September-October) when they were grazed continuously. Visual assessment of dry matter production was made along five fixed transect lines. Seasonal production measurements were taken after the first year of establishment. Ten capacitance meter readings were taken per plot, the mean of which was used to locate a 0.2 m^2 quadrat to be harvested. Samples were weighed then sub samples dried to calculate DM/ha^{-1}. Average production in the first year was 10.8 ± 1.14 t

DM/ha with no significant difference among cultivars. Annual yields in 1983-1984 ranged from 9.7-13.4 t DM/ha^{-1}, 1984-1985 from 8.4-13 t DM/ha^{-1} and in 1985-1986 from 8.2-13.6 t DM/ha^{-1}, (Figure 2.1). 'Rere' was the highest yielding lucerne cultivar over the five years. Figure 2.1 shows the comparison of mean monthly growth rates of pasture and 'Rere' lucerne over the five years, and highlights the advantage to lucerne during the summer months.

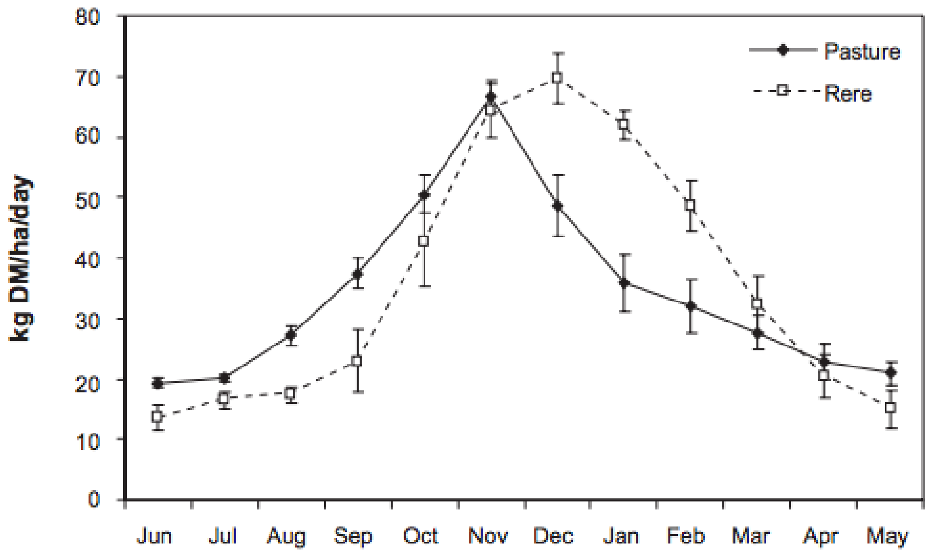

Figure 2.1 Mean monthly growth rates (kg DM/ha/d) of pasture and 'Rere' lucerne on hill country at Whatawhata over five years (1982-1987). From McGowan *et al.*, (2003).

2.1.2 Taupo

Baars *et al*., (1975) evaluated the growth rate of 'Wairau' lucerne in Wairaki, Central Plateau with comprehensive regional climatic data (Cox, 1968). The lucerne was sown on flat land into Artiamuri sand soils. It was described as marginal farmland with a humid and mesothermal climate. Spring temperatures were slow to rise and there was a wide diurnal temperature fluctuation over summer and autumn months. Winters were described as being wet and cool. Severe frosts could occur in any month of the year, with them more frequent from April to October. The annual rainfall was 1241 mm. Annual yields ranged from 10.3 to 15.7 t DM/ha^{-1} with a mean of 13.4 t DM/ha^{-1}. Seasonal yields were not correlated with temperature. However, spring yield (September, October and November) was correlated (P<0.01) with spring rainfall. Summer yield was also correlated

(P<0.01) with summer rainfall. This suggests that rainfall, which reflects soil moisture could be a suitable predictor of yield in spring and summer.

McQueen and Baars (1980) presented lucerne yields from the same area over nine sites. The mean annual lucerne yield across all the sites was 12.7 t DM/ha^{-1}. The lowest yield was recorded at Wairakei on both Artiamuri and Oruanui soils with 10.7 t DM/ha^{-1}. The highest was recorded at Rerewhakaaitu on a Tarawera gravel with 14.3 t DM/ha^{-1}.

Betteridge *et al*., (2007) reported annual yields of 4.5 t DM/ha^{-1}, 7.6 t DM/ha^{-1} and 11.5 t DM/ha^{-1} in a three year experiment in Taupo of lucerne on moderately rolling Oruanui sand soil. The 'Kaituna' lucerne was sown in October 2002. From sowing to January 2003, 354 mm of rain fell but only 88 mm fell in summer/autumn, which slowed establishment resulting in a low first annual yield. Rainfall in the following year (2003-2004) was 80% greater, which resulted in greater dry matter production. The final year yielded the greatest with 11.5 t DM/ha/yr.

2.1.3 Manawatu

In the Manawatu, 'Wairau' lucerne produced an annual yield of 20.2 t DM/ha on a Manawatu fine sandy loam soil (Theobald and Ball, 1983). The highest yields were recorded in spring and summer with 6.9 t DM/ha^{-1} and 7.6 t DM/ha^{-1}, respectively. Seasonal yields of 2.2 t DM/ha^{-1} and 2.9 t DM/ha^{-1} were achieved in winter and autumn respectively. These seasonal yields highlighted the importance of spring and summer in their contribution to annual yield. Thus, predicting spring yields when soil moisture is non-limiting is a part of the analysis in Chapter 4.

2.1.4 Marlborough

Hunter *et al.,* (1994) reported annual yields of dryland lucerne at Dashwood with a mean annual rainfall of 591 mm. The experiments were carried out between 1992 and 1994. Figure 2.2 shows the comparison of yield on stony soils and sandy soils at the three sites. Annual yields of 6 t DM/ha^{-1} and 9.5 t DM/ha^{-1} were achieved on sandy soils and 2.5 t DM/ha^{-1} and 6.5 t DM/ha^{-1} was on stony soils. A feature of these results is the low yields achieved in the establishment years. This is consistent with literature from Sim (2014) who showed that lucerne prioritised root growth until at least 5 t DM/ha^{-1} had been stored below ground. This means it takes more than one growth year for lucerne to establish in areas of low rainfall and on soils of low water holding capacity such as those used in this study. It is likely that if this experiment continued the stands would have continued to produce yields at the higher rates.

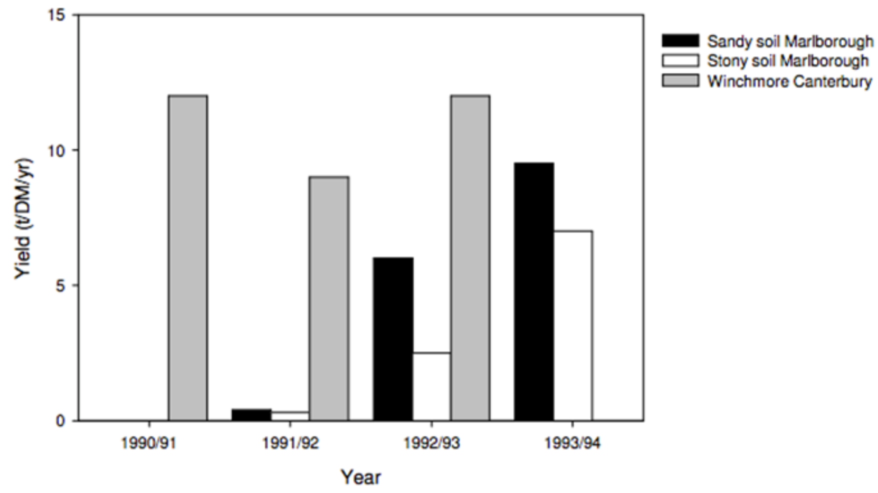

Figure 2.2 Annual yields (t DM/ha/yr) of lucerne monocultures grown at Winchmore, Canterbury or Dashwood, Marlborough. From Hunter *et al.,* (1994).

2.1.5 Canterbury

Hunter *et al.,* (1994) also reported growth rates of lucerne at Winchmore in Canterbury on a Lismore silt loam soil. Results show annual yields of 8.5 t DM/ha^{-1} and 12 t DM/ha^{-1}, (Figure 2.2).

Hayman (1985) compared the production of both dryland and irrigated lucerne in two experiments on 12 different Canterbury soil types from 1976-1983. Lucerne failed to persist at four sites (sites were not specified) due to being overcome with clover or dying under waterlogged conditions. Plots were cut four times per year in November, January, February/March and May. Annual fertiliser applications of 500-650 kg/ha^{-1} of superphosphate and 500 kg/ha^{-1} of potassium chloride were applied to maintain fertility. The 1981/82-1982/83 season was extremely dry and annual yields as low as 1.8 t DM/ha^{-1} on the Balmoral soils were recorded (Hayman, 1985). On a stony Balmoral soil yield, increased with the use of irrigation to 8.5 t DM/ha^{-1}. Irrigation also increased yield on a

Lismore soil (very stony) from 6.5 to 10.7 t DM/ha^{-1}. Yield on the Chertsey soil increased from 5.2 to 15.2 t DM/ha^{-1} with irrigation. Yield on the Wakanui, the deepest soil also increased from 12 t DM/ha^{-1} to 15.2 t DM/ha^{-1}. This can be compared with Brown *et al*., (2003) who showed that lucerne produced 20 t DM/ha/yr under irrigation on a Wakanui silt loam.

Hoglund *et al.,* (1974) compared the effects of defoliation timing and nitrogen on lucerne yield of a three year old 'Wairau' stand of lucerne. The trial was located in Lincoln on a Paparua sandy loam soil and the experimental period started in November 1968. Lime (2 t/ha) was applied at sowing and 100 kg of sulphur superphosphate was applied every three years. Nitrogen was applied onto half the plots after defoliation. Defoliation occurred at either the immediate pre bud stage, when 50% of the stems had viable buds or at first flower. The lucerne that was defoliated at first flower yielded 50% more than the pre bud defoliation treatment. The pre bud treatment yielded 10.3 t DM/ha^{-1}, the 50% bud treatment 12.5 t DM/ha^{-1} and the first flower treatment 15.6 t DM/ha^{-1} without nitrogen treatment. A maximum yield was achieved from the first flower defoliation treatment with added nitrogen fertiliser yielding 28.2 t DM/ha^{-1}. This is an interesting result considering nitrogen is in general not applied to lucerne due to its nitrogen being sourced from symbiosis with rhizobia. Nitrogen fixation was sufficient for lucerne growth in spring due to there being no response to additional nitrogen fertiliser. They stated that "because a nitrogen fertiliser growth response occurred, the nitrogen from the rhizobia symbiosis and soil nitrogen must have been insufficient" for maximum growth.

Moot (2003) compared lucerne growth rates with other pasture species at Lincoln University. The trial plots were sown in a Wakanui silt loam soil and had a mean annual rainfall of 660 mm. The lucerne produced higher growth rates than chicory and clover in September and December-May. The average daily growth rates were calculated from dry matter accumulation. In September the lucerne produced approximately 34 kg DM/day and had a five year mean growth rate maximum of 90 kg DM/ha/day. Brown (2004) reported results from the same experiment. Yields of 28 t DM/ha^{-1} and 21 t DM/ha^{-1} for irrigated and dryland lucerne respectively in 1997/98. Brown *et al.,* (2003) summarised annual and daily growth rates of this 'Kaituna' lucerne at Lincoln. Over the five years the area had a mean annual rainfall of 660 mm. Long term mean daily temperatures ranged from 6°C in June/July to 18°C in January/February. The mean diurnal fluctuation was 10°C. The long term mean rainfall was ~50 mm per month. The Penman ET potential was calculated from 40 mm per month in June/July to a maximum of 140 mm per month in December/January. Average daily growth rates were calculated from dry matter accumulation data using the rate of linear growth (10-25% of max yield). As noted the annual yield was 21 t DM/ha^{-1} in 1997/98 and >20 t DM/ha^{-1} in 1998/99 and 1999/00. Recorded yields declined in 2001-2002 ranging from 17.5 t DM/ha^{-1} and 19.3 t DM/ha^{-1}. A daily (five year mean) growth rate was calculated at 34 kg DM/ha/day for September. Mean daily growth rates of 70, 90, 50 and 20 kg DM/ha/day were calculated for the months of November, December/January, February and March/April/May respectively. Importantly for irrigated lucerne these growth rates were linearly related to mean air temperature (Figure 2.3). This dissertation will determine if these variations in mean growth rates can be attributed to environmental factors. Of note is the major separation in spring versus autumn growth rates Moot *et al.,* (2003) attributed this to differences in biomass partitioning. Specifically, that lucerne is remobilising assimilates to the shoots in spring so growth rates are higher than at the same temperature in autumn, when partitioning is to the roots and crown. Thus, the focus of the current research will be to quantify spring, summer and autumn growth rates separately.

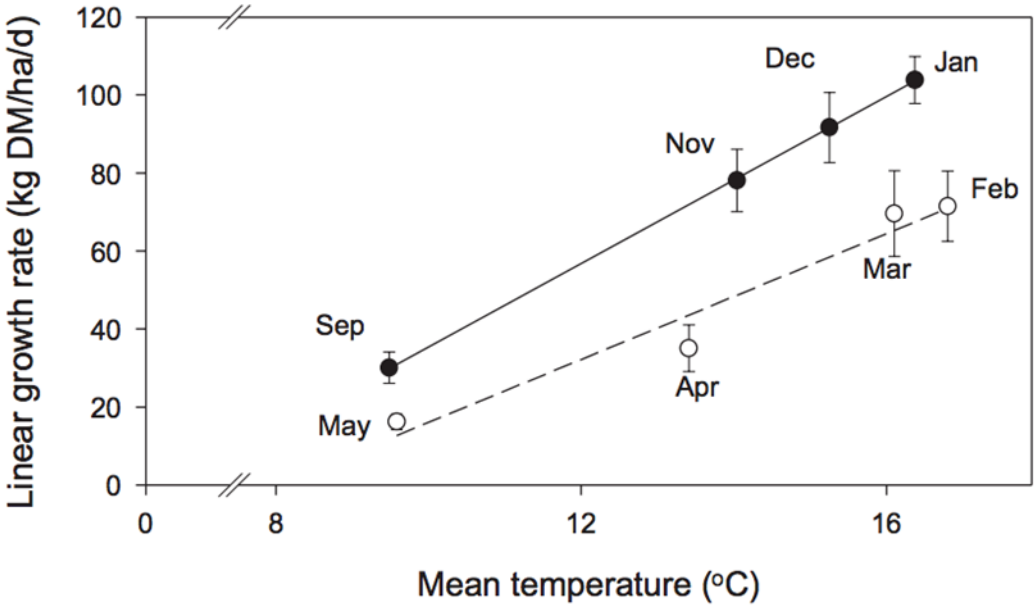

Figure 2.3 Linear growth rates (kg DM/ha/d) of irrigated lucerne in relation to mean temperature (°C) at Lincoln University, Canterbury, New Zealand. Each point represents the mean from 5 years data and bars represent one standard error either side of the mean. Linear regressions fitted to data from September–January (●, y = -71.5 + 10.7x, R^2 = 0.99) and February–May (○, y = - 64.7 + 8.0x, R^2 = 0.92). Adapted from Moot *et al*., (2003).

McKenzie *et al.,* (1990) carried out an experiment, which included the measurement of 'WL320' lucerne annual yield in 1988/1989. The experiment was located at Lincoln University and was on a fine Templeton sandy loam soil and was irrigated. Both short and long grazing rotation methods were used. The area had a long term mean rainfall of 568 mm however only half of this fell in the 1988/89 season. The lucerne monoculture yielded 12.3 t DM/ha/yr. Monthly yield of 2.8 t DM/ha^{-1} and 1.9 t DM/ha^{-1} were reported for November and January. March yielded 3.2 t DM/ha^{-1} and May and September 2.1 t DM/ha^{-1} and 3.1 t DM/ha^{-1}, respectively.

Baars *et al.,* (1990) carried out three experiments at Winchmore in Canterbury, both irrigated and dryland, and at Wairakei to accurately measure weekly growth rates of lucerne. These growth rates were then related to weather factors over time (Chapter 2.3). The first site at Wairakei was a stand of 'Wairau' lucerne in a uniform area including four paddocks of approximately 0.1 ha each. Sheep grazed the lucerne every eight weeks. "The starting date and hence subsequent grazing dates for each paddock were staggered at two week intervals". Measurements were taken from September-May in each growing season. At Winchmore, Canterbury, 'Wairau' was grown under irrigated (flood) and dryland conditions. Four quadrat cuts of 1 m^2 were taken from each paddock pre grazing. Each grazing was completed in one week, similar to that at Wairakei. A Bayesian smoothing technique was applied so that the data could determine the form of the curved created. The maximum of the yield and its standard error and the growth rate and its standard error were estimated as the maximum growth rate and corresponding time as the occurrence of maximum growth. Growth rates showed a clear short exponential phase, linear phase and a decline after the ceiling yield had been reached. The exponential growth was observed from September to November. The highest ceiling yields were calculated for the months of October and November. The linear growth phase was constant for up to seven weeks. Growth was consistent from October-January when irrigation was applied or without water stress at Wairaki. Wairakei growth rates were up to 185 kg DM/day and up to 136 kg DM/day at Winchmore. The maximum yield achieved at Wairakei was 8.5-10 t DM/ha^{-1} (Figure 6) and 7 t DM/ha^{-1} at Winchmore. Daily growth rates were up to 100 kg DM/ha^{-1} at Wairaki and 120 kg DM/ha^{-1} in Canterbury.

2.1.6 Otago

Musgrave (1983) evaluated the potential of lucerne grown at Omarama, North Otago. The area had a mean annual rainfall of 500 mm. Oversown lucerne yielded 5.3 t DM/ha^{-1} with 3.3 t DM/ha^{-1} grown between mid-August to late November. A detailed method for the oversowing procedure was not published.

Allen (1990) measured the annual production of lucerne at two sites in Otago. The first was at Invermay on a Wingatui soil with a mean annual rainfall of 680 mm. The second was at Dunback on a Claremont soil with a mean annual rainfall of 560 mm. At Invermay annual dry matter production was reported to be 12.9 t DM/ha^{-1} in 1970/71, 18.9 t DM/ha^{-1} in 1971/72 and 14 t DM/ha^{-1} in 1972/73. The annual dry matter production was reported as 7.7 t DM/ha^{-1} in 1971/72 and 8.8 t DM/ha^{-1} in 1972/73 at Dunback.

Thus, there are a number of data sets of annual yield and daily growth rates that may be useful as a guide to potential yields around New Zealand. These agronomic data all differ in collection method, cutting intervals and stand management so need to be interpreted with caution. However, they provide a guide to estimated yields. Table 2.1 summarises the lucerne annual yields (t DM/ha/yr) from different regions of New Zealand stated in this Chapter.

Table 2.1 Summary of lucerne annual yields (t DM/ha/yr) from different regions of New Zealand, 1974-2003.

Region	Annual yield (t DM/ha/yr)	
Waikato	8.2 - 13.6	McGowan *et al.,* (2003)
Taupo	10.3 - 15.7	Baars *et al.*, (1975)
	10.7 - 12.7	McQueen and Baars (1980)
	4.5 - 11.5	Betteridge *et al.*, (2007)
Manawatu	20.2	Theobald and Ball (19830
Marlborough	2.5 - 9.5	Hunter *et al.,* (1994)
Canterbury	10.3 - 28.2	Hoglund et al., (1974)
	1.8 - 15.2	Hayman (1985)
	8.5 - 12	Hunter *et al.,* (1994)
	7 - 10	Baars *et al*., (1990)
	12.3	McKenzie *et al*., (1990)
	21 - 28	Moot (2003)
	17.5 - 21	Brown *et al.*, (2003)
Otago	7.7 - 18.9	Allen (1990)

2.2 Predicting lucerne yields

The next section of this review aims to determine whether unifying relationships based on environmental parameters could be used to predict yields. It summarises the concepts of thermal time, potential evapotranspiration, the Penman formula and published studies that have attempted to link weather variables to lucerne yield. These concepts form the basis of the investigation of relationships between environmental factors and lucerne growth rates in the 'Maxclover' experiment that is used for the analysis in Chapter 4 of this dissertation.

2.2.1 Thermal time

Thermal time has been used to quantify the relationship between pasture yield, both annual and daily dry matter production, and temperature. Plants are poikilothermic as their temperature reflects that of their environment (Trudgill, Honek and Van Straalen 2005). Therefore their growth fluctuates depending on the temperatures they are exposed to. This is because temperature affects many physiological processes within a plant including enzyme activity. To calculate thermal time, values are required for the base temperature (T_b) for growth and daily minimum (T_{min}) and maximum (T_{max}) temperatures. $Tmean$ is the mean of the maximum and minimum daily temperatures. The base temperature is plant specific and differs among pasture species. To calculate T_b Tonmukayakul (2009) fitted linear regressions between accumulated yield and accumulated thermal time data for six different pastures including lucerne. A range of base temperatures was used from 0-8 °C and the highest R^2 value was used to determine the suitability of the T_b. A T_b of 0°C was considered the best fit and that "the R^2 value for cocksfoot/white clover declined as T_b increased". Similar results were obtained using both mean air temperature and 0.1 m soil temperatures. For the calculation of thermal time (Tt), the selection of which temperature parameter to use was important. The 0.1 m soil temperature data were deemed as being more suitable due to the growing point of pasture being below ground. This also resulted in a narrower range of x-axis intercepts compared with using mean air temperature. In contrast, Mills *et al.,* (2006) used daily mean air temperatures. A common challenge was when T_{min} falls below T_b which would result in the impossible sum of negative growth. When daily minimum temperature (T_{min}) is below the chosen base temperature (T_b) then a sinusoidal function was used (Jones and Kiniry 1986). This divides the day/s into 8 x 3 hourly fractions that excluded the period in which T_{min} fell below T_b. To ensure no negative growth values are calculated.

Equation 1

$$\Sigma Tt = \Sigma(Tmean - Tb)$$

Teixeira (2006) examined patterns of lucerne growth and development with different levels of crown and taproot reserves in a cool temperate environment. In doing so thermal time equations were used in the quantification of growth. The thermal time equations "assumed a linear accumulation of heat units above a constant crop specific base temperature, T_b, or temperature threshold". There was a common assumption that there was zero growth till 5°C, so the alternative T_b was set at 5°C. Tt accumulation increased linearly until the optimum of 30°C was reached then decreased linearly to the maximum temperature of 40°C (Fick *et al.,* 1988). Moot *et al.,* (2000) re-analysed work from Hampton *et al.,* (1987) to estimate the T_b and Tt for germination in temperate pasture species. Lucerne cultivars examined were 'Oranga', 'Wairau' and 'Rere' and had a T_b of 0.7, 0.7 and 1.2°C, respectively. The mean T_b for lucerne was 0.9, ± 0.17. In the current study, an analysis of T_b will be one of the objectives. Thermal time will be the first parameter used to test the relationship between environmental factors e.g. mean air temperature, and lucerne growth in the 'Maxclover' experiment. Sim (2014) used a broken stick thermal time model to account for the non-linear growth of lucerne at lower temperatures. Tt was zero for temperatures below T_b. Above T_b, Tt is accumulated linearly at a rate of 0.7°C/°Cd until 15°C and at 1.0°C/°Cd until the optimum of 30°C. The T_{max} was set at 40°C (Masiunas and Carpenter, 1984).

2.2.2 Penman formula and potential evapotranspiration 'PET'

This section examines the use of the Penman formula to calculate the effect of soil moisture on lucerne growth. Also included is background context for evapotranspiration.

The Penman formula (1952) had been used "successfully to quantify the relative effect of water deficit on annual crops in terms of PET". However lucerne crops differ from annual crops as they are often defoliated multiple times in one season. Van Housen (2015) described the Penman equation (Eq. 2) as a method of using climate data to estimate evapotranspiration. $\Delta R\eta$ is net radiation, G the soil heat flux and $\mathrm{P}\alpha$ the mean air density. $C\rho$ is the specific heat of the air at a constant pressure and Δ is the slope of the saturation vapour temperature relationship. es is the saturation vapor pressure and ea is the actual vapor pressure of the air above the given crop. $r\alpha$ is the aerodynamic resistances and λ the psychometric constant. y is the latent heat vaporisation and is equal to 2.45 MJ/kg. This calculates the evapotranspiration, water loss from a crop.

Equation 2

$$ET = \frac{\Delta R\eta - G + \mathrm{P}\alpha\, C\rho\, \frac{es - ea}{r\alpha}}{\lambda(\Delta + y)}$$

Martin (1984) formulated a simple model to calculate the yield reduction of lucerne caused by a soil water deficit. The model used a combination of PET, rainfall and irrigation data for lucerne grown in two soil types under flood irrigation in Canterbury.

One experiment consisted of lucerne grown at Winchmore Research Station, sown in November 1978. The second experiment was solely 'Wairau' lucerne sown in 1970 at Winchmore. All data were sourced from the Winchmore meteorological station except sunshine hours, which was recorded in Ashburton. An assumption of the model is that the yield of the partially or fully irrigated crop is that the crop is never so short of water that its growth is restricted. The crop determined as 'fully irrigated' was that with the most frequent irrigation regime. July 1st was the beginning of the model year.

The actual model was not reported but the terms 'D' and 'DL' from the model were well explained. 'D' represented the cumulative potential deficit, which was calculated every day. 'DL' represented the limiting cumulative potential and was calculated daily by adding the PET and subtracting water input values (rainfall or irrigation) from the previous days. DL was defined as "the maximum permitted value D could reach during a growth period". If the value of D was calculated as negative then it was set to zero. If D exceeded DL then D was set to DL, with the exception of water inputs exceeding PET then the deficit fell below DL. From these, predicted yields were calculated for each year "using the mean value (mean DL for each experiment was the mean of the optimum DL for each year)". The model was tested using the % error loss in yield. This was the regression of the 'fully irrigated – predicted yield' against 'fully irrigated – actual yield', expressed as a percentage.

The model predicted that lucerne growth would be limited on the Templeton silt loam when "the cumulative potential deficit, calculated using the Penman formula, exceeded approximately 320 mm. It was concluded that using the Penman formula gave a stronger prediction than Priestly Taylor. Values generated by Priestly Taylor were multiplied by a factor of 0.65. The reasoning behind the use of this factor was not discussed. However, it was stated that the Priestley-Taylor formula overestimated the larger lucerne yield reductions. In contrast, growth was predicated to be restricted at 190 mm on a stony Lismore silt loam. These values quantified the effect of soil type and associated soil water holding capacity on lucerne yield in terms of accumulated PET. The assumptions used in the model were said to 'work well' for the Templeton soil even with the somewhat crude assumptions used. The justification and successful use of the Penman formula in relation to lucerne growth was also noted.

The relationship used in this model is best described by Wilson *et al.,* (1985). Figure 4.1 shows the ratio of (Y/Yo) of the seed yield of unirrigated and partially irrigated field peas to that of a fully irrigated crop versus the maximum potential soil moisture deficit (Dm) that occurred between emergence and maturity in three experiments. The amount of yield reduction below the potential yield for the conditions was dependent on the severity of water deficits experienced by a crop during growth. No reduction in yield occurs if the critical deficit (Dc) for the specific crop/soil combination is not exceeded during growth. This is about 50% of the plant available water in the top 1 m of soil. A yield reduction occurs when the critical deficit is exceeded. This reduction is directly proportional to the difference between the maximum deficit (Dm) and Dc. The yield reduction is proportional to the potential yield in well watered conditions. Therefore, crops with high yield potentials incur the greatest yield losses if water deficits are allowed to persist. Water deficits are characteristic of summer dry conditions experienced in dryland farming systems reliant on rainfall events.

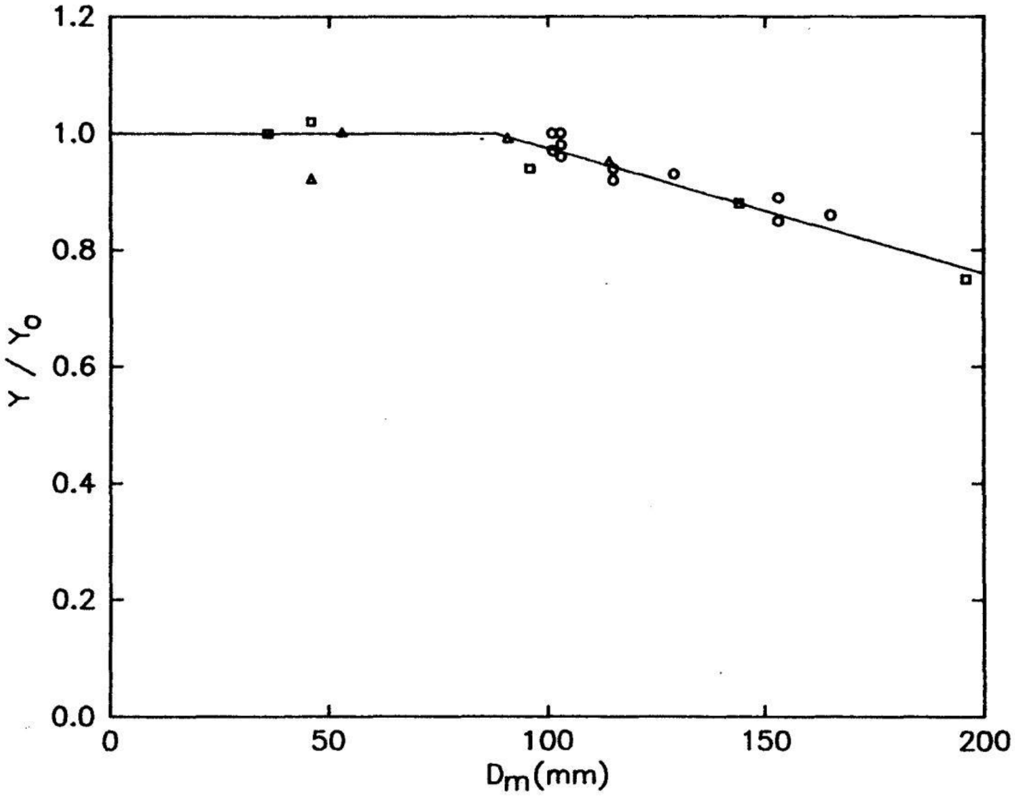

Figure 2.4 The ratio of (Y/Yo) of the seed yield of unirrigated and partially irrigated field peas to that of a fully irrigated crop versus the maximum potential soil moisture deficit (Dm) that occurred between emergence and maturity in three experiments. The slope of the line above the critical potential soil moisture deficit (88 ± 2 mm) is -0.0022 ± 0.0002 mm^{-1} (R^2 = 0.89***). From Wilson *et al.*, (1985).

2.3 Lucerne growth and weather variables

Linear and quadratic regressions were carried out to correlate the maximum monthly lucerne growth rates and yields with monthly weather data by Baars *et al.,* (1990). Yields from their Canterbury and Rotorua/Taupo region (2.1.2) were used to relate weather factors to lucerne growth from September 1977 for two years. Specific details about the source of their weather information was not outlined. Monthly weather data included means of radiation, maximum and minimum soil and air temperatures, total rainfall and evapotranspiration. Evapotranspiration (ET) was calculated using the Penman equation. At Wairakei there was no significant relationship between lucerne growth and daily minimum or maximum temperatures, rainfall, radiation and water deficits. Growth rates after November were however significantly correlated with both accumulated and monthly evapotranspiration (ET). Ceiling yields were significantly correlated with accumulated ET and radiation. On the Canterbury dryland plots growth rate in both the active growing season and after November were positively correlated with monthly Penman ET. For the Canterbury irrigated lucerne growth rates were significantly correlated with ET and radiation also. Less significant relationships were made with 10 cm soil temperature and mean air temperature. Daily growth rates after November at Wairaki were correlated with accumulated ET and monthly ET. Ceiling yields were also significantly correlated with accumulated evapotranspiration (R^2 = 0.78) and radiation. Growth rates in the active growing season and after November at Winchmore were also correlated with monthly ET (R^2 = 0.64, ET and maximum growth rates after November). The growth of the irrigated lucerne was correlated with Penman ET (R^2 = 0.69). It was less correlated with mean air temperature but ceiling yields were highly correlated (R^2 = 0.94) with ET and radiation. Data for specific ET values was not published.

An early theory by Kerr *et al.,* (1973) was that lucerne was an inefficient user of water due to a low stomatal resistance to water transpiration, explaining the connection with ET. In contrast it was problematic to define the effects of rainfall and water deficits on dryland lucerne yield. It was concluded that more detailed weather data and weekly cutting was required to further analyse this relationship. The lack of correlation between dryland lucerne growth rates and weather variables indicated that growth was not related simply to environmental factors over the growing season. This is because the "lucerne growth cycle is closely correlated to the amount of available carbohydrates stored in the roots". Lucerne management, especially in late summer to early autumn interacts with environmental factors, which determines the available quantities of carbohydrates for remobilisation in spring as well as seasonal changes in partitioning (Figure 2.3). Additional interactions occur with water deficits, making the influence of environmental factors on growth rates less clear. Because of the apparent correlation between lucerne yield and accumulated ET this dissertation will analyse lucerne growth from the 'Maxclover' long term experiment with accumulated PET values in each of the eight growing seasons. PET may be a stronger predictor of expected lucerne yield than accumulated thermal time.

2.3.1 Potential soil moisture deficit (mm)

As PET has been identified as a potential predictor of lucerne yield (Baars *et al*., 1990) it is also important to evaluate the use of potential soil moisture deficit 'PSMD' (mm) due to the inclusion of rainfall (Eq. 3). When PET exceeds rainfall a soil moisture deficit can occur. PSMD is associated with both rainfall distribution and PET (Sim, 2014). Sim (2014) stated that PSMD generally began to increase in September through to a maximum in April/May. $PSMD_{i-i}$ is the PSMD on the previous day and EP_i the PET for that day minus daily rainfall (mm). PSMD increases and decreases depending on daily PET values and the amount of daily rainfall. The equation doesn't account for rainfall runoff, but in free draining soils of Canterbury this is less of a problem than in other regions of New Zealand. Moot *et al*., (2008) calculated that lucerne produces ~30 kg DM/ha^{-1} per 1 mm of water extracted from the soil. Therefore, PSMD is of importance as it influenced the plant available water in the soil profile. If soil water is limited then lucerne dry matter production will be subsequently limited.

Equation 3

$$PSMD_i = PSMD_{i-i} + EP_i - rainfall$$

2.4 Conclusions

This literature review highlighted the variation in lucerne growth in different regions of New Zealand. The variation in soil types and climate indicated the influence of soil water holding capacity on lucerne growth. The data collated to meet Objective 1 can be referred to later in the dissertation to compare to predicted lucerne yields and growth rates. Objective 2 was achieved by describing previous attempts to predict lucerne yield and based on the main environmental drivers of thermal time, potential evapotranspiration soil moisture. The remainder of this dissertation will focus on Objective 3 to the relationship between these environmental factors and growth of lucerne in the 'Maxclover' experiment from 2002-2010. A broken stick threshold model (Sim, 2014) will be used to calculate accumulated thermal time. This will use a T_b of 0°C (Tonmukayakul, 2009), a T_{opt} of 30°C (Fick *et al*., 1988) and a T_{max} of 40°C (Masiunas and Carpenter, 1984; Fick *et al*., 1988).

3 MATERIALS AND METHODS

Details about the 'Maxclover' experimental methods were sourced from Mills *et al.,* (2006), Tonmukayakul (2009) and Morris (2011). The data set was collected over eight Years and forms the basis of the analysis presented in Chapter 4.

3.1 Experimental site

The experimental site was located at Lincoln University, Canterbury, New Zealand (43°38'S, 172°28'E) paddock H19. The soil type is a Templeton silt loam overlying alluvial gravels (Cox, 1978). The subsoil from 0.85 to 1.45 m deep consists of small quantities of sand and clay with primarily silt sized particles (Raeside and Rennie, 1974). The alluvial gravels consist of stones and gravels and rocks as well as large sandy particles (Khonke and Bertrand, 1959).

The 'Maxclover' experiment compared six dryland pastures in a randomized complete block design with six replicates. Replicates 1- 4 were sown at a rate of 5.7 kg/ha in February 2002. Replicates 5 and 6 were sown in autumn 2003 and are therefore not included in this analysis due to the age difference. Data from the replicates of the 'Kaituna' lucerne monoculture are presented. Each plot was 506 m^2 or 0.05 ha. The lucerne was inoculated with the appropriate peat based inoculant <24 hrs prior to sowing and sown at 10 kg/ha. Crops were left to establish for the first year and then managed by conventional grazing for the next eight years. It is the data from the conventionally grazed years that is used in the current analysis.

3.2 Grazing management

The lucerne in the 'Maxclover' experiment was grazed under best management guidelines. The lucerne replicates were rotationally grazed during active growing periods. Plots were destocked from June-August except for a few ewes to 'clean up' at some point in the winter period. The removal of stock over winter months was to simulate a commercial farming system where winter feed is available from specialist crops. From Years 1-7 the plots were grazed with Coopworth hoggets from spring into summer. In spring of Year 8 ewes with lambs at foot first grazed the lucerne then weaned lambs grazed from summer through to autumn. The stocking rate (E.g. 2009-2010) was 2-3 ewes with twins in spring and 8-10 lambs over the summer and autumn months.

3.3 Climate

Mean monthly temperatures and monthly rainfall totals (Figure 3.1) were sourced from NIWA's Cliflo, from the Broadfields meteorological station (Station 17603) located 2 km north of the experimental site. Error bars showing the standard error of the mean show large variation in mean monthly rainfall across the eight years. This indicates variation in seasonal rainfall, which is common for eastern areas of New Zealand. The long term annual mean was 630 mm/yr. In the summer of Year 3 rainfall totaled 184 mm, which was 28% above average. In September of 2004 snow fell, which broke upright stems of the lucerne, disrupting grazing and measurements. However, it regrew and recovered without detrimental effects. In the summer of Year 4 rainfall was 25% below average with 108 mm. In Year 6 overall annual rainfall was above average at 645 mm and summer rainfall above average at 177 mm, 23% higher from December-February. Year 7 was the wettest of the 8 years with an annual total of 783 mm (long term mean 635 mm). Rainfall for July-November in Year 8 was 195 mm, 30% below average. Rainfall was also below average in the summer of Year 8.

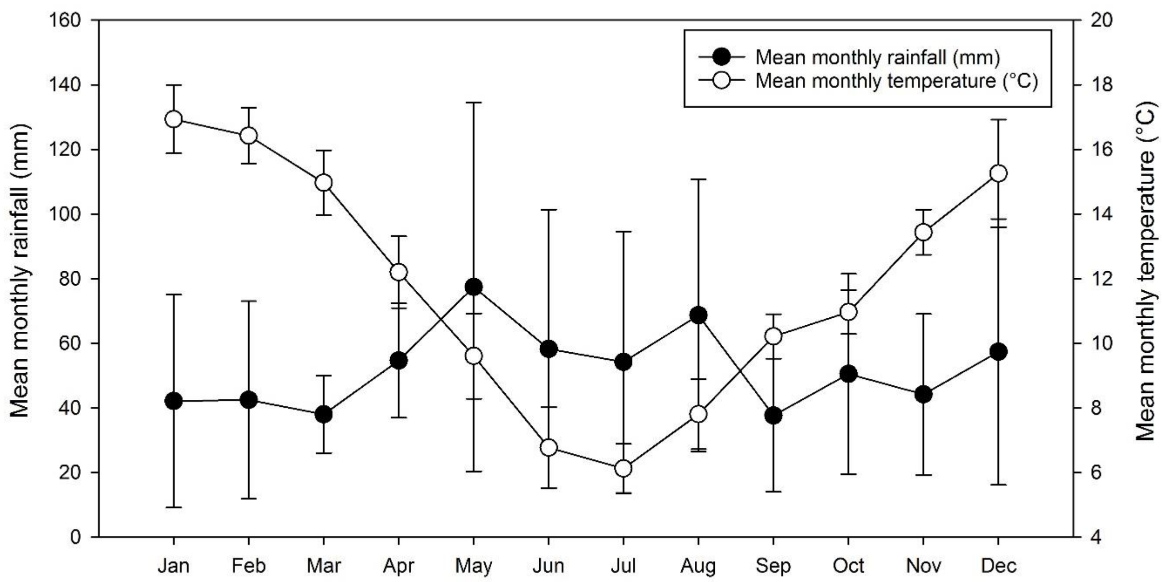

Figure 3.1 Mean monthly rainfall (mm) and temperature (°C) for the 'Maxclover' experiment from 2002-2010. Error bars represent the standard error of the mean and show the high variability of rainfall in this environment.

3.4 Measurements

3.4.1 Season start dates

The start date is described as the first day of dry matter measurement of the new season (Table 2.1) directly following the last harvest of the previous season. Yield is set to 0 kg DM/ha at the start of each season, following the final harvest of the previous year. Over the eight growing seasons of the 'Maxclover' experiment each had a different starting date. The earliest start date was in 'Year 6' on 20 June 2007. The latest season start was in 'Year 1', the establishment year, on 4 September 2002. These different start dates were taken into account in all analysis including yield accumulation (kg DM/ha/yr), thermal time accumulation (°Cd) and PET accumulation (mm). It is also noted that all harvests occurred on different days for each replicate for each of the six harvests per season (except for Year 1 with 8 harvests).

Table 3.1 Start dates for each growing season of 'Kaituna' lucerne in Years 1-8 of the 'Maxclover' experiment, 2002-2010, Lincoln University, Canterbury.

Year		Start of season
1	2002-2003	4/09/02
2	2003-2004	1/07/03
3	2004-2005	28/06/04
4	2005-2006	29/06/05
5	2006-2007	27/06/06
6	2007-2008	20/06/07
7	2008-2009	27/06/08
8	2009-2010	1/07/09

Note: Yield is set to 0 kg DM/ha at the start of each season, following the final harvest of the previous year.

3.4.2 Dry matter yield (kg DM/ha^{-1})

Herbage samples were taken from 0.2 m^2 quadrat cuts from 1140 x 760 mm closed cages in each plot, harvests for each replicate occurred on the same day. Yield was the sum of each cage cut (Appendix. 1). Samples were dried at 65 for at least 48 hours then weighed. Cages were shifted to a new site in the plot after each harvest.

3.4.3 Daily growth rates (kg DM/ha/day)

Daily growth rates (kg DM/ha/day) were calculated for each replicate by dividing the total yield after each harvest by the number of days between each harvest. An average was then calculated from the four replicates at each harvest. Standard errors of the mean were calculated for each harvest in each growing season.

3.4.4 Thermal time (°Cd)

Thermal time values were calculated in two ways to determine the best method of predicting spring lucerne growth. Values were calculated and accumulated from the start date of each growth season (Table 2.1). The first method used a standard lucerne Tt model (T_b 5°C, T_{opt} 30°C and T_{max} 40°C) (Fick *et al.,* 1988). Daily minimum and maximum air temperature data were input into the model. Daily minimum, maximum and mean temperatures were sourced from NIWA's Cliflo, from the Broadfields meteorological station (17603) located 2 km north of the experimental site. A second model to calculate Tt was a three-stage lucerne Tt model (T_b 0°C, 15°C, T_{opt} 30°C and T_{max} 40°C). This 'broken stick' model splits the initial linear phase of accumulation towards the optimum into two phases. The T_b of 0°C was selected due to it being more suitable for lucerne Tt calculation (Teixeira, 2011). Accumulated thermal time was calculated by adding each days Tt value to the sum of the previous days in that growing season.

3.4.5 Potential evapotranspiration (mm) and Potential soil moisture deficit (mm)

Potential evapotranspiration 'PET' (mm) was sourced from NIWA's Cliflo and was calculated using the Penman formula (Van Housen, 2015). Two methods of PET accumulation were used. The first accumulation from the start date of each year (Table 3.1). The second method from 1st September (Sim, 2014). Potential soil moisture deficit 'PSMD' (mm) was calculated using Equation 4 with PET (mm) and daily rainfall (mm) sourced from NIWA's Cliflo for each of the eight years of the 'Maxclover' experiment.

3.5 Data analysis

3.5.1 Split line regression

A split line regression in Genstat (18th ed.) was used to analyse the relationship between lucerne accumulated dry matter production (kg DM/ha^{-1}) and accumulated thermal time (°Cd). This method used a broken stick and was the best fit to the accumulated lucerne yield, compared with a simple linear regression. This analysis was performed for each of the four replicates over eight years to give 32 separate regression analysis. This produced two separate regression equations in which the first equation (Eq. 4) defined spring growth. a_1 is the y intercept and b_1 is the slope of the line.

Equation 4

$$Yield = a_1 + b_1x$$

The second equation (Eq. 5) represented the growth rate after limited soil water reduced lucerne growth. a_2 is the y intercept and b_2 is the slope of the line. a_2 is not given in the split line regression output as the second regression line is joined to the first.

Equation 5

$$Yield = a_2 + b_2x$$

To avoid bias the 'breakpoint' between these lines was selected as the best fit by Genstat. This is the point of transition from one constant growth rate to another. The predicted accumulated thermal time value and 'y' the predicted accumulated yield value (y_1) at (y_2) therefore differs with the coefficient for slope. The coefficient of determination (R^2) however, for each regression then represents the goodness of fit. Values for a_1 and a_2, the slope of each line, were estimated for each replicate. Values of the 'x' and 'y' intercepts were also calculated for each replicate. The exception was Replicate 4 in Year 1 (2002-2003) so a standard linear regression was fitted. No 'x' and 'y' breakpoint was detected. However, a breakpoint was forced for Replicate 1 of Year 4 (2005-2006) by splitting the data manually into two linear lines of '3' data points and '4' data points. It was noted that this replicate may have displayed a three phase growth pattern. The coefficients of the split line regressions (b_1, b_2, breakpoint 'x' axis, breakpoint 'y' axis, R^2, 'x' intercept and 'y' intercept) are summarized in Table 4.5 and Appendix 1 for each replicate in each growing season.

3.5.2 Analysis of variance

The 32 coefficients of the split line regression (a_1, a_2, breakpoint 'x' axis, breakpoint 'y' axis, R^2, 'x' intercept and 'y' intercept) were analysed with a general one way ANOVA in Genstat (Table 4.6 and Appendix 2). Two ANOVA's were carried out, one with and one excluding Year 1 (2002-2003) to evaluate the effect of the establishment year on results. The 32 PET values at the 'x' and 'y' breakpoint of each split line regression were also analysed with a one way ANOVA. P values <0.05 were deemed significant.

3.5.3 Potential evapotranspiration 'PET'

Accumulated potential evapotranspiration 'PET' (mm) was calculated for each of the four replicates of each of the eight seasons (Appendix 3 and Appendix 4). Accumulation was set from both the start date of each growth season (Table 4.3) and 1st September (Table 4.4). This was used to determine the accumulated PET value at each of the split line regression breakpoints. P values <0.05 were deemed significant.

3.5.4 Potential soil moisture deficit 'PSMD'

Accumulated potential soil moisture deficit 'PSMD' (mm) was calculated for each of the four replicates of each of the eight seasons (Appendix 5). Accumulation was set from the 1st September for PET, daily rainfall (mm) and PSMD (mm). This was used to determine the accumulated PSMD value at each of the split line regression breakpoints. P values <0.05 were deemed significant.

3.6 Hypothesis

The null hypothesis is that there is no difference in the slope (a_1 or a_2) of each section of the split line regressions for each lucerne replicate. A second null hypothesis is that there will be no difference in the coefficients of the coordinates of the 'breakpoint' in the split line regression in terms or their 'x' and 'y' (accumulated thermal time and yield). These predictions will be tested for all 4 replicates across each of the 8 growing seasons of the 'Maxclover' experiment.

4 RESULTS

This results section initially summarises the lucerne yields an agronomical and production perspective. This allows comparison with previous literature in Chapter 5 and whether variations in yield can be related to weather variables is the main focus of the analysis in this dissertation.

4.1 Annual yield (kg DM/ha)

Table 4.1 displays the mean annual yield (kg DM/ha/yr) of these lucerne monocultures, across Replicates 1-4, from 2002-2010 in the 'Maxclover' experiment. Year 3, 2004-2005, was the highest ($P<0.05$) yielding growing season with an annual yield of 19,200 ± 631 kg DM/ha/yr (19 t DM/ha^{-1}). The lowest yielding season was Year 4, 2005-2006, with an average of 10,100 ± 456kg DM/ha/yr (10 t DM/ha^{-1}), but this was not different from Years 2, 6, 7 or 8. Over the eight growing seasons the mean annual yield was 15,000 kg ± 1104 DM/ha/yr.

Table 4.1 Total annual yield (kg DM/ha/yr) of 'Kaituna' lucerne in Years 1-8 of the 'Maxclover' experiment, 2002-2010, Lincoln University, Canterbury. SEM is the standard error of the mean.

Year		Yield (kg DM/ha/yr)*	SEM (±)
1	2002-2003	17809^{b}	806
2	2003-2004	13099^{c}	190
3	2004-2005	19186^{a}	631
4	2005-2006	10116^{c}	456
5	2006-2007	18158^{ab}	150
6	2007-2008	14338^{c}	353
7	2008-2009	14014^{c}	152
8	2009-2010	13012^{c}	517
Mean	2002-2010	15000	1104

Note: *Average of four replicates (1, 2, 3 and 4). Superscripts indicate means that are different, L.S.D (5%).

4.2 Daily growth rates (kg DM/ha)

Figures 4.1 and 4.2 show that in most years the growth rates of lucerne followed a consistent pattern. Harvests for each replicate in each year were not all on the same day or the same month. This meant that monthly mean daily growth rates were determined by the data available for replicates in that month. Every year consisted of six harvests except for Year 1, which had eight. The consistent growth pattern started with a rapid increase in spring (September), with maximum growth rates of approximately 70 kg DM/ha/d in October in the first three years. November rates decreased slightly to 60 kg DM/ha/d but peaked at 108 kg DM/ha/d in December. Growth declined from 80 kg DM/ha/d in January to 20 in March and 30 kg DM/ha/d in May.

From 2005-2006 onwards the maximum December growth rate dropped closer to 80 kg DM/ha/d. After this peak growth rate there was usually a decline in January or February to 40-60 kg DM/ha/d with a further decline to 20-40 kg DM/ha/d in autumn. Winter growth rates recorded into June were as low as 6 kg DM/ha/d. The timing and extent of the decline in summer and autumn was unique for each season (Figure 4.1 and 4.2). The main aim of this dissertation is to determine if these variations in mean growth rates can be attributed to environmental factors. Further analysis initially examines the influence of temperature followed by soil water.

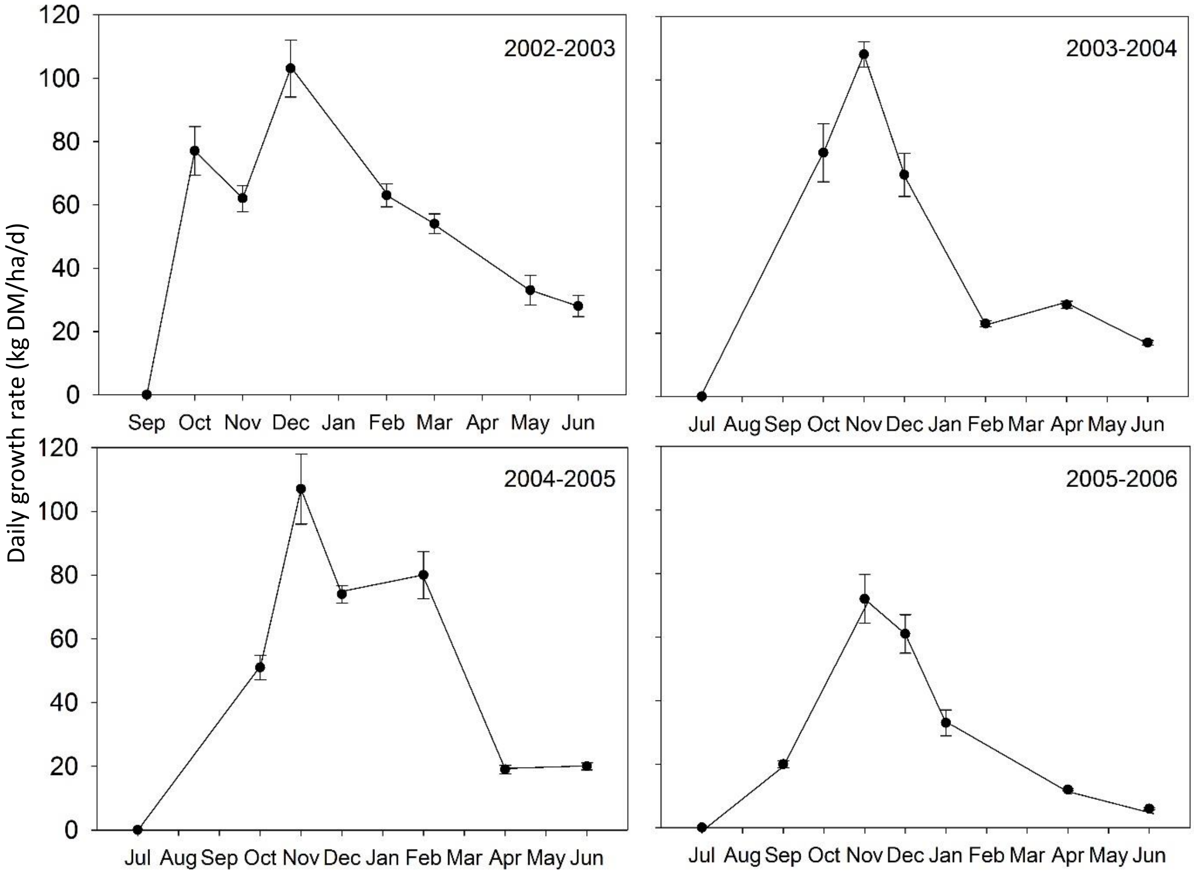

Figure 4.1 Mean daily growth rates (kg DM/ha/d) of lucerne in Years 1-4 of the 'Maxclover' experiment, 2002-2006. Error bars indicate the standard error of the mean.

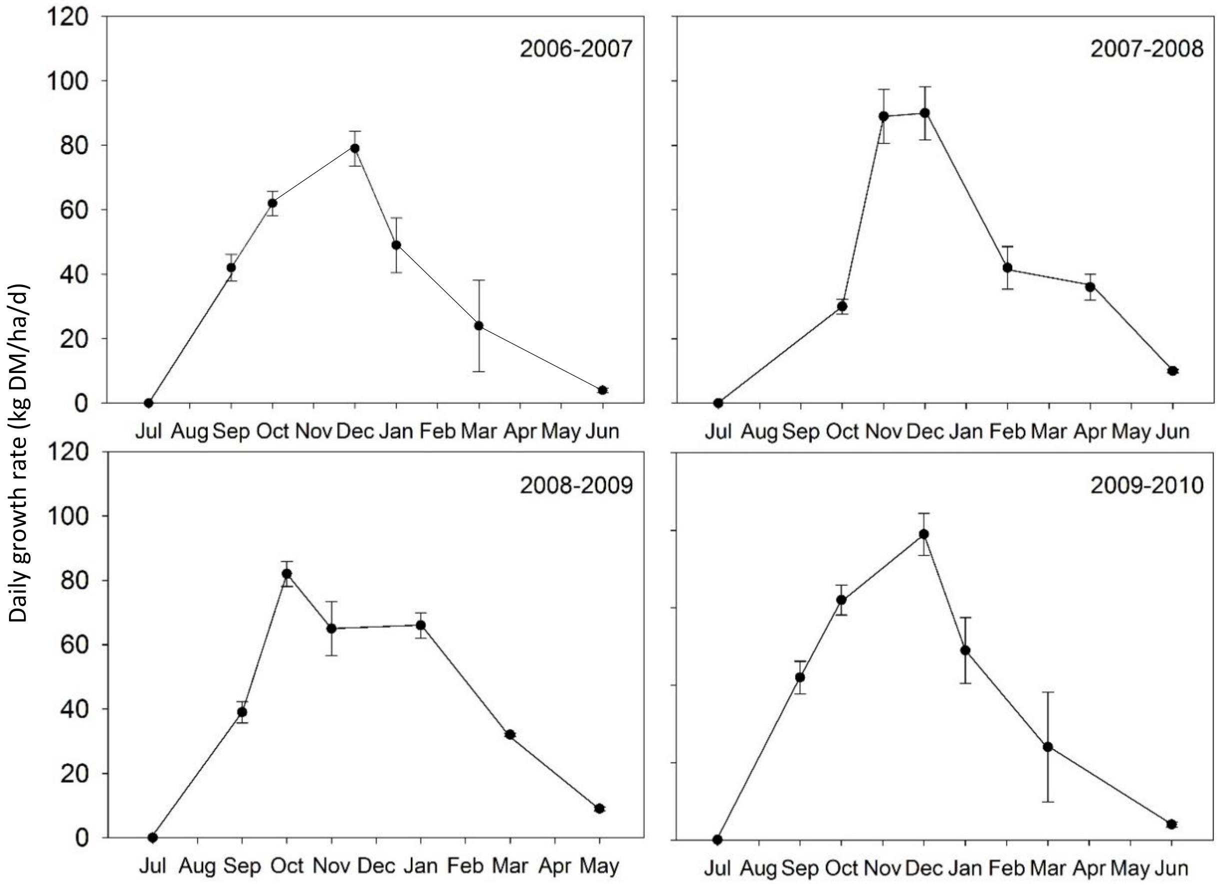

Figure 4.2 Mean daily growth rates (kg DM/ha/d) of lucerne in Years 5-8 of the 'Maxclover' experiment, 2006-2010. Error bars indicate the standard error of the mean.

4.3 Accumulated yield (kg DM /ha) and thermal time (°Cd)

Figures 4.3 to 4.10 show the accumulated yield (kg DM/ha) of lucerne against accumulated thermal time (°Cd) in Years 1-8 of the 'Maxclover' experiment (2002-2010). The mean y axis intercept of the split line regression was -1437 ± 260 kg DM/ha^{-1} (<0.001) and mean x axis intercept 177.6 ± 31°Cd (<0.001) across the eight years. However, these intercepts were not different across the eight years (P = 0.214 and P= 0.887, respectively). Dry matter accumulation continued linearly at a constant rate of 9.2 ± 0.29 kg DM/°Cd (P =0.64) until ~1410 °Cd ± 46 (P = 0.247). After this point growth plateaued to another consistent (P = 0.334) but reduced growth rate of 2.2 ± 0.24 kg DM/°Cd. The mean coefficients of the breakpoint and x intercept of the split line regression for each year are presented in Table 4.2. Also included is rainfall (mm/°Cd) to give an indication of rainfall event frequency and amount after the breakpoint.

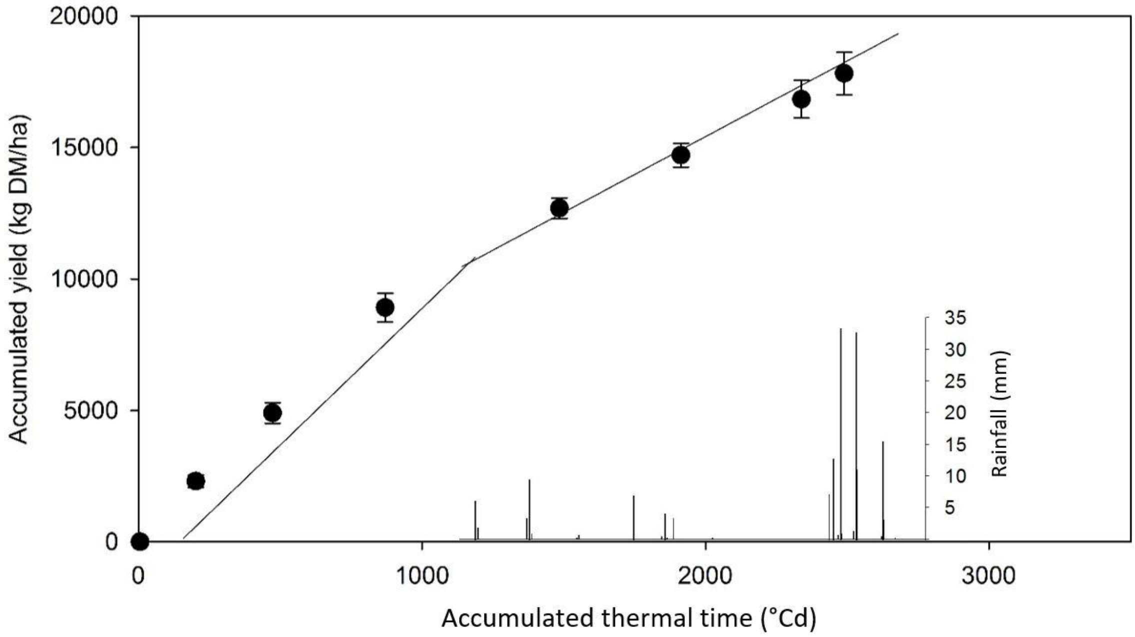

Figure 4.3 Accumulated lucerne yield (kg DM/ha^{-1}) of lucerne against accumulated thermal time (°Cd) and rainfall (mm/°Cd) in Year 1 of the 'Maxclover' experiment, 2002-2003.T_b 0°C. Error bars indicate the standard error of the mean. The breakpoint for the split line regression is (1114°Cd, 10470 kg DM/ha).

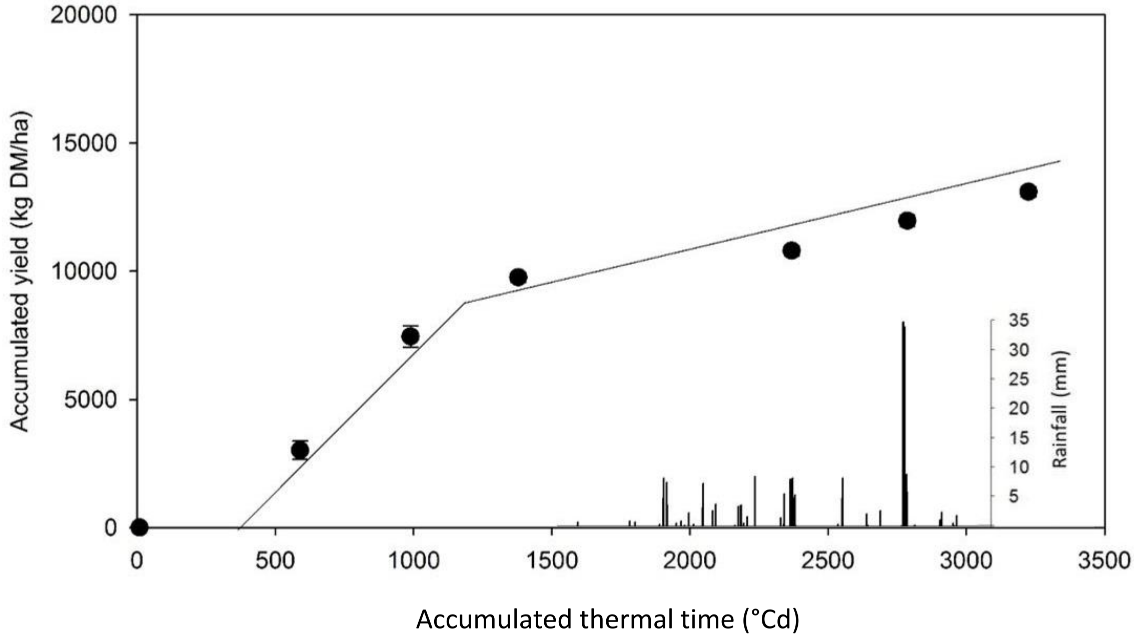

Figure 4.4. Accumulated lucerne yield (kg DM/ha^{-1}) of lucerne against accumulated thermal time (°Cd) and rainfall (mm/°Cd) in Year 2 of the 'Maxclover' experiment, 2003-2004. T_b 0°C. Error bars indicate the standard error of the mean. The breakpoint for the split line regression is (1140°Cd, 9103 kg DM/ha).

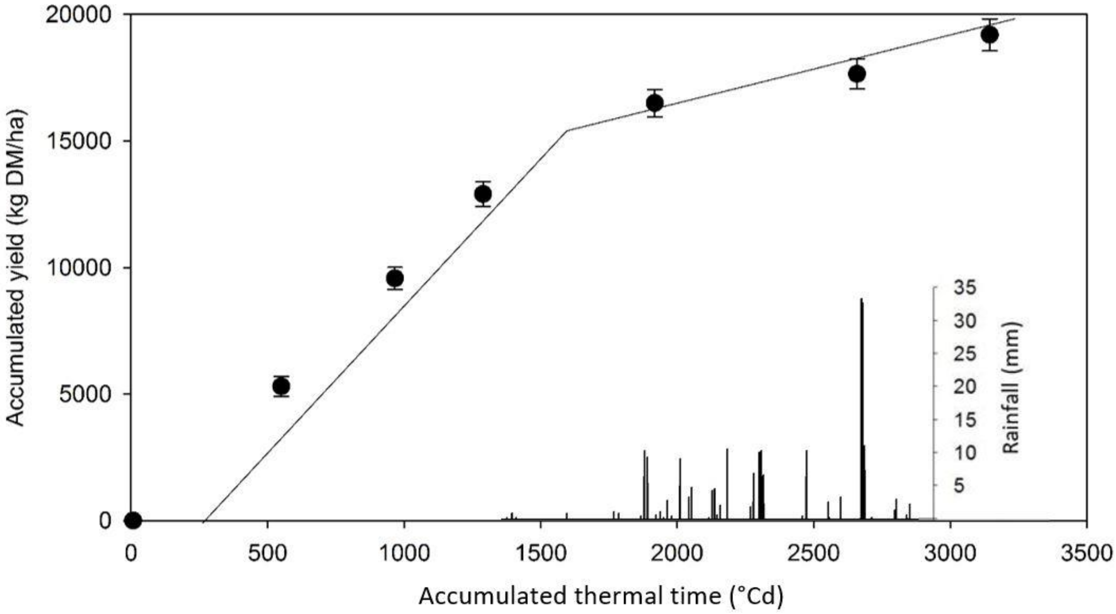

Figure 4.5 Accumulated lucerne yield (kg DM/ha^{-1}) of lucerne against accumulated thermal time (°Cd) and rainfall (mm/°Cd) in Year 3 of the 'Maxclover' experiment, 2004-2005. T_b 0°C. Error bars indicate the standard error of the mean. The breakpoint for the split line regression is (1555°Cd, 15597 kg DM/ha).

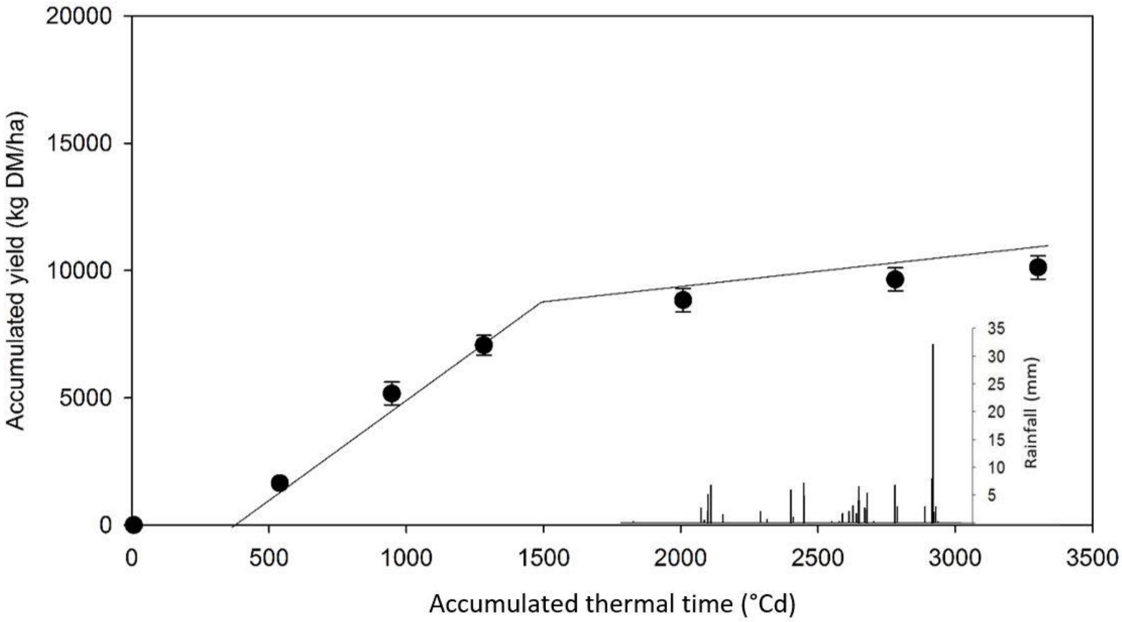

Figure 4.6 Accumulated lucerne yield (kg DM/ha^{-1}) of lucerne against accumulated thermal time (°Cd) and rainfall (mm/°Cd) in Year 4 of the 'Maxclover' experiment, 2006-2007. T_b 0°C. Error bars indicate the standard error of the mean. The breakpoint for the split line regression is (1484°Cd, 8351 kg DM/ha).

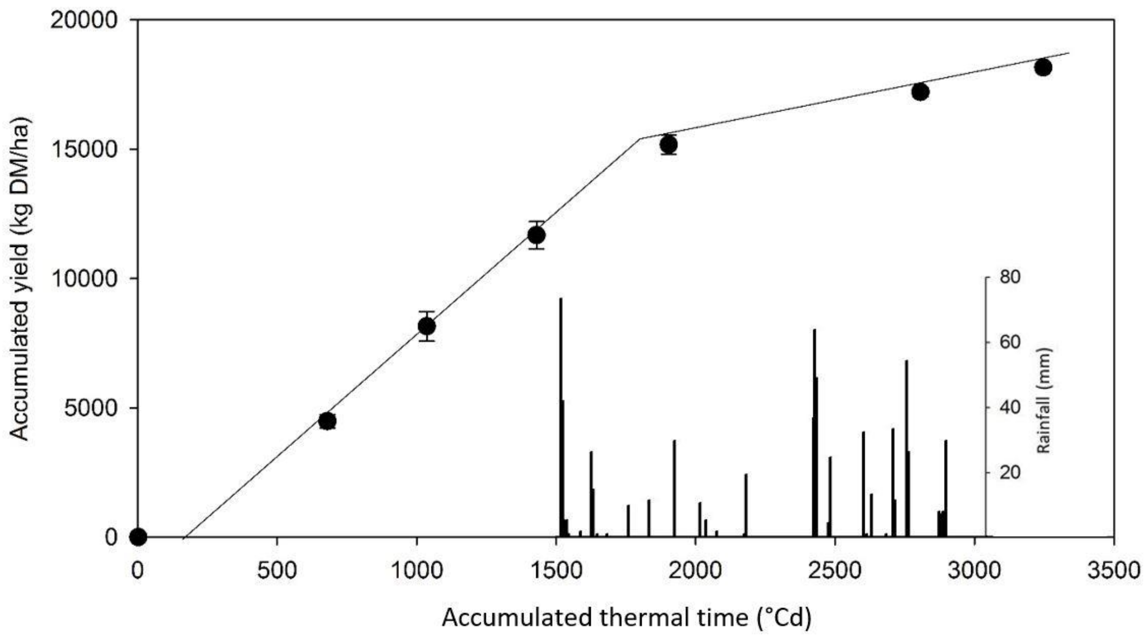

Figure 4.7 Accumulated lucerne yield (kg DM/ha^{-1}) of lucerne against accumulated thermal time (°Cd) and rainfall (mm/°Cd) in Year 5 of the 'Maxclover' experiment, 2006-2007. T_b 0°C. Error bars indicate the standard error of the mean. The breakpoint for the split line regression is (1791°Cd, 15108 kg DM/ha).

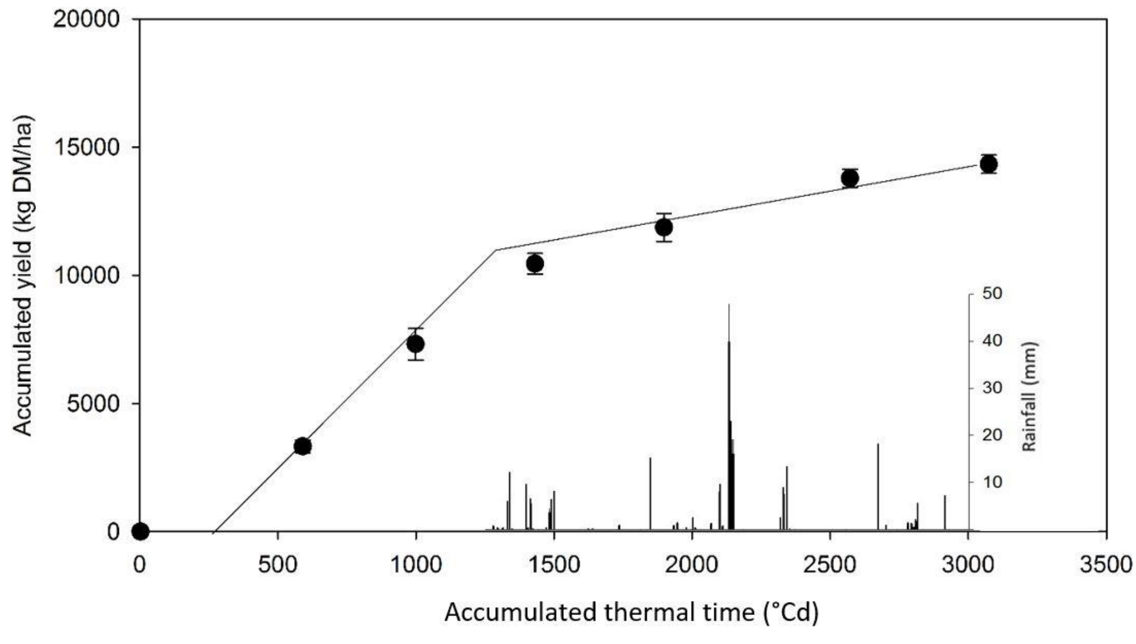

Figure 4.8 Accumulated lucerne yield (kg DM/ha^{-1}) of lucerne against accumulated thermal time (°Cd) and rainfall (mm/°Cd) in Year 6 of the 'Maxclover' experiment, 2007-2008. T_b 0°C.Error bars indicate the standard error of the mean. The breakpoint for the split line regression is (1318°Cd, 10443 kg DM/ha).

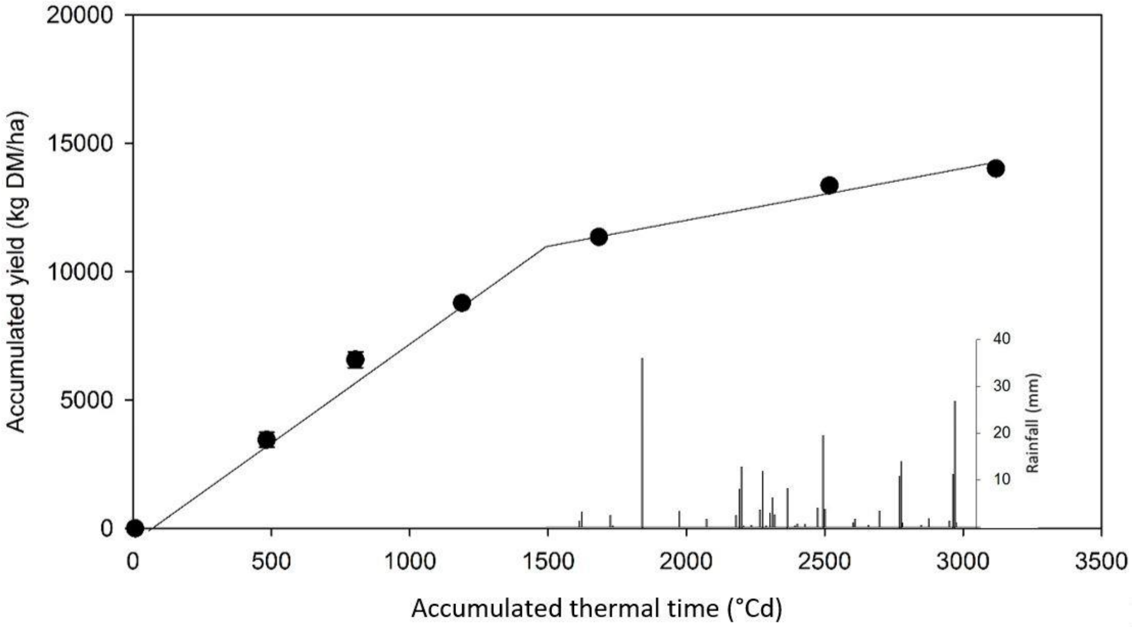

Figure 4.9 Accumulated lucerne yield (kg DM/ha^{-1}) of lucerne against accumulated thermal time (°Cd) and rainfall (mm/°Cd) in Year 7 of the 'Maxclover' experiment, 2008-2009. T_b 0°C. Error bars indicate the standard error of the mean. The breakpoint for the split line regression is (1425°Cd, 10191 kg DM/ha).

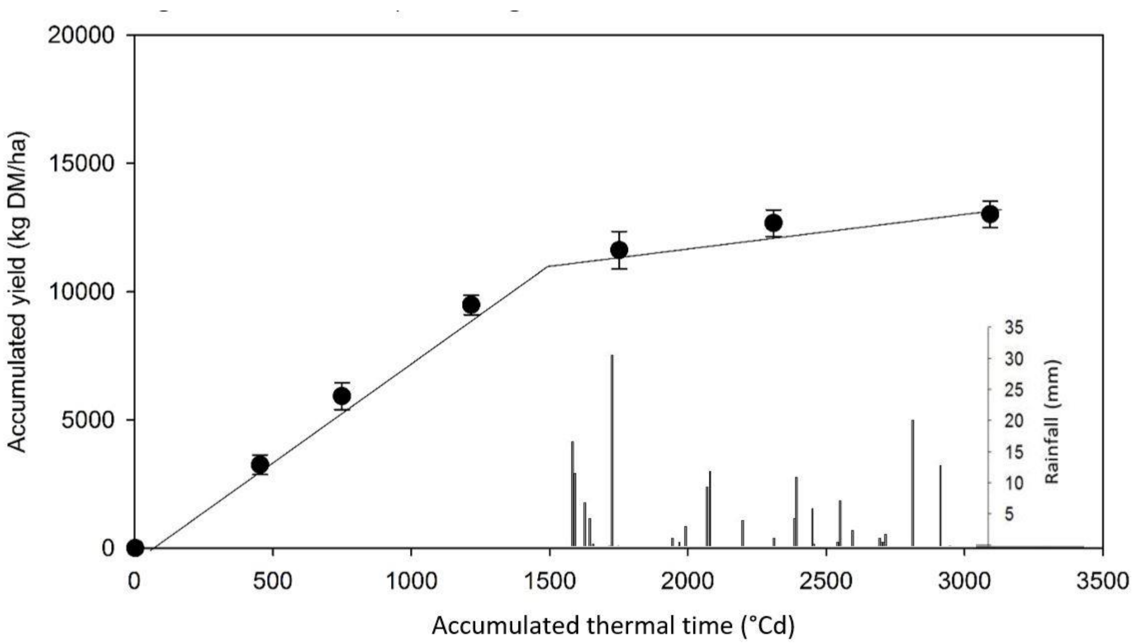

Figure 4.10 Accumulated lucerne yield (kg DM/ha^{-1}) of lucerne against accumulated thermal time (°Cd) and rainfall (mm/°Cd) in Year 8 of the 'Maxclover' experiment, 2009-2010. T_b 0°C. Error bars indicate the standard error of the mean. The breakpoint for the split line regression is (1453°Cd, 11463 kg DM/ha).

4.3.1 Split line regression

Table 4.2 also shows the summary of the analysis of variance on the coefficients of 32 split line regressions of accumulated lucerne yield (DM/ha/yr) against accumulated thermal time (°Cd) from 2002-2010 in the Maxclover experiment (Appendix 2). All of the coefficients (b_2, breakpoint ‘x’ axis, breakpoint ‘y’ axis, R^2, ‘x’ intercept and ‘y’ intercept) were not different ($P<0.05$) across the eight years, 2002-2010, of the ‘Maxclover’ experiment except for b_1 when Year 1 was included. This was probably due to the predicted influence of reduced dry matter production in the establishment year (Sim, 2014). So for comparative purposes it was from all of the all other analyses. b_1 is the slope of the first line equation (P=0.64) and b_2 the slope of the second (P=0.334). Breakpoint x is the yield accumulation change in terms of thermal time (°Cd) (P=0247). Breakpoint y is the yield accumulation change in terms of accumulated dry matter (DM/ha/yr) (P=0.744). The x and y intercepts are the point at which the split line regression crosses the x and y axis. The x axis intercept represents accumulated thermal time (°Cd) and the y axis accumulated yield (kg DM/ha). The coefficient of determination, R^2, represents the goodness of fit of the split line regression.

Table 4.2 Mean split line regression coefficients of accumulated lucerne yield (kg DM/ha/yr) against accumulated thermal time (°Cd) from 2002-2010 in the 'Maxclover' experiment. 'b_1' is the slope of the first line equation and 'b_2' the slope of the second (kg DM/ha/°Cd). Breakpoint x is the yield accumulation change in terms of thermal time (°Cd). Break point y is the yield accumulation change in terms of accumulated dry matter (DM/ha/yr). SEM is the standard error of the mean.

Year	b_1	b_2	Breakpoint x (°Cd)	Breakpoint y (kg DM/ha^{-1})	y Intercept	x Intercept	R^2
1	8.76	5.32	1113	10470	164	-19	99
2	11.11	1.77	1140	9103	-3533	320	99
3	10.29	2.15	1555	15597	-630	301	100
4	7.09	1.22	1484	8351	-2295	317	100
5	9.55b	2.11	1791	15108	-1915	202	100
6	10.17	2.38	1318	10433	-2799	275	99
7	8.30	1.85	1425	10919	-374	22	99
8	8.11	1.00	1453	11463	-326	38	98
Mean	9.2	2.2	1410	11431	-1437	177	
SEM (±)	0.26	0.24	46	469	260	31	
P	0.043[1] 0.640[2]	0.334	0.247	0.744			

Note: P< 0.05 significant difference*. Superscript [1] is the analysis of variance including Year 1 and [2] is excluding Year 1. Superscripts indicate means that are different, Fishers protected L.S.D.

4.4 Potential evapotranspiration 'PET'

4.4.1 Potential evapotranspiration from measurement start date

Table 4.4 shows the mean accumulated potential evapotranspiration 'PET' (mm) at the (x, y) breakpoint of the split line regression for the mean of the four replicates of each of the eight years of the 'Maxclover' experiment from 2002-2010. PET accumulation was set from the beginning of each growth season specified in Table 3.1. There was a difference (P<0.002) in the PET values at the breakpoint of the split line regression across the eight years of the 'Maxclover' experiment from 2002-2010. Specifically, the highest PET (mm) value at the split line regression breakpoint was 637 ± 20 mm in Year 5. The lowest PET (mm) value at the split line regression breakpoint was 396 ± 22 mm in Year 2. The mean PET at the split line regression breakpoint was 521 ± 26.3 mm.

Table 4.3 Mean accumulated potential evapotranspiration 'PET' (mm) at the breakpoint (x, y) of the split line regression for each of the four replicates of each of the eight years of the 'Maxclover' experiment from 2002-2010. PET accumulation was set from the beginning of each growth season specified in Table 3.1. SEM is the standard error of the mean.

Year	PET (mm)	SEM (±)
1	554^{ab}	45
2	396^{c}	22
3	571^{ab}	15
4	509^{b}	23
5	637^{a}	20
6	552^{ab}	18
7	454^{ab}	74
8	497^{b}	14
Mean	521	26.3
L.S.D	98.8	
P	<0.002	

Note: Superscripts indicate means that are different, L.S.D (5%).

4.4.2 Potential evapotranspiration from 1st September

Table 4.5 shows the mean accumulated potential evapotranspiration 'PET' (mm) at the 'x' and 'y' breakpoint of the split line regression for each mean of the four replicates of the eight years of the 'Maxclover' experiment from 2002-2010. PET accumulation was set from 1st September (Sim, 2014). There was a difference (P<0.001) in the PET values at the breakpoint of the split line regression for each four replicates of each of the eight years of the 'Maxclover' experiment from 2002-2010. Specifically, the highest PET (mm) value at the split line regression breakpoint was 564 ± 49 mm in Year 1. The lowest PET (mm) value at the split line regression breakpoint was 334 ± 22 mm in Year 2. The mean PET at the split line regression breakpoint was 451 ± 27.3 mm.

Table 4.4 Mean accumulated potential evapotranspiration 'PET' (mm) at the breakpoint (x, y) of the split line regression for each of the four replicates of each of the eight years of the 'Maxclover' experiment from 2002-2010. PET accumulation was set from 1st September. SEM is the standard error of the mean.

Year	PET (mm)	SEM (±)
1	564[a]	49
2	334[c]	22
3	468[ab]	18
4	509[ab]	23
5	517[ab]	22
6	381[b]	26
7	405[b]	72
8	433[b]	13
Mean	451	23.7
L.S.D	95.3	
P	<0.001	

Note: Superscripts indicate means that are different, L.S.D (5%).

4.5 Potential soil moisture deficit 'PSMD'

4.5.1 Potential soil moisture deficit 'PSMD' by year

Figures 4.11 to 4.18 show the potential soil moisture deficit (mm) against accumulated thermal time (°Cd) for the eight years of the 'Maxclover' experiment, 2002-2003. PSMD was calculated from 1st September to 30th April of each season as it was assumed that PSMD was 0 mm at 1st September (Sim, 2014). The PSMD increased over time (thermal time accumulation, °Cd) due to PET exceeding rainfall. The degree of this increase is dependent on rainfall frequency and amount (mm) over the summer-autumn period. This varies between seasons as seen in the fluctuations in PSMD in the following figures. PSMD decreases with the occurrence of rainfall.

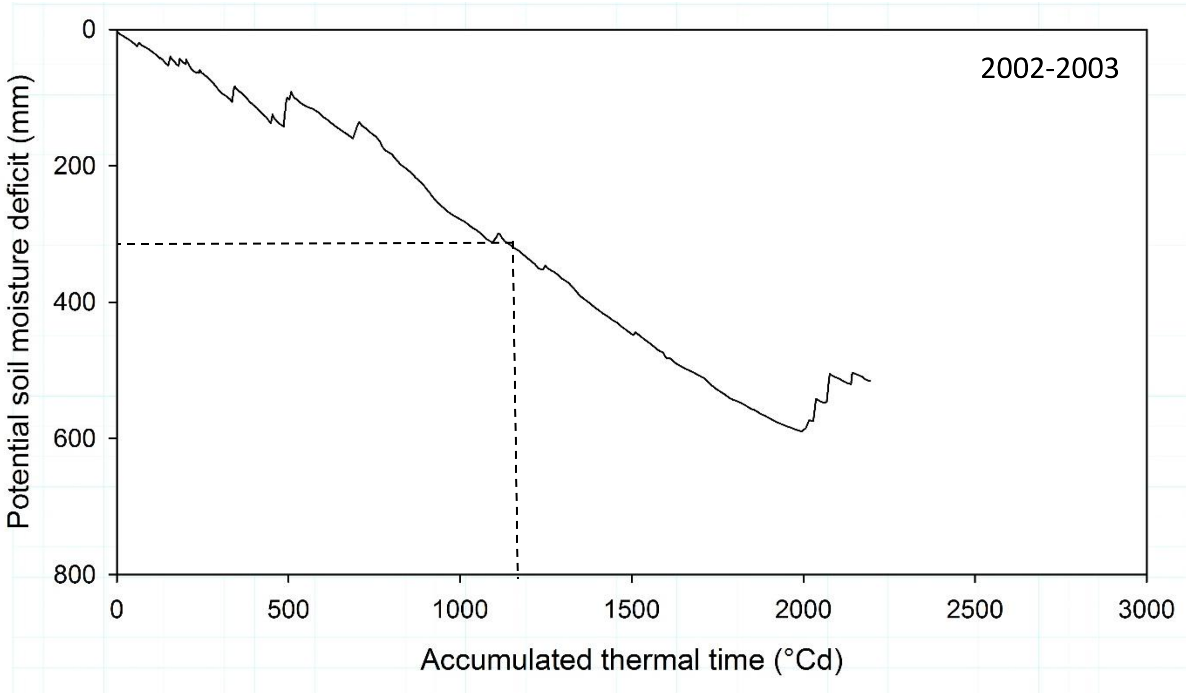

Figure 4.11 Potential soil moisture deficit (mm) against accumulated thermal time (°Cd) for Year 1, 2002-2003, of the 'Maxclover' experiment. (---) indicates the PSMD (mm) at the accumulated thermal time breakpoint (°Cd) from which the PSMD was calculated.

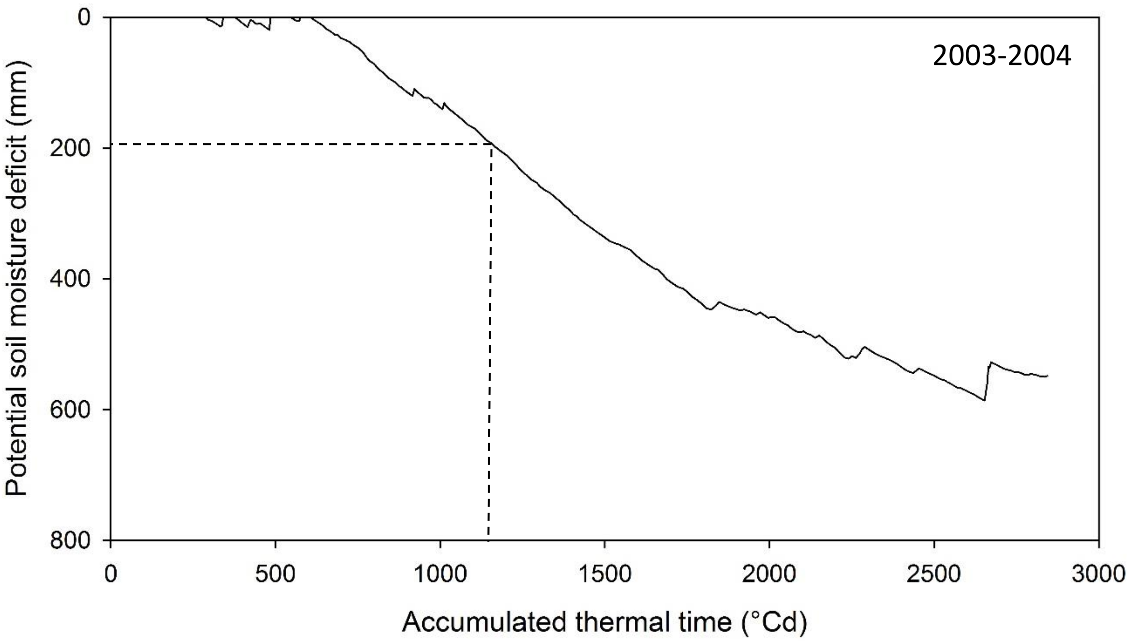

Figure 4.12 Potential soil moisture deficit (mm) against accumulated thermal time (°Cd) for Year 2, 2003-2004, of the 'Maxclover' experiment. (---) indicates the PSMD (mm) at the accumulated thermal time breakpoint (°Cd) from which the PSMD was calculated.

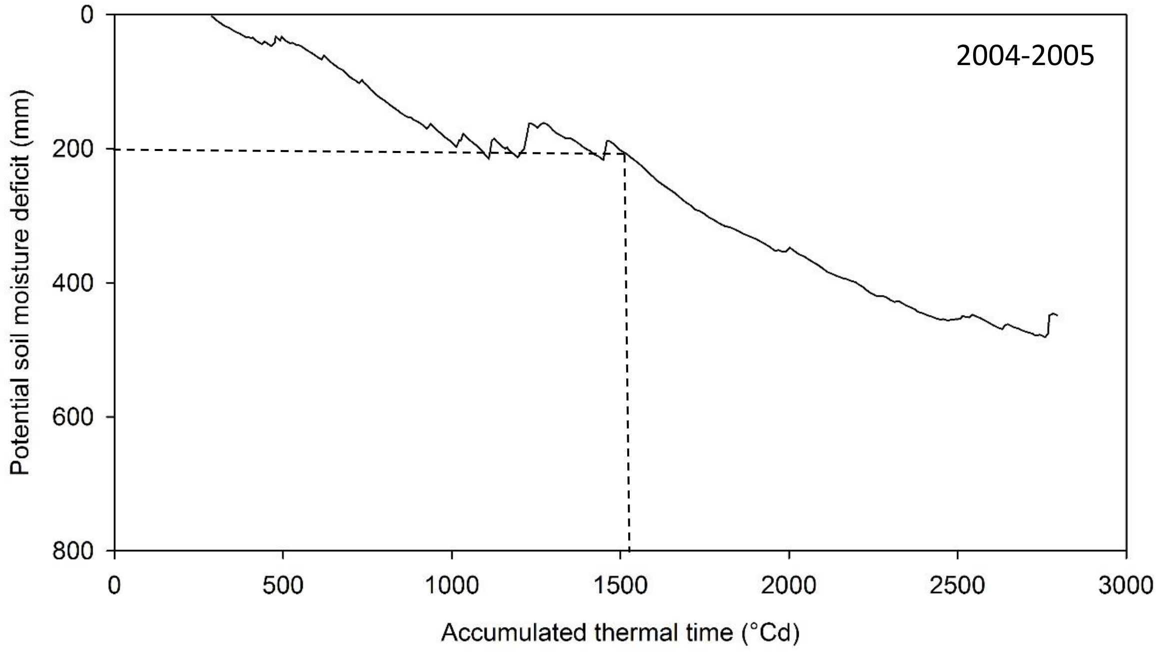

Figure 4.13 Potential soil moisture deficit (mm) against accumulated thermal time (°Cd) for Year 3, 2004-2005, of the 'Maxclover' experiment. (---) indicates the PSMD (mm) at the accumulated thermal time breakpoint (°Cd) from which the PSMD was calculated.

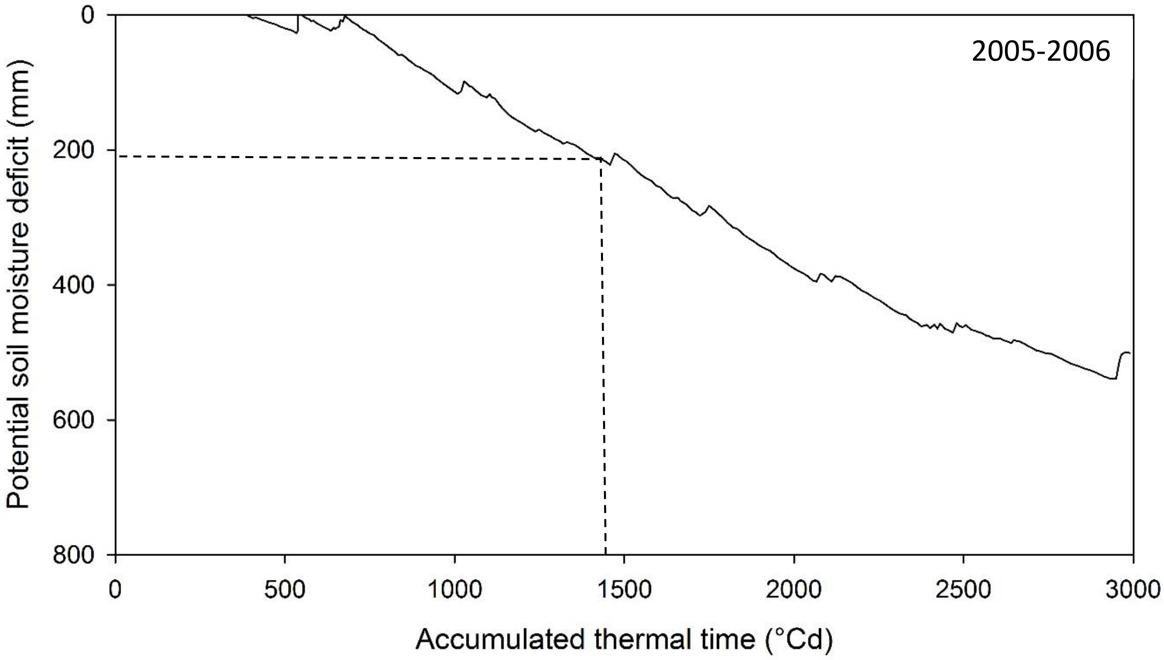

Figure 4.14 Potential soil moisture deficit (mm) against accumulated thermal time (°Cd) for Year 4, 2004-2005, of the 'Maxclover' experiment. (---) indicates the PSMD (mm) at the accumulated thermal time breakpoint (°Cd) from which the PSMD was calculated.

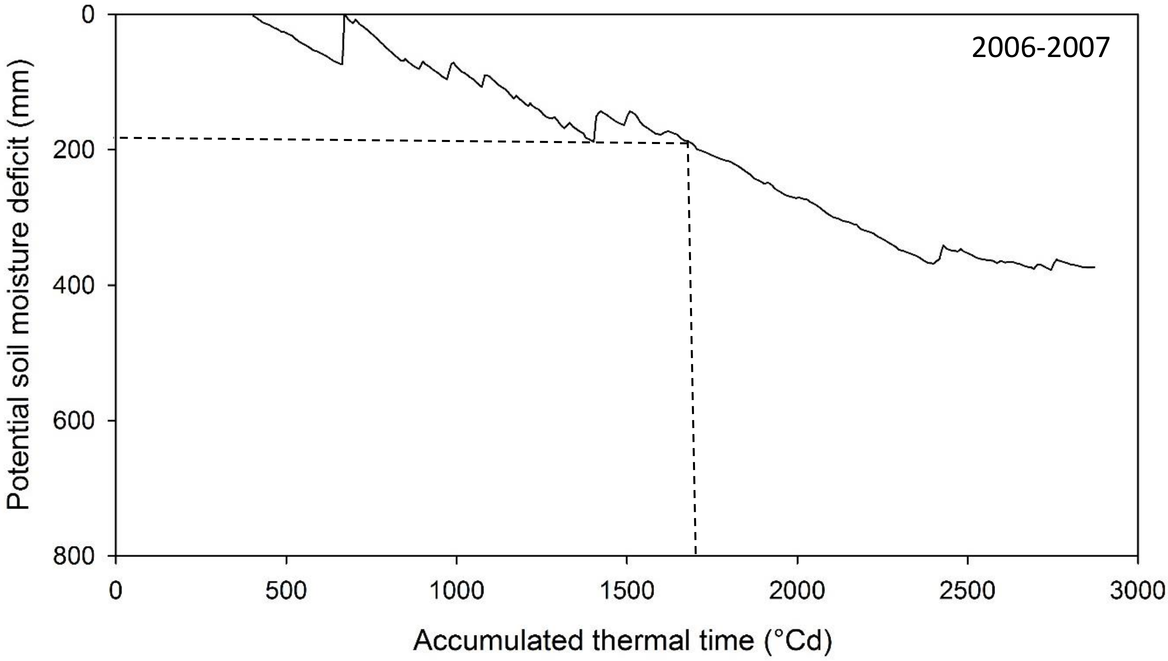

Figure 4.15 Potential soil moisture deficit (mm) against accumulated thermal time (°Cd) for Year 5, 2005-2006, of the 'Maxclover' experiment. (---) indicates the PSMD (mm) at the accumulated thermal time breakpoint (°Cd) from which the PSMD was calculated.

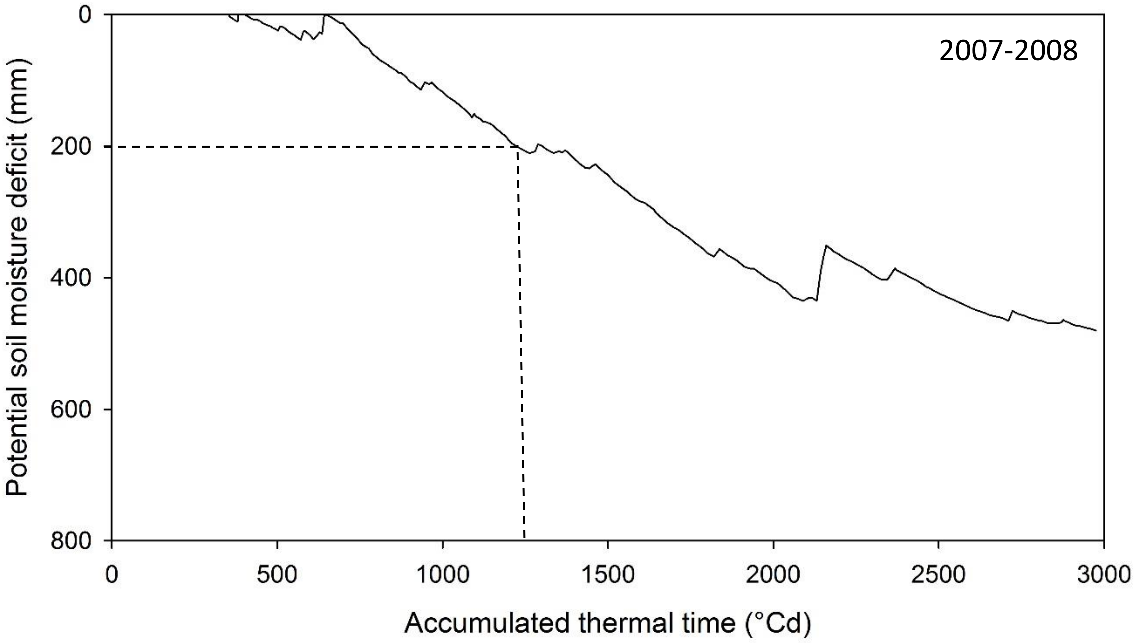

Figure 4.16 Potential soil moisture deficit (mm) against accumulated thermal time (°Cd) for Year 6, 2006-2007, of the 'Maxclover' experiment. (---) indicates the PSMD (mm) at the accumulated thermal time breakpoint (°Cd) from which the PSMD was calculated.

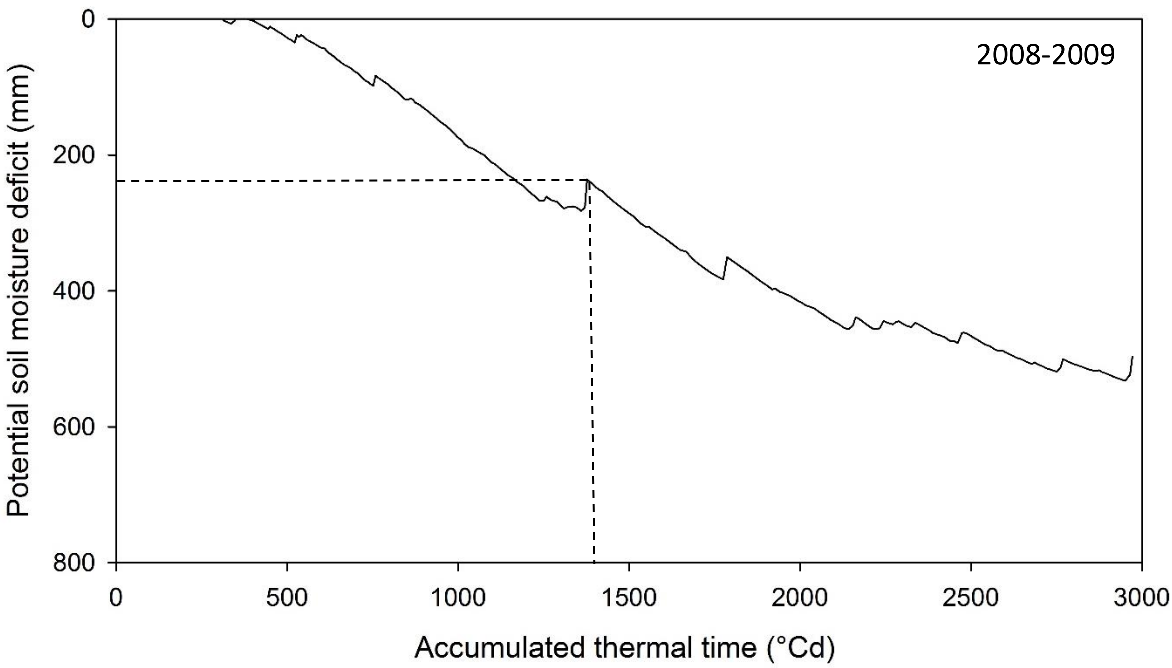

Figure 4.17 Potential soil moisture deficit (mm) against accumulated thermal time (°Cd) for Year 7, 2007-2008, of the 'Maxclover' experiment. (---) indicates the PSMD (mm) at the accumulated thermal time breakpoint (°Cd) from which the PSMD was calculated.

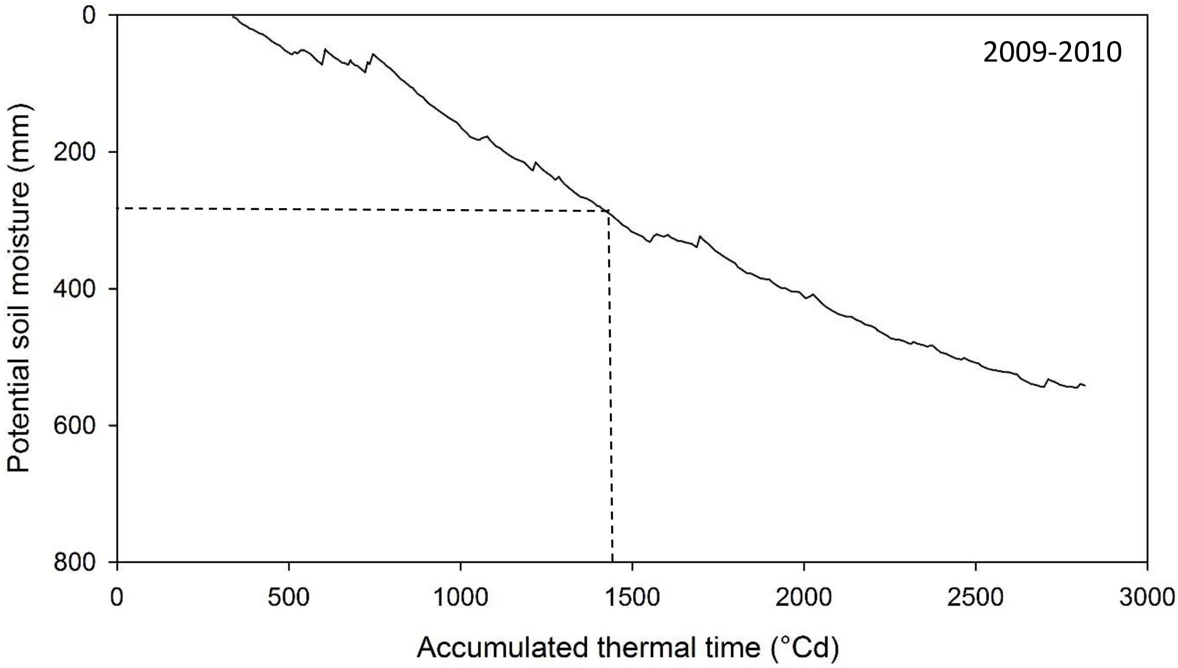

Figure 4.18 Potential soil moisture deficit (mm) against accumulated thermal time (°Cd) for Year 8, 2009-2010, of the 'Maxclover' experiment. (---) indicates the PSMD (mm) at the accumulated thermal time breakpoint (°Cd) from which the PSMD was calculated.

4.5.2 Mean potential soil moisture deficit 'PSMD'

Table 4.6 shows the mean accumulated potential evapotranspiration 'PET' (mm) and accumulated thermal time 'Tt' (°Cd) at the breakpoint (x, y) of the split line regression for the eight years of the 'Maxclover' experiment from 2002-2010. PET accumulation was set from 1st September and Tt (°Cd) accumulation from the season start date (Table 3.1). The highest PSMD (mm) value at the split line regression breakpoint was 370 ± 29 mm at an accumulated Tt (°Cd) of 1281 in Year 1. The lowest PSMD (mm) value at the split line regression breakpoint was 190 ± 28 mm in Year 2 at an accumulated Tt (°Cd) of. The mean PSMD at the split line regression breakpoint was 252.7 ± 12.6 mm. PSMD at the breakpoint was not different (P = 0.16) in Years 2-8. Year 1 was excluded due its high PSMD.

Table 4.5 Mean accumulated potential evapotranspiration 'PET' (mm) and accumulated thermal time 'Tt' (°Cd) at the breakpoint (x, y) of the split line regression for the 8 years of the 'Maxclover' experiment from 2002-2010. PET accumulation was set from 1st September and Tt (°Cd) accumulation from the season start date (Table 3.1).

Year	PSMD (mm)	SEM (±)	Accumulated Tt (°Cd)	SEM (±)
1	370^{a}	29.1	1113	89.8
2	190^{c}	28.3	1140	69.4
3	223^{b}	18.9	1555	43.2
4	270^{b}	18.7	1484	57.9
5	212^{b}	20.4	1791	70.4
6	210^{b}	14.0	1318	68.4
7	262^{b}	48.8	1425	190
8	284^{b}	19.1	1453	34.2
Mean	252.7	12.6		
L.S.D	78.9			
P	0.003			
P^1	0.16			

Note: P includes Years 1-8 and P^1 excludes Year 1.

5 DISCUSSION

5.1 Annual yield (kg DM/ha)

The mean annual yield of the 'Kaituna' lucerne in the 'Maxclover' experiment, 2002-2010, was 15 t ± 1104 kg DM/ha/yr. Annual yield ranged from 10 t ± 456 kg DM/ha/yr in Year 4 to 19 t ± 631 kg DM/ha/yr in Year 3 (Table 4.1). The maximum mean annual yield of Year 4 is similar to Brown *et al.,* (2003) who reported an annual yield of 20 t DM/ha/yr for 'Kaituna' lucerne sown on a deeper Wakanui silt loam at Lincoln. In contrast, McKenzie *et al*., (1990) reported 12.3 t DM/ha/yr for 'WL320' lucerne sown on a fine Templeton silt loam at Lincoln. This is comparable with the 15 t DM/ha produced by the 'Maxclover' lucerne on the same soil type. This highlights the influence of soil type on yield potential. Soil type and its associated characteristics e.g. water holding capacity is a key driver of lucerne production. A deeper soil such as the Wakanui silt loam would be expected to have a far greater water holding capacity, 400 mm at a depth of 2.5m, compared to 140 mm for a Templeton sandy loam at a depth of 1 m. This influences the plant available water for dry matter production as deeper soil are able to store more in season rainfall, where a shallower soil has a smaller 'bucket' to fill and draw from. Annual yields of dryland lucerne are influenced by soil type due to the variation in water holding capacity. The water availability is also driven by rainfall event severity and frequency throughout the season. The high mean annual dry matter yield produced could be attributed to the summer rainfall of Year 3, 2004-2005 being 28% above average. The timing of this rainfall is crucial to maintaining dry matter production over the summer months. Rainfall events over a critical amount, approximately 15 mm, are required to gain a yield response in lucerne. The frequency of these rainfall events is also important as their occurrence evenly over the typically dry summer months would extend the rate of dry matter production for a longer period of time, compared with a soil moisture limited lucerne stand e.g. Lucerne grown in Marlborough reported by Hunter *et al*., (1994) yielding a maximum annual yield of 9.5 t DM/ha (Chapter 2.1.4). This highlights the influence of a regions climate on the yield potential of a lucerne stand. Annual yield is limited by the timing of the growth breakpoint in dry matter accumulation, which is determined by the soil moisture deficit. In a low rainfall region, e.g. Marlborough with a mean annual rainfall of 591 mm, this would occur much earlier in spring-summer than in a region with higher spring-summer rainfall, e.g.

Lincoln with an annual long term mean of 635 mm. The ability to use this in season rainfall for production is then determined by the water holding capacity of the soil. A soil with a moderate to high soil water holding capacity, e.g. Templeton sandy loam ~280 mm, would have a different critical breakpoint than a shallower soil. The low mean annual dry matter production produced in the 'Maxclover' experiment in Year 4, 2005-2006, could be due to the summer rainfall being 108 mm, 24% below average (135 mm) and the snowfall event in September 2004, limiting lucerne spring growth. The weight of the snow broke stems and prevented light interception for many days. However, the lucerne recovered and regrew without detrimental effects after Year 4. Years 6 and 7, 2007-2009 both had above average annual rainfall but produced only 14 t DM/ha^{-1} annually. This highlights the influence of rainfall distribution. The high summer rainfall (184 mm) as in Year 3 (Figure 4.5) was able to maintain high lucerne production. The lower than average annual dry matter production achieved in Year 8 was caused by a combination of rainfall from July-November being 195 mm, 30% lower than average (254 mm) and low summer rainfall. The influence of environmental factors on lucerne yield and growth rates is further discussed in the following sections.

5.2 Daily growth rates (kg DM/ha/d)

The mean daily growth rates across the eight years of the 'Maxclover' experiment followed a consistent pattern. The increase of daily growth from 34 kg DM/ha/d in September to 60-70 kg DM/ha/d in October/November was consistent with a five year daily growth rate mean of 70 kg DM/ha/d for November recorded by Moot *et al*., (2003). This rapid increase in daily dry matter production through canopy expansion is characteristic of lucerne over the spring period due to assimilate remobilisation. Assimilates are remobilsed from root reserves that were accumulated over the previous autumn. The further increase in daily growth to 80-108 kg DM/ha/d in December and January in 2002-2004 was also similar to 90 kg DM/ha/d in Moot *et al*., (2003). However, the lucerne in Moot *et al*., (2003) was irrigated. Increasing daily mean temperatures and sufficient rainfall events enable lucerne to extend its spring growth period to give higher yields. Baars *et al*., (1990) reported a maximum daily growth rate of 120 kg DM/ha/d for 'Wairau' lucerne in Canterbury, but the month that this occurred in was not specified. It is assumed that this was for late spring-early summer. December-February daily growth rates declined from 2005-2006 onwards and produced closer to the 50 kg DM/ha/d reported by Moot *et al*., (2003) for February. Daily growth rates in the 'Maxclover' experiment and those presented by Moot *et al*., (2003) were 20-40 kg DM/ha/d. Daily growth rates decline with the decline in mean daily temperatures from late summer into autumn months. Growth is limited further is there is insufficient rainfall. Figure 5.2 combines the daily growth rates from Moot *et al.*, (2003) (Figure 2.3) and the 'Maxclover' experiment. Daily growth rates as low as 6 kg DM/ha/d into June in the 'Maxclover' experiment highlight the contrast of autumn and spring growth rates at similar mean air temperatures. Reserve accumulation in the form of assimilate partitioning is prioritised to the perennial organs (roots and crown) over dry matter production and is reflected in the mean daily growth rates of both experiments. This is evident in the dry matter comparison of the same mean air temperatures in spring vs. autumn. At a mean air temperature of 9°C lucerne mean daily growth rates varied by ~10 kg DM/ha/d between May and September. This variation increase at ~13°C where the mean daily growth rate varied by ~40 kg DM/ha/d between April and November. The greatest difference was identified between January and February-March where daily growth varied by ~50 kg DM/ha/d at ~16°C. A regression was fitted to both growth patterns to further quantify the relationship between mean air temperature and daily lucerne growth with seasonal partitioning priorities. From September to January the $R^2 = 0.93$ and indicated that dry matter accumulation was ~9.5 kg DM/ha/d/°C. From February to May the $R^2 = 0.67$ and indicated that dry matter accumulation was ~3.3 kg DM/ha/d/°C. Daily points from the 'Maxclover' experiment for March and January were excluded from the regression due to the effect of water stress. This further illustrates the effect of seasonal assimilate partitioning priorities of lucerne. There is a distinct difference in dry matter accumulation between spring and autumn months at the same mean air temperature. These values are similar to those generated by the split line regression of the accumulated yield in the 'Maxclover' experiment (Table 4.2). Differences in the daily dry matter accumulation values calculated in this dissertation and those reported by Moot *et al*., (2003) can be attributed to soil water limitations, specifically, their results were from irrigated stands, e.g. January, February and March kg DM/ha/d. October, November, December, February and April daily growth rates were not water limited. With the additional values from the 'Maxclover' experiment in this dissertation suggest that the regression equations in Figure 5.1 would be appropriate for predicting yields in non-water limited conditions. In contrast the March value from 'Maxclover' was significantly below the values from Moot *et al.,* (2003), which suggests this value was further affected by moisture stress. Of note, is the agreement of values for February and April from dryland 'Maxclover' and irrigated lucerne previously reported, which suggests a consistency of response between experiments. April in dryland conditions must have then be fully recharged.

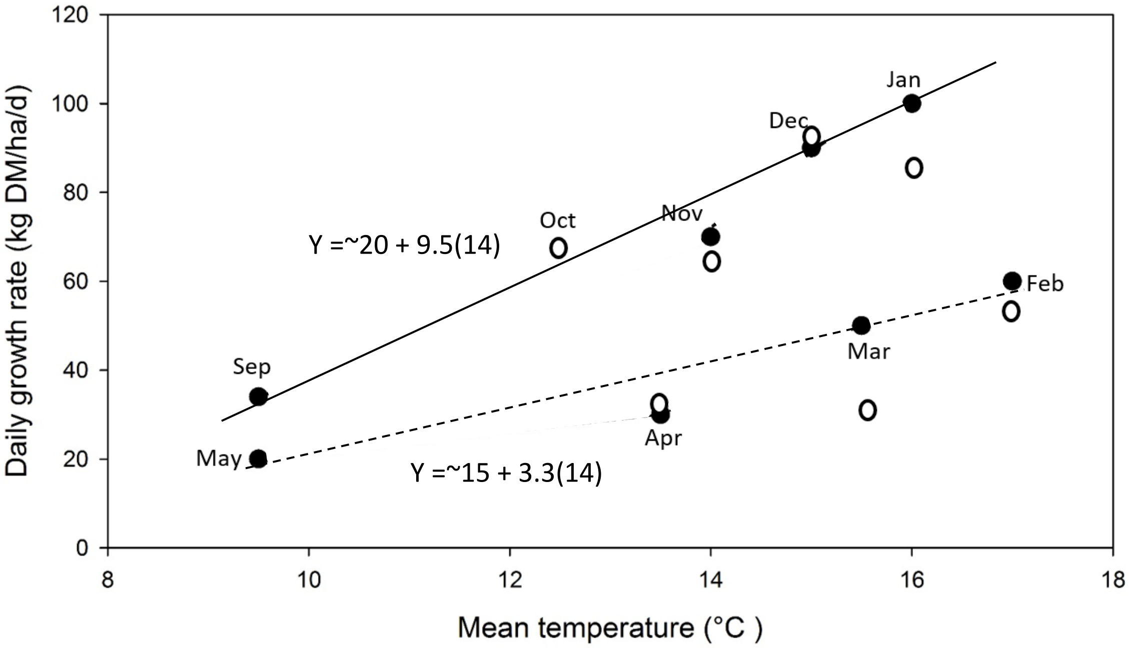

Figure 5.1 Daily growth rates (kg DM/ha/d) of irrigated lucerne (●) from Moot *et al*., (2003) and dryland lucerne in the 'Maxclover' experiment (○), 2002-2010, in relation to mean temperature (°C) at Lincoln University, Canterbury, New Zealand. Each point for the irrigated lucerne represents the mean from 5 years data and dryland eight years. (**-**) R^2 = 0.94, (--) R^2 = 0.67. Adapted from Moot *et al.,* (2003).

5.3 Accumulated yield (kg DM/ha) and thermal time (°Cd)

Figures 4.3-4.10 show the accumulated yield (kg DM/ha^{-1}) of lucerne against accumulated thermal time (°Cd) in Years 1-8 of the 'Maxclover' experiment (2002-2010). The mean rate of dry matter accumulation was 9.2 ± 0.29 kg DM/°Cd, over this period and it was consistent from Years 2-8 (P= 0.43) until ~1410°Cd (Table 4.5). Year 1 was excluded from the analysis of dry matter accumulation in the first equation due to the influence of the establishment year (Sim, 2014). This first growth period can be defined as non-water limited spring growth. There was no significant difference (P = 0.247) in the duration of dry matter accumulation in this period in terms of thermal time (°Cd) accumulation with a breakpoint of ~1410°Cd, indicating a consistent pattern. There was also no difference (P = 0.744) in the duration of this period in terms of dry matter (kg DM/ha^{-1}) accumulation with a breakpoint of ~11430 kg DM/ha^{-1}. This initial period of high dry matter production per °Cd coincides with the high stock demand for feed during lambing and lactation. This, suggests that in this environment a dryland farmer could expect 11.5 t DM/ha^{-1} to grow during spring. This represents ~70% of the total dry matter accumulation and highlights the importance of maximizing spring yields for animal production. The success of dry matter accumulation in this spring period is dependent on the lucerne being non water limited. Water limitations would cut this period short and greatly reduce potential yield. This is influenced by soil water holding capacity and rainfall. A soil with a greater water holding capacity, e.g. Wakanui, would be expected to maintain a greater spring growth period than, e.g. a Templeton, due to the availability of stored water in the soil, assuming the soil is at field capacity at the beginning of spring.

Tonmukayakul (2009) also found that there was a linear relationship between spring dry matter accumulation (kg DM/ha^{-1}) and thermal time (°Cd) specifically in Year 7 of the 'Maxclover' experiment. This relationship also declined with the onset of moisture stress. This coupled with analysis in Chapter 5.2 indicates that thermal time (°Cd) could be a suitable predictor of lucerne yield during the spring period as the rate of dry matter accumulation per °Cd was similar each year. After this point growth plateaued to another constant (P = 0.334) but a reduced growth rate of 2.2 ± 0.24 kg DM/°Cd. The rate of dry matter accumulation in this second phase after ~1410°Cd was constant. This was attributed to variations in late spring/summer rainfall. When this second growth phase is displayed with the rainfall totals (mm/°Cd) for each of the eight years, relationships can be drawn between increases in dry matter accumulation and rainfall event frequency and number (mm). Year 1 had multiple rainfall events >20 mm after approximately 2500°Cd was accumulated. This maintained production towards the last two harvests of the season. Rainfall in Year 2 after the breakpoint was less than the previous year with smaller rainfall event <10 mm but they were more frequent, equating to a below average dry matter accumulation of ~1.77 kg DM/ha/°Cd. A larger rainfall event of 35 mm occurred at ~2750 °Cd. Year 3 had a similar rainfall pattern to Year 2 in terms of rainfall frequency and number (mm) but produced the highest annual yield. The dry matter accumulation in Year 3 was greater at 2.15 kg DM/ha/°Cd. This was potentially due to summer rainfall being 28% above average at 184 mm. Year 4 was also similar but rainfall events were mostly <~5 mm, equating to only 104 mm over the summer months. I believe that rainfall events of this number are ineffective in producing a growth response. However, I estimated that events >15 mm with enable a growth response in lucerne. This reduced summer production to ~1.22 kg DM/ha/°Cd. Year 5 had a greater amount of rainfall events between 20–80 mm from 1400°Cd to 3000°Cd. This probably contributed to Year 5 producing the second highest annual yield over the eight years with summer dry matter accumulation of ~2.11 kg DM/ha/°Cd. Year 6 had a more sporadic rainfall pattern with minimal events after 2500°Cd, with summer production of 2.38 kg DM/ha/°Cd. Years 7 and 8 had frequent rainfall events below 20 mm with a significant event of 40 mm at ~2750°Cd and ~1700°Cd, respectively. Summer production was ~1.85 kg DM/ha/°Cd in Year 7 and only ~1 kg DM/ha/°Cd in Year 8. The rate of dry matter accumulation over the summer period is not in fact linear but a combination of periods of zero growth followed by growth that may be up to 9 kg DM/°Cd. If large rainfall events are accumulated, >20 mm, and divided by the herbage grown after the breakpoint the growth rate for autumn can be estimated. This was not evaluated in this dissertation as the focus was on spring and summer growth rates. Further analysis in this dissertation includes the examination of the additional relationship between the breakpoint and subsequent dry matter production with PET (mm) and PSMD (mm).

5.4 Potential evapotranspiration (mm)

Accumulated potential evapotranspiration 'PET' ranged from 396-637 mm and 334-364 mm from the start of each season and from 1st September, respectively at the split line regression breakpoint. Statistical analysis was carried out to determine if the breakpoint in lucerne growth rate occurred at the same PET value each year in the 'Maxclover' experiment. This would indicate that moisture stress occurred at the same PET value each season and it could then be estimated easily using readily available weather data. However, there was a difference ($P < 0.002$) in the PET values accumulated from the beginning of the season. There was also a difference ($P < 0.001$) in the PET values from 1st September, at the breakpoint of the split line regression for each of the four replicates of each of the eight years. This indicated PET alone cannot be used to determine the point of growth rate change in dryland lucerne at this site. Therefore, accumulated thermal time would be a more suitable predictor of lucerne production in dryland conditions. Accumulated thermal time can be used to predict the rate of dry matter accumulation in spring, the breakpoint (x, y) and dry matter accumulation after the breakpoint. Potential soil moisture deficit is then analysed to incorporate the influence of soil moisture on lucerne production.

5.5 Potential soil moisture deficit 'PSMD' (mm)

Figures 4.11-4.18 show a consistent pattern of an increase in potential soil moisture deficit 'PSMD' (mm) as accumulated thermal time (°Cd) increases. PSMD was calculated from 1st September as it is assumed that the soil is at field capacity (Sim, 2014). This was expected as PSMD increases into the dry summer months typical of dryland Canterbury. The extent of increase in PSMD was dependent on rainfall event totals and their frequency, which were unique in every season. This analysis enabled a PSMD (mm) value to be calculated for each breakpoint in the split line regression across the eight years. Similar to that of PET, it was expected that if all the PSMD values at the breakpoint were similar then it would be a strong predictor of the change in lucerne growth rate. However, there was a difference ($P < 0.003$) in the PSMD values accumulated from 1st September across the eight years, when Year 1 was included. Further analysis of Years 2-8 indicated that in fact the PSMD at the breakpoint was the same ($P = 0.16$). Therefore, PSMD may potentially be an adequate predictor of the change in lucerne growth rate from spring to summer, breakpoint x (°Cd), when combined with accumulated thermal time. This concept has not been analysed in published literature but there is future potential to fully quantify this relationship. There is potential for the use of rainfall (mm/°Cd) to be used as a predictor of lucerne yield in the summer-autumn growth period. The maximum PSMD of each year also varies and consequently affects the soil moisture status of the following season. The final PSMD of each season is then the amount of rainfall required (mm) to recharge the soil, which may not occur. The assumption of a PSMD of zero mm on 1st September may therefore not always be true so refining this method by a soil water budget may explain some of the variation in yearly values, especially between Year 1 and 2. The highest PSMD in Year 1 suggests that Year 2 had no started the season fully recharged, hence it had the lowest PSMD at the breakpoint.

6 GENERAL DISCUSSION AND CONCLUSIONS

6.1 General discussion

This dissertation met Objectives 1, 2 and 3 as well as the overall aim to quantify the relationship between lucerne growth in response to temperature and soil moisture. Annual lucerne yields across different regions of New Zealand were collated and summarised (Table 4.1) to serve as a library for future reference. These may be used to test the simple relationships identified in this dissertation. Previous experiments analysing relationships between lucerne growth and weather variables were evaluated to identify any potential methods for use in the analysis of the 'Maxclover' experiment in this dissertation. Relationships between lucerne growth in the 'Maxclover' experiment and environmental factors were then analysed with methods used in previous literature and new methods. The relevance of relationships between lucerne dry matter production and weather variables extends further than the ability to quantify the relationships and predict growth rates (kg DM/ha/d) and yield (kg DM/ha/yr). The ability of quick and accurate prediction calculations using easily accessible and understandable environmental data is the key to the use of this research. The ability for farmers to use records they already collate or have access to (e.g. daily mean air temperatures, °C, and daily rainfall, mm, PET and soil water holding capacity) in a format that is easily transposed and relevant to their on farm environment. These values can be sourced for their specific region or district. The future extension of this dissertation would be to build a simple model in which weather data could be entered and farmers could predict the yield potential or daily growth rates of their lucerne stand in not only dryland Canterbury but other regions of New Zealand. For now the relationships identified between accumulated thermal time (°Cd), potential soil moisture deficit (mm) and lucerne growth may be used to calculate predicted estimates of lucerne yield and growth rates.

6.2 Conclusions

- There was a strong relationship between mean air temperature and lucerne growth results analysed in this dissertation. These were consistent with that previously published by Moot *et al*., (2003).
- Lucerne dry matter production was ~9.2 kg DM/°Cd until the onset of moisture stress in the 'Maxclover' experiment, 2002-2010.
- The breakpoint in dry matter production occurred at ~1410°Cd, after which production lowered to ~2.2 kg DM/°Cd.
- Dry matter production after the breakpoint was influenced by temperature and rainfall events, both the amount (mm) and frequency.
- 11.5 t DM/ha^{-1} was consistently produced each spring. This production in other locations would be dependent on available the soil water holding capacity and in season rainfall, as these influence the total water available to the lucerne for extraction for dry matter production.
- Potential soil moisture deficit (mm) from 1st September can be used to predict breakpoint x (°Cd) in lucerne growth.

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APPENDICES

Appendix 1 Yield (kg DM/ha) of 'Kaituna' lucerne over eight years, 2002-2010, in the 'Maxclover' experiment at Lincoln University, Canterbury.

Year	Lucerne yield (kg DM/ha)								Annual yield
1	4/09/2002	4/10/2002	15/11/2002	24/12/2002	13/02/2003	22/03/2003	25/05/2003	29/06/2003	
	0	1853	2486	3542	4080	1734	1248	763	15706
	0	2507	2816	3278	4200	2295	2328	831	18255
	0	2006	2156	4525	3570	2015	2376	1046	17693
	0	2856	2926	4680	3264	2015	2568	1275	19584
2		1/07/2003	15/10/2003	25/11/2003	27/12/2003	10/03/2004	22/04/2004	27/06/2004	
		0	2353	4022	2934	1049	1043	1248	12649
		0	2564	4744	2290	1008	1175	1144	12926
		0	3227	4644	2100	1152	1251	1092	13468
		0	3936	4336	1900	946	1213	1023	13354
3		28/06/2004	10/10/2004	19/11/2004	26/12/2004	9/02/2005	11/04/2005	28/06/2005	
		0	4323	4102	3100	3985	914	1652	18063
		0	4982	5561	3200	3587	1188	1574	20080
		0	6020	3697	3661	4159	1267	1667	20458
		0	5868	3722	3361	2664	1244	1291	18141
4		29/06/2005	20/09/2005	8/11/2005	9/12/2005	31/01/2006	9/04/2006	26/06/2006	
		0	1757	4359	1359	1286	877	400	10030
		0	1674	2966	1919	1560	819	500	9430
		0	1773	3956	2197	2256	756	500	11428
		0	1373	2821	2104	1986	799	500	9576
5		27/06/2006	6/10/2006	14/11/2006	24/12/2006	2/02/2007	19/04/2007	19/06/2007	
		0	3876	2949	3489	3855	2814	1100	18083
		0	4308	3492	3739	3807	1969	1000	18316
		0	4664	3787	3581	3239	1603	900	17774
		0	5091	4456	3279	3101	1732	800	18459
6		20/06/2007	5/10/2007	20/11/2007	25/12/2007	28/01/2008	21/03/2008	18/05/2008	
		0	2698	3061	3663	1319	2193	550	13483
		0	3035	3932	3262	900	2329	600	14059
		0	3323	4629	3314	1436	1750	600	15052
		0	3842	4745	2314	1991	1405	460	14757
7		27/06/2008	23/09/2008	31/10/2008	4/12/2008	12/01/2009	16/03/2009	27/05/2009	
		0	3022	2937	2722	2772	1947	650	14050
		0	2896	3310	2628	2498	1969	550	13851
		0	3852	3421	1520	2160	2075	700	13728
		0	4043	2803	1969	2836	2024	750	14425
8		1/07/2009	17/09/2009	30/10/2009	15/12/2009	28/01/2010	12/03/2010	2/06/2010	
		0	2364	2382	3836	1579	2206	320	12686
		0	3018	2396	4067	1801	2006	210	13498
		0	4198	2898	3341	3229	0	460	14126
		0	3419	3025	2975	1931	0	390	11740

Appendix 2 Mean split line regression coefficients of accumulated lucerne yield (DM/ha/yr) against accumulated thermal time (°Cd) from 2002-2010 in the 'Maxclover' experiment. b_1 is the slope of the first line equation and b_2 the slope of the second. Breakpoint x is the yield accumulation change in terms of thermal time (°Cd). Break point y is the yield accumulation change in terms of accumulated dry matter (DM/ha/yr).

Year	Replicate	b_1	b_2	Breakpoint x	Breakpoint y	Y intercept	X intercept	R^2
1	1	9.02	3.61	1222	11067	48	-5	100
1	2	9.06	5.43	1078	10575	812	-90	100
1	3	10.11	5.38	932	9169	-252	25	100
1	4	6.88	6.88	1222	11067	48	-5	97
2	1	10.07	1.75	1231	8811	-3588	356	99
2	2	11.88	1.77	1123	8903	-4443	374	99
2	3	11.63	1.87	1107	9239	-3633	321	99
2	4	10.86	1.70	1099	9460	-2469	227	98
3	1	9.75	2.02	1616	14734	-1025	105	100
3	2	11.93	2.20	1478	16238	-1393	117	99
3	3	9.91	2.34	1649	16776	-45	444	100
3	4	9.56	2.04	1476	14641	-56	538	100
4	1	6.67	1.70	1500	8200			
4	2	6.64	1.08	1434	7603	-1911	288	100
4	3	8.38	1.02	1483	9736	-2693	321	99
4	4	6.67	1.06	1521	7867	-2280	342	100
5	1	8.45	2.50	1990	14946	-1876	222	100
5	2	9.65	2.21	1798	15107	-2235	232	100
5	3	9.82	1.85	1713	14901	-1916	195	100
5	4	10.29	1.89	1664	15479	-1635	159	99
6	1	8.01	2.39	1510	9989	-2103	263	99
6	2	9.65	2.49	1299	9864	-2666	276	99
6	3	11.36	2.34	1276	11100	-3388	298	99
6	4	11.64	2.30	1187	10779	-3037	261	98
7	1	7.98	1.84	1494	11223	-701	88	99
7	2	8.36	1.79	1427	11012	-918	110	99
7	3	10.68	2.53	927	8594	-1306	122	97
7	4	6.16	1.25	1853	12847	1431	-232	99
8	1	8.15	1.79	1386	9951	-1346	165	98
8	2	8.49	1.56	1420	11182	-877	103	98
8	3	8.08	0.36	1585	13532	724	-90	100
8	4	7.73	0.30	1423	11187	195	-25	99

Appendix 3 Accumulated potential evapotranspiration 'PET' (mm) at the 'x' and 'y' breakpoint of the split line regression for each of the four replicates of each of the eight years of the 'Maxclover' experiment from 2002-2010. PET accumulation was set from the beginning of each growth season specified in Table 3.1.

Year	Replicate	Date	PET (mm)
1	1	23-Jan	582
1	2	10-Jan	513
1	3	31-Dec	456
1	4	14-Feb	666
2	1	24-Dec	453
2	2	8-Dec	396
2	3	27-Nov	345
2	4	6-Dec	388
3	1	20-Jan	582
3	2	11-Jan	527
3	3	22-Jan	594
3	4	11-Jan	582
4	1	26-Dec	443
4	2	7-Jan	511
4	3	11-Jan	533
4	4	14-Jan	549
5	1	9-Feb	643
5	2	24-Jan	578
5	3	19-Jan	670
5	4	15-Jan	656
6	1	1-Jan	506
6	2	15-Dec	586
6	3	13-Dec	574
6	4	7-Dec	541
7	1	31-Dec	485
7	2	26-Dec	454
7	3	13-Nov	264
7	4	23-Jan	614
8	1	29-Dec	472
8	2	1-Jan	489
8	3	13-Jan	536
8	4	1-Jan	489

Appendix 4 Accumulated potential evapotranspiration 'PET' (mm) at the 'x' and 'y' breakpoint of the split line regression for each of the four replicates of each of the eight years of the 'Maxclover' experiment from 2002-2010. PET accumulation was set from 1st September.

Year	Replicate	Date	PET (mm)
1	1	23-Jan	581
1	2	10-Jan	519
1	3	31-Dec	465
1	4	14-Feb	692
2	1	24-Dec	392
2	2	8-Dec	335
2	3	27-Nov	284
2	4	6-Dec	327
3	1	20-Jan	517
3	2	11-Jan	462
3	3	22-Jan	429
3	4	11-Jan	464
4	1	26-Dec	443
4	2	7-Jan	511
4	3	11-Jan	533
4	4	14-Jan	549
5	1	9-Feb	580
5	2	24-Jan	515
5	3	19-Jan	495
5	4	15-Jan	479
6	1	1-Jan	456
6	2	15-Dec	370
6	3	13-Dec	366
6	4	7-Dec	334
7	1	31-Dec	436
7	2	26-Dec	405
7	3	13-Nov	214
7	4	23-Jan	565
8	1	29-Dec	411
8	2	1-Jan	424
8	3	13-Jan	471
8	4	1-Jan	424

Appendix 5 Potential soil moisture deficit 'PSMD' (mm) and accumulated thermal time (°Cd) at the 'x' and 'y' breakpoint of the split line regression for each of the four replicates of each of the eight years of the 'Maxclover' experiment from 2002-2010. PSMD accumulation was set from 1st September and Tt accumulation from the season start date (Table 3.1).

Year	Replicate	PSMD (mm)	Accumulated Tt (°Cd)
1	1	350.8	1229
1	2	307.7	1077
1	3	371.2	1314
1	4	448.3	1504
2	1	268.9	1334
2	2	181.6	1127
2	3	140.7	1007
2	4	170.2	1104
3	1	247.6	1609
3	2	192.5	1479
3	3	259.3	1642
3	4	192.5	1479
4	1	217.7	1508
4	2	275.7	1666
4	3	297.5	1723
4	4	290	1768
5	1	267.1	1965
5	2	211.3	1763
5	3	193.4	1698
5	4	177.6	1647
6	1	249	1509
6	2	199.1	1298
6	3	207.8	1279
6	4	183.8	1189
7	1	284.5	1496
7	2	253.7	1423
7	3	140.6	923
7	4	370.7	1845
8	1	237.5	1384
8	2	284.4	1414
8	3	328.9	1538
8	4	284.4	1414