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Effect of total defoliation on maize growth and yield

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Abstract

Maize seedlings can be damaged through a variety of means including traffic, stock grazing, insect damage, hail, and wind damage. The aim of this experiment was to determine the effect of timing of total maize plant defoliation by ground level cutting on crop growth and yield. Two trials were conducted in the 2007-08 season (Hawke's Bay and Canterbury). At each site, defoliation at maize growth stages V2, V4, V6 and V8 were compared with an uncut control. Each treatment was replicated four times, and plant growth, leaf area and final crop yield measured. There was no grain yield loss when plants were cut up to growth stage V4 but defoliation delayed maturity resulting in higher grain moisture content. Defoliation at V6 severely reduced grain yield by 60% in Hawke's Bay and 20% in Canterbury. The crop did not recover when plants were defoliated at growth stage V8. Defoliation of maize up to growth stage V4 will have minimal effect on grain yield but may delay maturity, and defoliation by cutting does not take into account other impacts associated with defoliation in field situations such as compaction, freezing, shear stress, bruising and other secondary impacts.

Additional keywords: *Zea mays*, time of defoliation

Introduction

Maize seedlings can be damaged by a variety of means including vehicular traffic, stock grazing, cutworm, hail, and wind damage. The impact of losing leaves or the entire plant from ground level shortly after emergence will affect crop regrowth and final yield. Growers will often replant their fields if damage occurs. However, the timing of the damage and its severity will both influence the decision to replant. Understanding the effect of defoliation at different growth stages will assist growers in re-plant decisions if their crop is damaged.

Partial defoliation (loss of leaves) has been studied internationally (e.g. Lauer *et al.*, 2004) but nothing has been published on total defoliation of maize under New Zealand conditions. This initial feasibility study aims to determine the effect of timing of total defoliation, in early season, on the subsequent yield of the maize crop.

Materials and methods

Two trials were conducted in the 2007-08 season, one in Hawke's Bay and the other in Canterbury. While the

treatments were similar at the two sites, more detailed measurements were conducted in the Hawke's Bay trial. For this reason, the approach used at the two sites will be described separately.

Hawkes's Bay site details

The trial was conducted at Plant & Food Research, Hastings, in a crop sown on 15 October 2007 (hybrid 34D71, population 100 kg ha^{-1}). The soil type at the site was a Mangateretere silt loam. Fertiliser applied before and at sowing was urea at 200 kg ha^{-1} (92 kg N ha^{-1}) and DAP at 200 kg ha^{-1} (36 kg N ha^{-1} and 40 kg P ha^{-1}). This was followed by a broadcast application of urea at 300 kg ha^{-1} (138 kg N ha^{-1}) on 26 November 2007. The trial was fully irrigated, with irrigation scheduled from weekly neutron probe soil moisture monitoring.

Leaf area assessments were made on 20 March 2008. The length and width of three leaves were measured from five plants in each plot. The leaves measured were those immediately below the ear (cob), the ear leaf, and immediately above the ear. Leaf area was calculated by multiplying the product of length and width by a factor of 0.73 (Wilson *et al*., 1995). The area of the largest leaf is strongly linked to the total plant leaf area thus affecting radiation interception and therefore crop yield (Muchow *et al*., 1990).

Final crop yields were determined on 12 May 2008 by removing 2.5m of the three central rows of each plot. Total plant biomass and dry matter content (DM %) were measured along with grain yield and grain moisture content. Grain yield is reported at 14% moisture content.

Canterbury site details

The trial was conducted at the Foundation for Arable Research, Chertsey site in a crop sown on 4 November 2007 (hybrid 39G12 at 120 kg ha^{-1}). The soil type was a Chertsey silt loam. Fertiliser N applied before and at sowing was 108 kg N ha^{-1} which, along with the existing soil mineral N pool, was enough to meet crop requirements. The trial was fully irrigated and irrigation scheduled by three-weekly soil moisture monitoring by neutron probe to 0.6 m.

In the Canterbury trial, four treatments were imposed in a Latin square design with four replicates. Plots were 5 rows wide (row width = 0.762 m) and 6 metres long. The treatments were applied at different growth stages by cutting the maize off at ground level using secateurs. All plants in each plot were cut. The four treatments were, control (uncut), V3 (plants cut at growth stage V3), V5 (plants cut at growth stage V5) and V6 (plants cut at growth stage V6). The Hawke's Bay trial was similar except the trial was a randomised complete block design and the cutting treatments were imposed at growth stages V2, V4, V6 and V8.

For each cut, plant population, plant growth stage, total biomass and leaf area were determined. Leaf area was measured on entire sample rather than per plant so standard errors were not calculated for this measure. Final crop yield was determined on 11 April 2008 by removing all plants from a 2.5 metre length of the two central rows of each plot. Total plant biomass and dry matter content (DM %) were measured. Grain yield was determined by removing and drying grain from three cobs per plot.

Results

Hawke's Bay

Plant assessments at cutting

Good regrowth after cutting was observed within three to five days in treatments V2 and V4 (Table 1) although defoliation did check crop development (Table 2). Regrowth of plants cut at V6 was mostly as new tillers rather than regeneration of the main stem of the plant. No plants recovered from cutting at V8. Leaf area assessments made on 20 March 2008 found the area of the largest leaf (A_{max}) was significantly less ($P<0.001$, $LSD_{0.05} = 57$) in the plants cut at V6 (654 cm^2) than those in the control, V2 and V4 treatments (average of 761 cm^2).

Table 1: Crop assessments conducted at each defoliation event in Hawke's Bay (standard errors in brackets).

Treatment and date	Biomass removed (kg DM ha^{-1})	Leaf area (cm^2 $plant^{-1}$)	Growth stage at cutting	Regrowth after cutting
V2 - 5 Nov	20 (1.1)	28	1.9 (0.1)	Good
V4 - 16 Nov	80 (2.2)	169	3.8 (0.1)	Good
V6 - 26 Nov	584 (41)	394	6.0 (0.1)	Poor
V8 - 10 Dec	2416 (117)	4319	8.3 (0.1)	Nil

Table 2: Regrowth assessments made on 26 November in Hawke's Bay.

Treatment	Leaf area (cm^2 $plant^{-1}$)	Growth stage
Control	394	6.0 (0.1)
V2 - 5 Nov	213	4.6 (0.2)
V4 - 16 Nov	82	4.1 (0.1)

Crop yield assessments - 12 May 2008

Due to the well fertilised and irrigated growing conditions, crop yields were very high. There was no significant effect on plant population (average 103,000 plants ha^{-1}) although tillering was more evident in the V6 plots. Tiller counts were not assessed.

The control (uncut) plots produced more total biomass than all other treatments yet the grain yield was the same as the V2 and V4 treatments (Table 3). Harvest index (HI, the percentage of total biomass that is grain) in the control treatment tended to be lower than the V2 and V4 treatments but the difference was not statistically significant. The control treatment had the lowest grain moisture content. The V2 and V4 treatments produced similar total biomass and grain. Grain moisture content was less in the V2 treatment than the V4 treatment.

The V6 treatment produced the least amount of total biomass (18.2 t DM ha^{-1}) and grain (8.2 t ha^{-1}). Both plant and grain moisture content was highest for these plants, suggesting a difference in crop maturity. Visually, the plants in the V6-cut treatment were greener and less advanced than the other treatments. Interestingly, HI in this treatment (% of total biomass that is grain) was much

lower than all other treatments. This was probably due to many of the plants in this treatment being tillers.

Table 3: Effect of defoliation on maize yield, moisture content and harvest index in Hawke's Bay.

Treatment	Total biomass t DM ha^{-1}	Plant DM %	Grain yield t ha^{-1}	Grain moisture %	Harvest Index (HI) %
Control	33.1a	63.7a	20.4a	19.6a	53.6a
V2	27.7b	57.3a	20.4a	20.9b	60.3a
V4	25.5b	56.6a	18.9a	22.3c	64.8a
V6	18.2c	47.6b	8.2b	27.2d	40.4b
Significance	<0.001	<0.01	<0.001	<0.001	<0.01
$LSD_{0.05}$	3.9	7.5	3.3	1.1	12.4

Canterbury

Plant assessments at cutting

The amount of biomass removed at each cut is shown in Table 4. Due to site, sowing time and hybrid differences, it is not meaningful to compare these results with Hawke's Bay. Regrowth assessments were not made.

Table 4: Crop assessments conducted at each defoliation event in Hawke's Bay (standard errors in brackets).

Treatment and date	Biomass removed (kg DM ha^{-1})	Leaf area (cm^2 $plant^{-1}$)
V3 – 4 Dec	35 (1)	48
V5 – 13 Dec	133 (8)	234
V6 – 21 Dec	396 (11)	337

Crop yield assessments - 11 April 2008

Unlike the Hawke's Bay experiment, plant population was significantly reduced in the V6 treatment, lowering total biomass (Table 4). Biomass of individual plants was reduced in all plots that were defoliated, following a similar trend to Hawke's Bay. Plant dry matter content, an indication of crop maturity, was greatest in the control and declined with cutting. The same result was found with grain moisture in Hawke's Bay.

Like total yield, grain yield in the V6 plots was significantly less than in the uncut treatment (Table 5). Due to the declining population, the grain yield per plant was greater in V6 treatment than in the uncut or V3 treatment. This is quite different to the Hawke's Bay site where grain per plant in the V6 treatment was less than half that found in the other treatments.

Table 5: Effect of defoliation on plant population, yield and moisture content in Canterbury.

Treatment	Population 000 ha^{-1}	Total biomass t DM ha^{-1}	Plant DM %	Grain yield t ha^{-1}	Harvest Index %
Control	116a	15.4a	55.5a	9.3a	50a
V3	118a	14.7a	49.7b	8.4ab	49a
V5	117a	14.8a	45.2c	9.5a	53b
V6	97b	11.8b	39.3d	7.4b	54b
Significance	<0.05	<0.05	<0.001	P=0.054	<0.05
$LSD_{0.05}$	14	2.0	4.1	1.3	3

Discussion

Up to growth stage V4 total defoliation to ground level did not result in loss of maize grain yield at either trial site. The leaf area removed at these stages is minimal in relation to total plant and the size of the largest leaves around the cob was unaffected by V2 and V4 defoliation, thus it is not surprising that yield loss is minimal. However we found that defoliation up to V4 may affect total biomass, which was reduced in Hawke's Bay but not Canterbury. The reason for the different response between grain and total yield is not known.

Defoliation at V6 will had a significant impact on yield, particularly grain yield. Harvest index was severely reduced with cutting at V6 in Hawke's Bay but not in Canterbury where plant population was severely affected instead. The difference in response between sites is considerable and may be related to different hybrids, sowing times and climatic conditions. Lauer *et al*. (2004) also found the response to defoliation varied among growing environments and seasons.

While grain yield may not be affected with defoliation up to growth stage V4, consistent between sites and with other observations (e.g. Hicks *et al*., 1977) is the delay in crop maturity as a result of defoliation. This has implications for harvest scheduling and crop quality, particularly in field situations where only parts of the paddock may be affected.

The conclusion from this study is that defoliation of crops up to growth stage V4 will have a minimal effect on maize yield although crop maturity may be delayed. This simulated defoliation by cutting does not take into account other impacts associated with defoliation in the field, such as compaction, freezing, shear stress, bruising and other secondary impacts. Growers should assess crop regrowth before deciding to replant damaged crops.

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Optimum plant population for maize silage in Canterbury

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Abstract

Few studies have investigated the optimum plant population for maize silage in the South Island. Most planting recommendations come from studies in the warmer North Island. Growers in the South Island face a different environment and use shorter season hybrids. For these reasons it is likely that optimum plant populations may be higher in Canterbury. This research examined the effect of plant population (65,000 plants ha^{-1} to 190,000 plants ha^{-1}) on maize silage dry matter yield, quality (grain yield) and economic value in a trial on a mid-Canterbury farm. Increasing the population increased DM yield, but there was no clear yield plateau. Plant population had no effect on grain yield. The change in dry matter content during maturation and therefore the projected harvest dates were not affected by plant population. An economic assessment showed there was increased profitability at plant populations as high as 150,000 or 170,000 plants ha^{-1}. This is well beyond currently recommended plant populations.

Additional keywords: sowing rate, maize hybrids, plant density, *Zea mays*

Introduction

Choice of plant population is a key factor in maximising profitability of silage crops. In New Zealand, research on optimum maize population density has generally been focused on grain crops in the North Island. Stone *et al*. (2000) studied maize grain yield at three North Island sites and found a yield plateau at around 120,000 plants ha^{-1}. In a rare study with maize silage crops, Densley *et al*. (2003) identified optimum plant populations of 115,000 to 130,000 plants ha^{-1}.

Modern maize hybrids have been bred with improved tolerance to stresses such as low moisture levels, low night temperatures and improved growth at high sowing rates. These hybrids enable growers to increase sowing rate and yield (Tollenaar and Wu, 1999). As plant population is increased, yield has been reported to increase until a plateau is reached (Cusicanqui and Lauer, 1999). Limitations to yield at high populations are driven by the crop's capacity to intercept solar radiation (Stone *et al*., 1998). The point at which a yield maximum is reached will depend on the agronomic practices used and the growth potential in the target environment (Olson and Sander, 1988).

North and South Island growing environments are very different and therefore hybrid choice is important for ensuring crops develop to maturity. Growers in the South Island plant hybrids with shorter growth duration

than in warmer North Island situations. The interactions between physical environment, hybrid and population have not been adequately evaluated. The potential benefits of higher plant populations in more southern latitudes may result from:

(1) Improved light capture. In southern regions a higher plant population may be necessary for short season hybrids to maximise solar radiation interception. Short season hybrids typically yield less as they have a shorter crop duration with fewer and smaller leaves than long season hybrids. Therefore, they intercept less solar radiation.

(2) More efficient canopy growth. Higher plant population minimises the time for crops to reach canopy closure. Cool spring air temperatures in South Island locations mean that leaf area development is delayed, and therefore optimum plant populations may well be higher for southern latitudes.

The aim of this study was to investigate the effect of plant population on maize silage yield, quality and profitability in Canterbury. The proportion of grain in the harvested dry matter (DM) was used as an indicator of silage quality.

Materials and Methods

Site and agronomic management

The trial was sown in a commercial maize crop near Southbridge, mid-Canterbury (43.81 °S, 172.25 °E). The paddock had previously been in perennial ryegrass pasture for six years. The soil was a Tai Tapu silt loam with good fertility (Table 1).

Table 1: Soil test results for samples taken on 23 September 2008.

Depth (mm)	pH	P (ug ml^{-1})	Ca	Mg	K	Na	S (ug g^{-1})	Anaerobic mineralisable N (kg ha^{-1})	Ammonium NH_4 (mg kg^{-1})	Nitrate NO_3/NO_2 (mg kg^{-1})
0-200	6.0	29	10	25	7	11	8	188	2.7	22.5
200-400	6.2	7	6	33	4	14	9	38	0.3	9.4
400-600	-	-	-	-	-	-	-	13	0.2	2.3
600-900	-	-	-	-	-	-	-	6	1.1	0.5
900-1200	-	-	-	-	-	-	-	4	0.3	0.4
1200-1500	-	-	-	-	-	-	-	4	3.5	0.8

The paddock was sprayed with Roundup @ 4 l ha^{-1} on 20 August 2008 and was cultivated using conventional implements between 25 September 2008 and 6 October 2008. The trial was sown on 13 October 2008 using a 16-row commercial maize planter, with 0.76 m between rows. The hybrid used was 38V12, which has a comparative relative maturity (CRM) of 87 (Anonymous, 2008). The trial was a randomised block design with five target plant populations, 75,000, 90,000, 110,000, 130,000 and 150,000 plants ha^{-1} with four replicates. Each plot was one drill width wide and 15 m long. Due to the short plot length and limitations of the drill reaching the targeted sowing rates within 15 m there was some

variation between target and achieved plant populations and there was substantial variation among replicates (Figure 1). Therefore, the plant population achieved in individual plots was used in all subsequent analyses and no attempt was made to average populations across treatments.

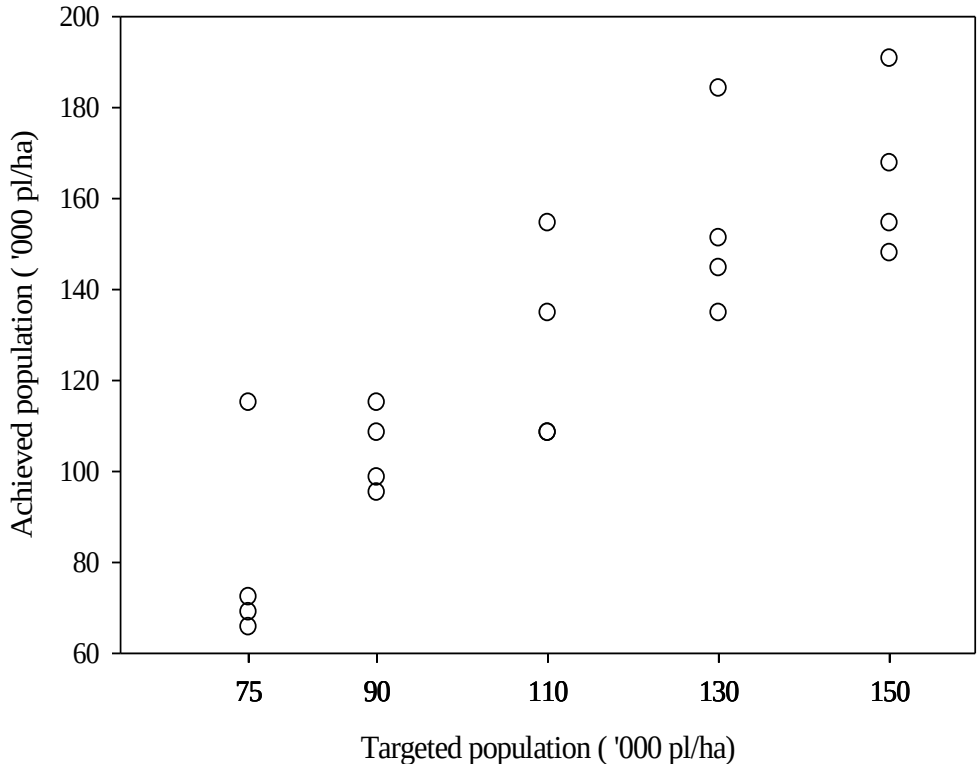

Figure 1: Comparison of target and actual populations. Note for the target population of 110,000 two replicates achieved the same population (108,553 plants ha^{-1}).

Compound fertiliser (12:10:10) was applied at sowing to give 42 kg N ha^{-1}, 35 kg P ha^{-1} and 35 kg K ha^{-1}. The site received two further separate applications of 69 kg N ha^{-1} broadcast as urea. On 20 November 2008 a post-emergence herbicide mixture of Emblem at 2.5 kg ha^{-1} and Atranex WG at 1 kg ha^{-1} in 300 l water ha^{-1} was applied to control wireweed (*Polygonum aviculare* L.), fathen (*Chenopodium album* L.) and cornbind (*Polygonum convolvulus* L.). The paddock was irrigated using a gun irrigator and received a total of 135 mm of irrigation.

Measurements

The trial was harvested on 1 April 2009. Two rows, 2 m in length, were cut from the middle of each plot and plant number and fresh weight recorded. A three plant sub-sample was weighed fresh and then split into leaf, stem and cob components before being dried at 90 °C for 4 days.

Results and Discussion

Population effect on dry matter yield

As plant population increased, crop DM yield increased (Figure 2). Both a

linear regression (R^2 = 0.58) and an exponential response (R^2 = 0.62) fitted the data similarly. However, based on an assessment of the residuals and previous results (Cusicanqui and Lauer, 1999), the exponential relationship was chosen. In both analyses, the relationship demonstrated that the biologically optimum plant population was likely to be greater than 120,000 plants ha^{-1}. The results from the final DM yield do not show a clear plateau, which suggests the biologically optimum sowing rate for this environment may have been greater than the highest population tested.

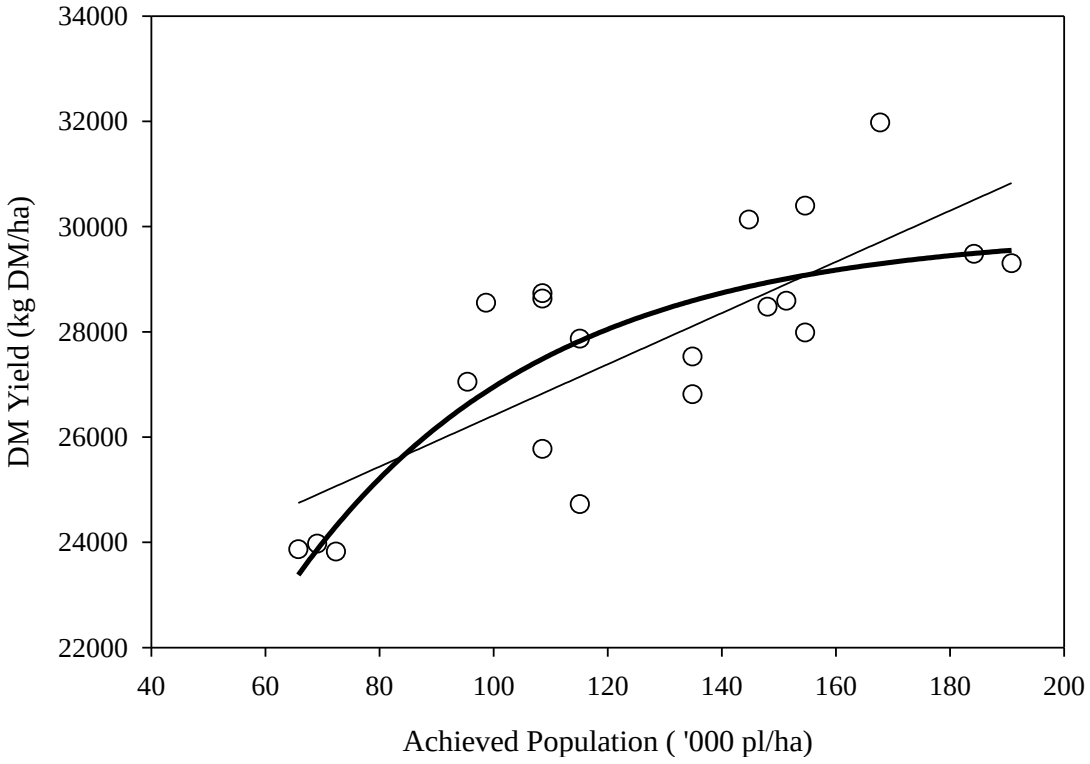

Figure 2: Relationship between maize silage DM yield and plant population. The equation for the linear regression is y = 21546.70 + 0.0486x (R^2 = 0.58). The equation for the exponential response is y = 29911.9 * (1-exp(-2.3131E-005*x)) (R^2 = 0.62).

Population effect on yield per plant

Higher plant population reduced plant size. This decreased exponentially from 362.6 g at 65,789 plants ha^{-1} to 153.6 g at 190,789 plants ha^{-1} (Figure 3). At higher populations smaller plants with narrower stems may be more susceptible to lodging, however, no lodging was observed in this trial. If growers were to adopt higher populations, this risk of lodging should be considered.

While the results for DM yield per plant showed a declining trend with increasing population there was again no clear lower limit within the treatments. The biologically optimum sowing rate for the Canterbury environment was possibly greater than the highest population used in this study.

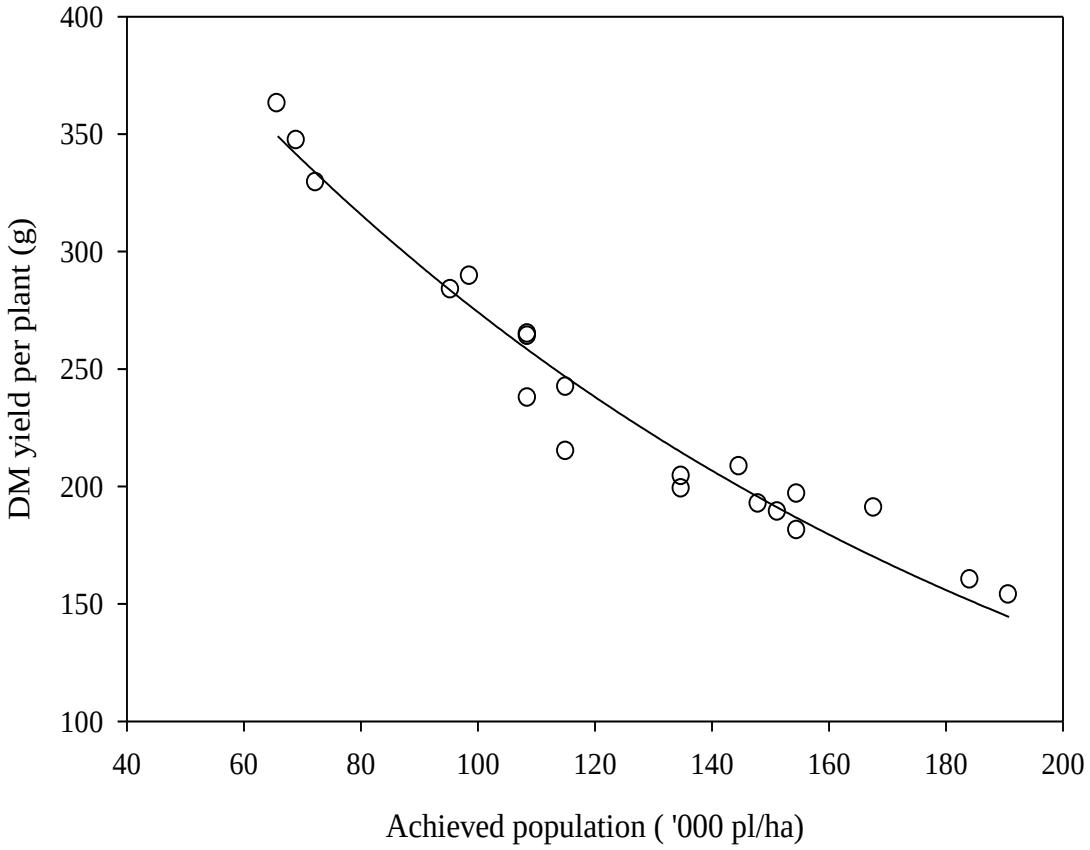

Figure 3: Relationship between DM yield per plant and achieved plant population. The fitted equation is:
$Y = 555.4*\exp(-7.058E\text{-}006*x)$ ($R^2 = 0.95$).

Population effect on crop maturity

The similar DM values suggest plants still mature at a similar time regardless of population. If growers increase populations they will still produce good quality silage and the crop will be ready for silage harvest at the same time.

The proportion of grain in the harvested DM did not change with plant population (data not shown). It was consistently 43%. This suggested that the silage quality of the crops was similar. Average crop DM was 33% and this was not affected by plant population (data not shown). This also indicated that crop maturity was not affected.

Economics

Although increasing sowing rates increase yield (Figure 2) they comes at a cost. Compared to other crops, maize seed is relatively expensive and a dense crop may suffer from more disease or water stress, with further costs for

agrichemicals and irrigation which were not investigated in this study. It is important to know the point at which the cost of increasing plant population will exceed the increased value of the silage and whether the yield advantage will offset the costs.

To estimate the most economic plant population for the current trial, the exponential regression shown in Figure 2 was used to calculate the increase in silage yield. Seed cost was assumed to be $ 325 bag^{-1} of 80,000 seeds. We also assumed fixed costs (for example paddock preparation (cultivation), fertiliser application, spraying and irrigation) of $2,500. We calculated gross margins for a maize silage price of either $0.20 or $0.30 kg^{-1} of DM.

At $0.20 kg^{-1} silage a maximum profit of $2,687 ha^{-1} came from planting at 150,000 plants $ha^{-1.}$ However, at $0.30 kg^{-1} silage a maximum profit of $5,607 ha^{-1} was achieved by planting 170,000 plants ha^{-1} (Figure 4). Clearly, the economically optimum population varies with the price of silage. However, these sowing rates are substantially higher than the current recommendation of 120,000 plants ha^{-1}. These economically optimum rates must be treated with caution because they are close to the highest population tested in this trial and uncertainty remains as to the overall effect of increasing plant population (Figure 2). However, the results indicate that plant populations could be increased above 120,000 without any loss of profit. Furthermore, although the hybrid used was short season (CRM = 87), even shorter season hybrids are available in New Zealand (e.g. 39G12 CRM = 78; Anonymous, 2008) and it may be possible to produce acceptable returns from plant populations exceeding 150,000 plants ha^{-1}.

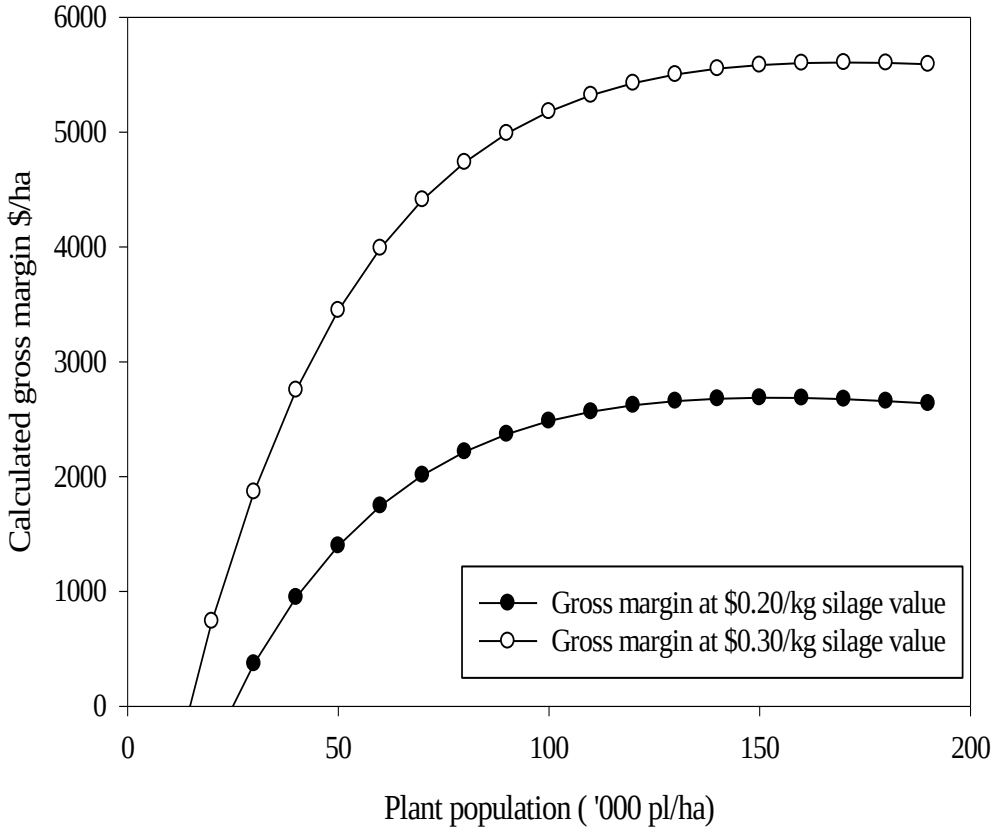

Figure 4: Effect of plant population on gross margins assuming values of maize silage of \$0.20 kg^{-1} and \$0.30 kg^{-1}.

Conclusions

This study showed that populations for maize silage crops in Canterbury could be raised well above current recommendations and still be profitable. At the plant populations tested, yield did not plateau so the biologically optimum sowing rate for the South Island may exceed those used in this study.

Increasing plant population also increased maize silage yield with no clear upper limit. At high populations plant size decreased significantly and there was a potential detrimental effect on quality. However, even at the highest plant populations there was little effect on dry matter development i.e. no effect on harvest timing.

Moreover, harvest index did not differ among plant populations and therefore the quality of the maize was not affected.

Peak gross margins were achieved in the range of 150,000 to 170,000 plants ha^{-1}, with a slow decline in profitability at high populations cause by the additional seed costs out weighing the yield increase. There was little reason to recommend sowing rates beyond 150,000 plants ha^{-1}. However, further study is required to confirm these results.

Acknowledgements

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Leaf area development in maize hybrids of different stay-green rating

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Abstract

In maize, soil nitrogen (N) influences the rate of leaf expansion and consequently the amount of light intercepted. In this study, the rate of leaf appearance and green area development of four 'stay-green' (sgr) maize hybrids (P39K38 (sgr 6), P38V12 (sgr 7), P38F70 (sgr 8) and P38G43 (sgr 9)) were examined in response to N fertiliser. Crops were grown with no fertiliser N or 270 kg N ha^{-1}. The rate of leaf appearance was consistent at around 34.3 ^{o}Cd per leaf tip and around 50.2 ^{o}Cd per ligule with no difference among cultivars. A maximum mean green area index (GAI) of 5.3 was achieved in the N fertilised crops compared with 3.9 for the non-fertilised crops. The maximum GAI ranged from 5.0 in P38F70 (sgr 8) to 6.0 in P38V12 (sgr 7) with 5.2 for P38G43 (sgr 9) and 5.1 for P39K38 (sgr 6). At maximum GAI, P38F70 (sgr 8) had 16.8 leaves compared with 15.9 for both P39K38 (sgr 6) and P38G43 (sgr 9) while P38V12 (sgr 7) had 15.2. Given that leaves appeared at a constant rate in all hybrids, the higher GAI was attributed to differences in the rate of leaf expansion. These differences may affect total radiation interception and consequently biomass yield.

Additional keywords: *Zea mays*, stay-green maize, green area index, leaf appearance

Introduction

Under non-limiting conditions, temperature has a greater influence on leaf area development in maize (*Zea mays* L.) than radiation or nutrient availability (Wilson *et al.*, 1995). The main influence of temperature is on the rate of leaf tip appearance (Stone *et al.*, 1999) and the duration of leaf expansion (Warrington and Kanemasu, 1983b). Stable rates of leaf appearance against mean temperature can be derived (Muchow and Carberry, 1989) because leaf initials appear at a constant rate from emergence until the onset of reproductive growth (Warrington and Kanemasu, 1983a). Available evidence suggests a linear response between the rate of development and mean temperature within given temperature limits (Warrington and Kanemasu, 1983b; Muchow *et al.*, 1990). This linear increase in leaf initiation with increased temperature (Warrington and Kanemasu, 1983a), makes the time based concept of thermal time (Tt) an appropriate way of characterising leaf appearance rates

(Muchow and Carberry, 1989). In a number of plant species a constant number of leaves appear per unit of thermal time (Hay and Porter, 2006).

The ontogenic development of leaf area consists of three important stages. The initial stage of leaf initiation and expansion, the fully expanded and active photosynthetic stage and finally leaf senescence (Dale and Milthorpe, 1983). Maximum biomass production depends on the full utilisation of the period between full canopy expansion and the onset of senescence. During plant senescence proteins and nucleic acids are broken down (Thomas and Stoddart, 1980) leading to a loss of chlorophyll and a decline in photosynthetic activity (Leopold, 1980). A number of plant species, including maize and sorghum (*Sorghum bicolour* L. Moench), exhibit a characteristic known as 'stay-green' where the normal process of senescence is delayed (Borrell and Hammer, 2000). It is manifested through a delayed onset or a reduced rate of leaf senescence (Thomas and Howarth, 2000). By delaying senescence or reducing its rate, hybrids with 'stay-green' characters may have the opportunity to intercept more solar radiation and hence potentially accumulate more dry matter (DM). In maize, the greatest biomass increase occurs after silking (Muchow *et al.*, 1990) when leaf area is at its maximum, and when the pool of reserves available for partitioning to grain has a direct influence on potential biomass.

In New Zealand, maize is used as a rotation crop with the potential for high DM production (Wilson *et al.*, 1994) and is primarily used as a high quality feed in dairy systems. Previous studies have quantified the relationship between temperature and developmental events in maize in terms of accumulated thermal units (Wilson *et al.*, 1995; Fletcher *et al.*, 2008). However, data on maize hybrids that differ in their 'stay-green' rating are limited. In this study the relationship between accumulated Tt and leaf appearance rate was determined for four maize cultivars with 'stay-green' ratings ranging from 6-9. A score of 9 is assigned to the cultivar with the highest number of non-senescent leaves below the ear three weeks prior to silage harvest maturity. This is followed by an investigation of the influence of N on the rate of leaf appearance and the development of green leaf area.

Materials and Methods

Experimental design

The experiment was a split plot in a randomised complete block with two irrigation treatments (dry or fully irrigated) as main plots. Two rates of N (0 and 270 kg N ha^{-1}) and four maize hybrids (P39K38 (sgr 6), P38V12 (sgr 7), P38F70 (sgr 8) and P38G43 (sgr 9)) were then arranged in fully randomised sub-plots and replicated three times. Each plot measured 4.9 x 10 m with 0.7 m between maize rows and 0.15 m, within rows.

Cultural practices

The experiment was sown on 24 October 2008 into a Typic Immature Pallic Soil (Hewitt, 1998) with 0.4-1.0 m silt loam overlying gravel that had previously been sown in oats (*Avena sativa* L.) (2005 and 2008) and consecutive crops of wheat (*Triticum aestivum* L.) (2006 and 2007). Soil tests showed a pH of 6.0, an Olsen P level of

14 mg l^{-1} and 74 kg available N to 150 mm. Two seeds were sown per hole using a jab planter and thinned to one plant $hole^{-1}$ three weeks later. A deep N analysis taken to 1.0 m indicated a mineral N content of 44 kg N ha^{-1}. During land preparation, 560 kg ha^{-1} of 20% Potash Super, containing 7.4% P, 10% K, 8.6% S and 16% Ca was applied. A soil test four weeks after emergence showed that the Olsen P level had risen to 33 mg l^{-1}.

A pre-emergence application of atrazine (Nu-Traize 900 DF, 900 g kg $a.i^{-1}$) at 1.5 l ha^{-1} was used to control broad leaf weeds.

Two weeks after sowing, 50% of the plants had emerged. Ten days later five plants were selected for non-destructive sampling and tagged. After hand thinning the mean population was 9.25 plants m^{-2}. Additional N for the fertilised treatment was provided as urea (46% N) and was broadcast in two applications each of 135 kg N ha^{-1} at 16 and 37 days after emergence (DAE). A light overhead sprinkler irrigation of 10 mm followed each N application to dissolve the urea.

Measurements

During vegetative growth, leaf appearance was monitored every 3-4 days by recording the number of emerged leaf tips and fully expanded leaves. A fully expanded leaf and an emerged leaf tip were recorded as defined by Muchow and Carberry (1989). Green area increase was measured every 14 days whenever the weather allowed using a Sun Scan (Delta-T Devices, Cambridge-England). Water extraction from the profile was monitored weekly using Time Domain Reflectometry (TDR) (Trase System 1 Model 6050 X1) and a Neutron Probe (NMM Model 3300) at 0.1 m intervals to a depth of 0.4-1.0 m dependent on the depth to gravel. Irrigation water was applied to restore the moisture depleted from the top 0.2 m of the soil profile to near field capacity when the total available water content dropped to 15%. Air temperatures were logged hourly with three thermistors located in the central plot of each replicate.

Calculations and data analysis

This paper only reports the data from the fully irrigated treatment. Daily thermal units were accumulated after emergence from air temperatures using the modified sine curve method (Fletcher, 2005) with a base temperature of 0 ^{o}C (Wilson *et al.*, 1995) and an optimum temperature of 34 ^{o}C (Muchow and Carberry, 1989). Usually the final three leaves appear at a faster rate because of their smaller size (Warrington and Kanemasu, 1983b) and this distorts the linear relationship between leaf appearance rate and Tt. In this study a two-stage linear regression was fitted to the relationship between leaf appearance and Tt using a series of dummy variables (Draper and Smith, 1998). The maximum R^2 was used as the criterion to partition data points to the two line segments (Fletcher *et al.*, 2008). Green area index (GAI) data were plotted as functions of time.

Statistical analysis was done with Genstat 11, Release 11.1 (Lawes Agricultural Trust, Rothamsted Experimental Station, UK, 2008). All variates were analysed using ANOVA procedures in a randomised complete block design structure and the least

significant difference (P<0.05) was used to separate means.

Results

There were no interactions between hybrids and N treatment. Therefore main effects of hybrid and N treatments only are reported.

Leaf appearance rate

The relationship between the number of visible leaf tips and accumulated thermal time above a base temperature of 0 ^{o}C was linear. Nitrogen did not influence (P<0.49) the rate of leaf tip appearance (reciprocal of the coefficient of the linear regression). The phyllochrons were 35 and 33.9 ^{o}Cd leaf tip^{-1} for the 0 and 270 kg N ha^{-1} treatments, respectively, but were not significantly different.

Among hybrids, leaf tips appeared linearly with accumulated thermal time (Figure 1a). The phyllochrons ranged (P<0.36) from 33.3 ^{o}Cd leaf tip^{-1} in P38F70 (sgr 8) to 35.2 ^{o}Cd leaf tip^{-1} in P38G43 (sgr 9). The other cultivars were intermediate with 33.8 ^{o}Cd for P39K38 (sgr 6) and 35.1 ^{o}Cd for P38V12 (sgr 7). The appearance of fully expanded leaves over time was also unaffected by N fertiliser or cultivar and successive fully expanded leaves appeared after 50.0 ^{o}Cd (Figure 1 b).

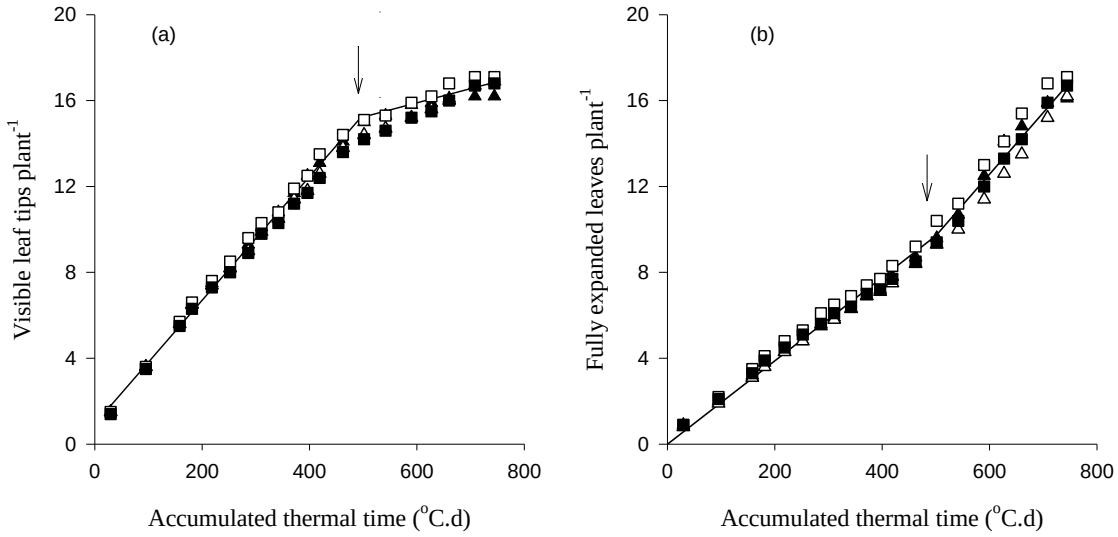

Figure 1: The Number of visible leaf tips (a) and fully expanded leaves (b) plant^{-1} against accumulated thermal time (T_b = 0 ^{o}C) for P39K38 (sgr 6) (▲) P38V12 (sgr 7) (∆) P38F70 (sgr 8) (□) and P38G43 (sgr 9) (■) grown at Lincoln University in 2008-09. Fitted regressions were
(a) Y = 0.0291x+1 (R^2 = 0.99) (S.E = 0.156 leaf tips plant^{-1}) and
(b) Y = 0.0200x (R^2 = 0.99), (S.E = 0.19 leaves plant^{-1}), respectively.
Solid lines indicate the two-stage linear regression of visible leaf tips and fully expanded leaves on Tt. Arrows indicate the point of inflection.

Green area index

The GAI increased slowly from emergence and was still less than 1.0 at 40 DAE (Figure 2). It then increased rapidly until it reached a maximum at 75 DAE. Nitrogen fertiliser increased ($P<0.001$) the rate of green leaf area development. Mean maximum GAI in treatments without N was 3.9 (Table 1) compared with 5.3 for those that received 270 kg N ha^{-1} (Table 1) and these remained above the critical GAI of 4.0 for about 70 days (Figure 2 b). Nitrogen therefore increased GAI duration, enabling fertilised crops to intercept solar radiation for longer.

Hybrid differences ($P<0.05$) were observed for maximum GAI which ranged from 3.2 in P38F70 (sgr 8) to 4.8 in P38V12 (sgr 7) with no added N (Figure 2 a). Hybrids with the highest maximum GAI tended to be those with the lowest 'stay-green' ratings. These hybrids either developed more leaves or had larger leaves. Table 1 shows that P38V12 (sgr 7) had the highest GAI, but fewer ($P<0.001$) leaves than other hybrids. Under low N, the only hybrids that reached critical GAI (P38V12 (sgr 7) and P39K38 (sgr 6)) were those with a low 'stay-green' rating.

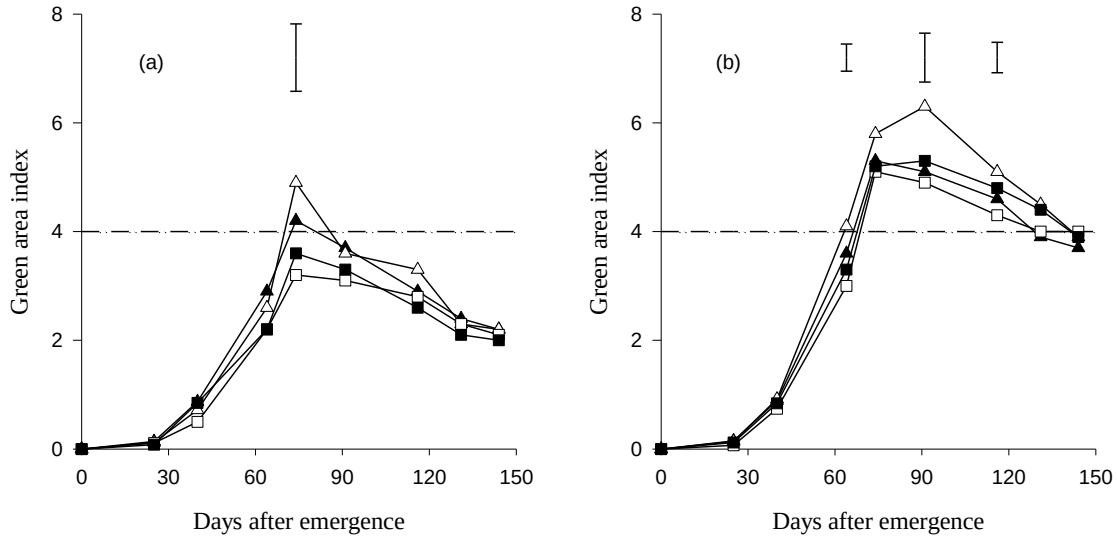

Figure 2: Green area index plotted against DAE for non-fertilised (a) and fertilised (b) crops of P39K38 (sgr 6) (▲), P38V12 (sgr 7) (△), P38F70 (sgr 8) (□) and P38G43 (sgr 9) (■) grown at Lincoln University in 2008-09. Each point is the mean of 3 replicates. Standard error = 0.296. The dashed line indicates the critical green area index.

Table 1: Maximum green area index and final number of leaves of four maize hybrids grown without or with 270 kg N ha^{-1} at Lincoln University in 2008-09.

	Maximum GAI		
Hybrid	270 kg N ha^{-1}	No N	Final number of leaves
P3K38 (sgr 6)	5.1b	4.2a	15.9b
P38V12 (sgr 7)	6.0a	4.8a	15.2c
P38F70 (sgr 8)	5.0b	3.2b	16.8a
P38G43 (sgr 9)	5.2b	3.4b	15.9b
Significance level	<0.001		< 0.001
LSD	0.59		0.66
CV (%)	15.6		4.9

Means followed by the same letter are not significantly different based on least significant tests at $\alpha = 0.05$.

Discussion

The conservative linear relationship between leaf tip appearance and accumulated Tt with or without additional N (Figure 1) is indicative of the constancy of initiation of phytomers at the stem apex (Hay and Porter, 2006). Successive leaf tips appeared after approximately 34.5 ^{o}Cd and each fully expanded leaf after 50 ^{o}Cd. These results are consistent with those of Vos *et al.* (2005) in two glasshouse experiments where the rates of N applied ranged from 0.5-6.0 g pot^{-1}. Both studies reported an average rate of leaf appearance of 50 ^{o}Cd $leaf^{-1}$. Muchow (1988) observed relatively small differences in leaf appearance rates in a field trial where N treatments ranged from 0 to 42 g N m^{-2}.

Linearity between accumulated Tt and leaf tip appearance (Figure 1a) or fully expanded leaf appearance (Figure 1b) rates among the hybrids was also observed. These results support the idea that the rate of leaf appearance (phyllochron) is a development process that is strongly related to temperature and is only influenced by fertility at extreme levels.

The influence of N was mainly on the temporal pattern of GAI development. Most maize crops intercept more than 90 % of the oncoming solar radiation when their GAI is greater than or equal to 4.0 (Birch *et al.*, 2003). A GAI of 4.0 was considered a critical minimum value for assessing growth and development responses in this study. Nitrogen deficiency limited green area increase in the non-fertilised crops with two of the hybrids not attaining the critical GAI of greater than or equal to 4.0 (Figure 2a). The non-fertilised crops therefore had GAI values below the critical GAI for most of the season which would reduce the total amount of solar radiation intercepted. In contrast, the fertilised crops were above the critical GAI for about 70 days (Figure 2b). Nitrogen deficiency reduces the rate of cell division and expansion (Dale and Milthorpe, 1983) by influencing the capacity of a plant to accumulate solutes resulting in restricted cell growth (Wolfe *et al.*, 1988). Because reductions in leaf area are permanent (Begg and Turner, 1976), there is a reduced potential to intercept solar radiation, specifically when the GAI is below critical values.

Figure 2 shows that both P39K38 and P38V12 had consistently higher GAIs under both N regimes. These hybrids had the two lowest 'stay-green' ratings of 6 and 7, respectively. It appears that under low N availability, both hybrids efficiently utilised available N to expand the leaf canopy. This was potentially achieved by mobilising available N from older leaves into younger and more actively growing leaves. Alternatively, these hybrids could also have partitioned more of the available N into leaf growth. According to Sinclair and Horie (1989), during early vegetative growth, plants must partition a certain proportion of available N between the demand for leaf growth and the maintenance of leaf nitrogen concentration. Greater partitioning to leaf growth enhances the development of leaf area (Vos *et al.*, 2005). Future analysis of leaf N concentrations will be used to examine the impact of 'stay-green' on nitrogen allocation.

Conclusion

The timing of developmental events during maize vegetative growth was unaffected by N fertiliser and maize hybrid. Temperature was a strong driver of development as defined by leaf tip appearance and rates of fully expanded leaf production. Nitrogen influenced the maximum GAI and GAI duration and there were differences among hybrids in their ability to accumulate GAI in both the low and high N treatments.

In most cases the hybrids P38V12 and P39K38, with low 'stay-green' rating developed a larger green leaf area than the other hybrids (P38F70 and P38G43). This may have occurred by mobilising N reserves to support leaf enlargement, but the rate of decline of leaf area was higher toward the end of grain filling. There appeared to be no relationship between 'stay-green' rating and phyllochron.

Acknowledgement

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Alternative tillage practice for establishing maize silage and reducing soil nitrogen mineralisation

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Abstract

Intensive cultivation practices require significant energy inputs and repeated working of the soil, ultimately resulting in a breakdown of soil structure. Nitrogen (N) mineralization can also be extremely high in these situations, especially following permanent pasture. Where this nutrient release exceeds the demand of the subsequent crop it can create an environmental risk. Four field trials were undertaken in farm paddocks to determine if strip tillage, a reduced cultivation approach, could be used to establish maize silage and reduce soil N mineralisation. Trials were conducted in two seasons (2007-08, 2008-09). At each site strip tillage (ST) was compared to conventional tillage (CT). There were 4 or 6 replicates of each treatment. Tillage practice had no significant effect on mean plant spacing at any site. There was also no effect of tillage practice on silage yield at harvest; across sites, yields averaged 22.6 t DM ha^{-1} and 23.0 t DM ha^{-1} for the ST and CT treatments, respectively. The dry matter (DM %) content averaged 35% across treatments and sites. Early in the season, soil minN levels were often significantly ($P<0.01$ to 0.08) lower under ST. This was due primarily to lower minN in the mid-row of ST plots than in the mid-row of CT plots (reflecting differences in cultivation in this zone). An estimation of the balance of minN supply during the season (accounting for soil N prior to cultivation and at harvest, fertiliser N, and plant N in the harvested silage) indicated less minN was released under ST. Thus ST appears to have good potential as an alternative approach to establish maize silage and to reduce soil N mineralisation.

Additional keywords: Strip tillage, conventional tillage, forage, *Zea mays*

Introduction

Maize rotations typically include a grass phase, the length of which can vary considerably. This can be as short as six months in continuous cropping systems and up to several years in mixed arable-pastoral systems. The restorative benefits of grass phases on soil quality are well documented in New Zealand (Haynes and Beare, 1997; Francis *et al*., 1999). However, during the conversion of pasture back into cropping, soils are often exposed to intensive cultivation practices. Such practices require significant energy inputs and repeated working of the soil, increasing the rate of

organic matter decomposition and ultimately resulting in a loss of soil structure. Mineralisation of nutrients such as nitrogen (N) can also be very high in these situations. Recent work in the Waikato has shown that > 300 kg N ha^{-1} can be released in the first year following cultivation of permanent pasture (Johnstone *et al*., 2009). Where such mineralisation exceeds crop N demand (approximately 200-250 kg N ha^{-1} in maize), it can be both a waste to the farmer and pose an environmental risk. One alternative to manage paddocks coming out of pasture is to adopt a reduced cultivation approach such as strip tillage (ST). Strip tillage significantly reduces the area of land that is cultivated compared with conventional approaches, offering a number of agronomic and economic benefits (Hoyt *et al*., 1994; Vetsch *et al*., 2007; Overstreet and Hoyt, 2008). Work over the past decade across the North Island of New Zealand has shown that reduced tillage practices often have no adverse affect on yield or profitability of row crops like maize, sweet corn, squash and peas (Reid *et al*., 2001; Pearson and Wilson, 2002; Searle and Hosking, 2007). These findings are largely consistent with those reported overseas, where the practice is widely used. In maize, many studies have shown that no yield penalty associated with ST, and that gross margins are often improved as a result of reduced cultivation (Al-Kaisi *et al*., 2005; Licht and Al-Kaisi, 2005; Vetsch *et al*., 2007; Archer and Reicosky, 2009). This project was undertaken to demonstrate to farmers that ST can be used to establish maize silage and reduce soil N mineralisation.

Materials and Methods

Background

Four trials were conducted in farm paddocks in two seasons (2007-08, 2008-09). Paddocks were located in central Hawke's Bay and Waikato. All had been in pasture for varying durations (6 months up to 30+ years) and were sprayed off with herbicide approximately 1-4 weeks prior to cultivation.

Trial design and crop management

In each paddock, areas were set up to compare a conventional tillage (CT) approach with ST. Conventional tillage at all sites was by a single plough pass followed by power harrow (Sites 1 and 4), discs (Site 2), or roll only (Site 3). The effective cultivation depth under CT was approximately 20-30 cm. Strip tillage was by a modified power harrow (Site 1) or either a single (Site 2) or double pass (Sites 3 and 4) with a mole knife implement (the cultivated strip was 33 cm wide at Site 1 and 15 cm wide at Sites 2-4). The effective cultivation depth under ST was approximately 15-25 cm. Row spacing at all sites was 76 cm. Experimental design was a randomised complete block at Sites 1 and 4 comparing the two tillage treatments (CT and ST) each replicated 4 or 6 times. Individual plots were eight rows wide by at least 10 m in length. Sites 2 and 3 were larger demonstration trials. Six or nine paired plots were established for each treatment, each plot was eight rows wide by 10 m long. With the exception of tillage practice, each crop was grown according to the farmer's standard practice. Sites 2 and 3 were irrigated as required by centre pivot. A summary of important crop and management details is provided in Table 1.

Background measurements

Prior to cultivation, intact cores were collected from the trial area to determine soil bulk density. Sampling depth was either 0-15 cm (Sites 1-3) or 0-35 cm (Site 4). Basic soil fertility indicators (soil pH, Olsen P, exchangeable cations, CEC and base saturation) were measured on a composite sample of 20 cores collected at sowing. Sampling depth was 0-15 cm. In general, basic soil fertility indicators at sowing were interpreted as sufficient for maize production (Table 2). There were no major weed or pest and disease issues at any trial site. Growing conditions in both regions were favourable during each season; mean daily temperature and radiation levels were high during the most active periods of plant growth (November-February). Soil moisture was good at Sites 1 and 4 due to regular rainfall; irrigation was applied as required at Sites 2 and 3.

Table 1: Crop and management details of the four trial sites, 2007-09.

Site	Site 1	Site 2	Site 3	Site 4
Region	Hawke's Bay	Hawke's Bay	Hawke's Bay	Waikato
Soil type	Flaxmere sandy loam	Takapau sandy loam	Takapau sandy loam	Otorohanga silt loam
Pasture history[1]	20 years	<1 year	<1 year	>30 years
Conventional tillage approach	Plough, power harrow	Plough, discs	Plough, roll	Plough, power harrow
Strip tillage approach	Modified power harrow	Mole knife	Mole knife (x2)	Mole knife (x2)
Maize hybrid	39K38	38H20	39F58	36M28
Sowing rate (# ha^{-1})	108,000	115,000	105,000	105,000
Planting date	4 Nov 2007	16 Nov 2007	18 Nov 2008	18 Nov 2008
Fertiliser at sowing[2]	150 kg DAP ha^{-1}	200 kg DAP ha^{-1}	200 kg DAP ha^{-1}	Nil
In-season fertiliser[3]	190 kg Urea ha^{-1}	200 kg Urea ha^{-1}	225 kg Urea ha^{-1}	Nil
Harvest date	25 Mar 2008	2 Apr 2008	15 Apr 2009	26 Mar 2009

[1]Sites 1 and 4 had been in long-term perennial grass with regular dairy grazing, whereas Sites 2 and 3 had been in short-term annual grass with regular cropping. [2]DAP (diammonium phosphate) contains 18:20:0 NPK. [3]Urea is 46:0:0 NPK.

Table 2: Soil fertility characteristics at sowing of the four trial sites, 0-15 cm[1].

Site	Site 1	Site 2	Site 3	Site 4	Medium range
Soil pH	5.9	5.8	5.5	6.2	5.6-6.4
Olsen P (mg l^{-1})	9	19	15	42	14-30
MAF K	5	8	3	15	8-15
MAF Ca	10	10	4	11	5-10
MAF Mg	29	15	6	18	10-16
MAF Na	6	11	6	7	1-10
CEC (me 100 g^{-1})	15	20	18	22	12-25
Base saturation	70	53	29	62	50-85
Organic matter (%)	5.1	9.6	14.3	7.9	7-12
Bulk density (g cm^{-3})	1.23	1.03	1.03	1.14	

[1]Soil test results do not include starter fertiliser where applied.

Crop measurements

Mean plant spacing was determined at all sites approximately four weeks after sowing (WAS). For this measurement, two 4 m sections of adjacent rows were marked in each plot, and the distance between each individual plant recorded. Mean plant spacing and standard deviation estimates were derived from these figures. At Sites 3 and 4 whole plant (above-ground only) samples were collected from all plots 4, 8 and 12 WAS. In each instance a composite of 10 plants was randomly selected. Plant dry biomass, total N concentration and N uptake were calculated. Silage yields were determined at each site at commercial maturity (after kernels had reached a ⅔ milk line). For this measurement, two 2.5 m-sections of adjacent rows were harvested from each individual plot. Plant population and total standing plant biomass were determined. A sub-sample of mulched silage was collected from all plots and analysed for DM content (% DM) and total N concentration, and crop N removal was estimated.

Soil nitrogen measurements

At Sites 3 and 4 soil mineral N (minN, the sum of nitrate-N and ammonium-N) was measured at sowing, and at 4, 8 and 12 WAS, and at harvest. At sowing four cores were collected from within the plant row and four from the mid-row of each individual plot. On subsequent dates only two cores were collected from each sampling position. Sampling depth was either 0-30 cm (Site 3) or 0-60 cm (Site 4). The shallower samples taken at Site 3 was due to a stony subsoil layer below 30 cm. Samples were analysed separately by plant and mid-row positions for both tillage approaches (CT and ST); the exception to this was at sowing, when plant and mid-row positions under CT were composited. A weighted mean was calculated for the ST plots to reflect the proportion of row width that was and was not cultivated (as represented by the plant and mid-row, respectively). At Site 1 soil minN was only measured prior to cultivation (a composite from across the trial area, 0-60 cm) and at harvest (by each individual plot, as described for Sites 3 and 4). Soil minN was not followed at Site 2.

Statistical analyses

Relevant data were analysed using a one-factor ANOVA. Significance values were recorded where P<0.10 values between 0.05 and 0.10 are considered weakly significant and should be interpreted with appropriate caution. Values of P above 0.10 were considered not significant (ns). Least Significant Difference (LSD) values were calculated to separate treatment means and were based on a P value < 0.05.

Results and Discussion

Crop performance

There was no significant effect of tillage practice on mean plant spacing at any site (Table 3). However, at two sites variation around the mean spacing (indicated by the standard deviation) was significantly higher (P<0.03 to 0.09) under ST. This appeared to reflect seed placement issues related to cloddy seed beds under ST. Despite these observations, there was no significant effect of tillage practice on silage yield at any of the four sites. Across sites the average silage yield was 22.6 t DM ha^{-1} and 23.0 t DM ha^{-1} for the ST and CT respectively. Individual plant biomass was also unaffected by tillage practice, indicating that plants reached similar biomass potentials. Dry matter content was largely unaffected by tillage practice. The exception to this was at Site 2, where DM was significantly higher under ST than CT. The practical importance of this effect appeared minor as the difference was small (< 2% DM) and could be accounted for by delaying harvest until these plots had achieved a higher DM. The ideal range for ensiling maize silage is between 32 and 38%. Total N concentration in the harvested maize silage was unaffected by tillage practice and ranged from 0.8 to 1.1% across sites.

Soil nitrogen mineralisation

At Sites 3 and 4 soil minN increased rapidly after cultivation before declining steadily due to plant N uptake (Table 4). Weighted soil minN levels (accounting for the separate results from mid-row and plant row positions) were significantly lower in ST plots 8 WAS at Site 3 and at sowing and 4 WAS at Site 4. Although side dressing with N fertiliser (104 kg N ha^{-1}) at Site 3 would have influenced soil minN results at 8 WAS, there is little reason to expect that the broadcast application would have affected observations made under each tillage practice differently. At both sites, lower soil N levels under ST were primarily due to less minN in the uncultivated mid row of the ST plots than in the cultivated mid row of the CT plots (Figure 1a). Generally, soil minN levels in the plant row of CT and ST plots were not significantly different during the season (Figure 1b). The exception to this was at 12 WAS at both sites, though the importance of these observations is not clear as the difference between treatments was relatively small (9-24 kg N ha^{-1}). In general, then, tillage intensity resulting from the two approaches (i.e. mole knife compared with ploughing) had little impact in this zone. The effect of tillage practice on residual soil N at harvest was not strong at any site. At Site 1 there was considerable variability in soil minN, limiting statistical analyses. At Site 3 the difference in residual N at harvest, though weakly significant, was

comparatively small (28 kg N ha^{-1}). At Site 4, this observation appeared to be confounded by significantly higher plant N uptake under CT. In general, reduced cultivation will lower mineralisation rates (Johnson and Hoyt, 1999); this has been highlighted in many studies where soil minN is higher under CT than with no- or reduced-tillage approaches (Catt *et al*., 2002; Pearson and Wilson, 2002).

At Sites 1, 3 and 4 a simplified N balance was estimated for CT and ST. For this calculation, the sum of plant N and soil minN at harvest was adjusted for minN of the uncultivated soil; these uncultivated samples were representative of 'baseline' soil minN levels in each paddock, and were taken either prior to cultivation at Site 1 or from the uncultivated mid-row of the ST plots at sowing at Sites 3 and 4. Fertiliser N was also subtracted where applied (equivalent to 87 kg N ha^{-1} at Site 1 and 140 kg N ha^{-1} at Site 3). Using this approach, net mineralisation during the cropping season for the CT and ST plots respectively was estimated to be 188 kg N ha^{-1} and 90 kg N ha^{-1} (Site 1, $P<0.08$), 134 and 105 kg N ha^{-1} (Site 3, $P<0.01$), and 288 and 232 kg N ha^{-1} (Site 4, $P<0.04$). These estimates assume that there was minimal leaching and volatilization loss of either soil-generated N or fertiliser-supplied N and that there was a minimal supply of N from below the major rooting depths (60 cm at Sites 1 and 4, and 30 cm at Site 3). The large difference among sites in their ability to mineralise N during the season appeared likely to reflect the combined influence of different durations under pasture (up to 30 years at Site 4 and less than 1 year at Site 3), pasture quality (very poor at Site 1) soil type and depth, and local environmental conditions (particularly soil temperature and soil moisture). Collectively, these factors determine the potential N pool in the soil and its subsequent rate of release following cultivation.

Conclusions

Collectively, findings from both seasons suggest that ST has potential as an alternative approach to establish maize silage and reduce soil minN after pasture. This work confirmed that N mineralisation can vary significantly depending on cultivation approach. Current tools used by farmers to predict N requirements of maize (e.g. AmaizeN) do not account for this factor when generating recommendations. This may result in inaccurate predictions of soil N supply, ultimately reducing farmer profit. Until cultivation approach is incorporated into such programmes, farmers should consider collecting a representative soil minN sample from the paddock shortly before making in-season N fertiliser decisions. These test results can be entered into AmaizeN to provide the best estimate of what is currently available and ensure that crops are not N deficient.

Table 3: Effect of tillage practice on mean plant spacing and standard deviation at 4 WAS and on crop performance indicators at harvest, all sites.

	Mean plant spacing (cm)[1]	Standard deviation (cm)[2]	Silage yield (t DM ha^{-1})	Individual plant dry biomass (g $plant^{-1}$)	Dry matter content(%DM)	Total N conc.(%N)
Site 1						
CT	12.5	5.5	24.3	232	42	0.8
ST	13.4	6.2	22.9	221	43	0.8
P-value[3,4]	ns (1.8)	ns (2.7)	ns (3.3)	ns (33)	ns (6)	ns (0.2)
Site 2						
CT	11.6	5.2	20.9	187	28	1.1
ST	12.0	5.5	20.9	198	30	1.1
P-value	ns (2.4)	ns (1.9)	ns (1.4)	ns (20)	0.01 (1)	-[5]
Site 3						
CT	13.0	4.3	18.7	187	37	1.1
ST	13.7	5.8	19.5	190	36	1.1
P-value	ns (1.4)	0.09 (1.9)	ns (2.3)	ns (30)	ns (2)	ns (0.1)
Site 4						
CT	12.6	4.2	28.1	266	33	1.0
ST	12.8	5.4	26.9	254	33	0.9
P-value	ns (0.8)	0.03 (1.1)	ns (2.4)	ns (35)	ns (2)	ns (0.2)

[1]Each farmer's target sowing rate was equivalent to 108,000 plants ha^{-1} (12.2 cm), 115,000 plants ha^{-1} (11.4cm), 105,000 plants ha^{-1} (12.5cm) and 105,000 plants ha^{-1} (12.5cm) at Sites 1-4, respectively. [2]66% of plants had a mean spacing ± the standard deviation. [3]ns = not statistically significant at P<0.10. Values between 0.05 and 0.10 are considered weakly significant and should be interpreted with caution. [4]LSD values are provided in parentheses and represent the smallest difference necessary between two means for a statistically significant test result (P<0.05). [5]Total N data were not replicated at Site 2.

Table 4: Effect of tillage practice on soil mineral N (minN) and plant N uptake during the season, Sites 1, 3 and 4.

	Sampling occasion									
	Precult.[1]	Sowing	4 WAS[2]		8 WAS		12 WAS		Harvest	
	Soil minN[3]	Soil minN[3]	Soil minN[3]	Plant N uptake[4]	Soil minN[3]	Plant N uptake[4]	Soil minN[3]	Plant N uptake[4]	Soil minN[3]	Plant N uptake[4]
Site 1										
CT	51								131	195
ST									50	179
P-value[5,6]									ns (145)	ns (32)
Site 3										
CT	20	27	78	3	195	83	69	164	83	211
ST		21	71	4	120	90	74	181	55	210
P-value		ns (9)	ns (31)	0.01 (<1)	0.01 (21)	ns (17)	ns (41)	ns (48)	0.09 (33)	ns (26)
Site 4										
CT	75	131	197	29	49	155	51	175	69	294
ST		84	155	27	60	129	49	174	59	248
P-value		0.03 (38)	0.08 (48)	ns (7)	ns (19)	ns (39)	ns (8)	ns (101)	ns (21)	0.06 (47)

[1]Precultivation soil minN was taken either prior to cultivation at Site 1 or from the uncultivated mid row of ST plots at sowing at Sites 3 and 4. [2]WAS = weeks after sowing. [3]kg N ha^{-1}, 0-60cm. [4]kg N ha^{-1}. [5]ns = not statistically significant at P<0.10. Values between 0.05 and 0.10 are only weakly significant and should be interpreted with caution. [6]LSD values are provided in parentheses and represent the smallest difference necessary between two means for a statistically significant test result (P<0.05).

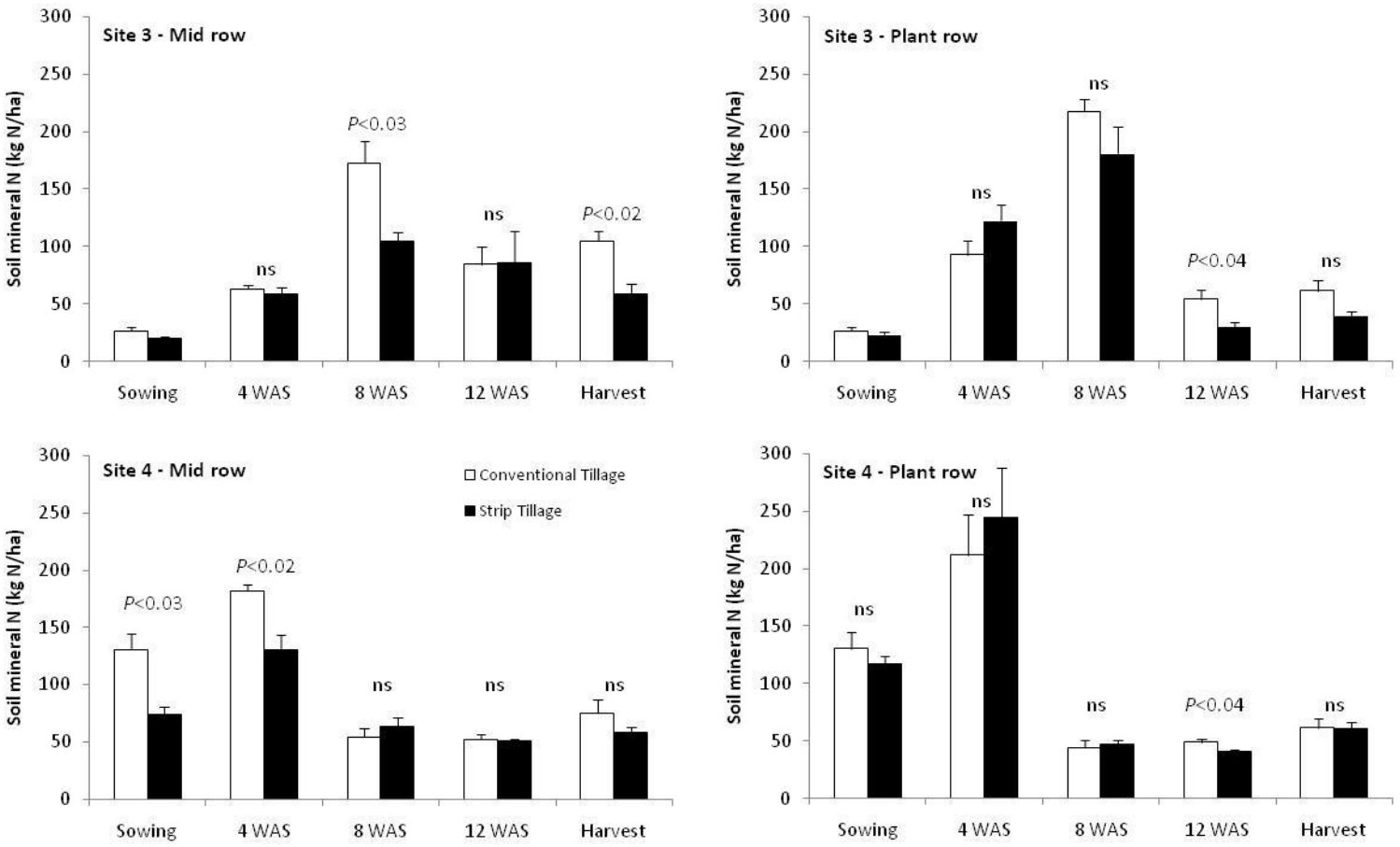

Figure 1: Effect of tillage practice on soil mineral N at sowing, at 4, 8 and 12 WAS, and at harvest in the mid-row and plant row separately (Site 3 and 4 only). Vertical bars indicate standard error. P-values represent the ANOVA outcome on the effect of tillage practice on each individual sampling zone separately; ns = not statistically significant. No means separation is provided at sowing at either site because the mid row and plant row results of the CT plots were composited. Seasonal N fertiliser application was equivalent to 140 kg N ha^{-1} (Site 3) and 0 kg N ha^{-1} (Site 4).

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Intercropping maize-silage in New Zealand[1]

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Abstract

Simultaneous intercropping of maize silage with a secondary crop may increase the productivity of farm rotations in New Zealand. The aim of this research was to help identify the most suitable species and intercrop sowing times for intercropping with maize. Field experiments were conducted in 2006-07 and 2007-08. In 2006-7, the intercrops (Italian ryegrass, cv. Moata; kale, cv. Grunner; forage brassica, cv. Hunter and balansa clover, cv. Bolta) were sown in the maize crop at various intervals (at maize sowing, eight weeks after maize sowing, and soon after the maize-silage harvest). Intercrops sown at the same time as the maize significantly reduced maize and total silage (maize + intercrop) dry matter (DM) yields compared with maize alone. Delaying intercrop sowing had no effect on maize or total DM yields. In all cases, the intercrops established well but either died or failed to produce productive stands over the winter. In the second season several refinements were made to the intercropping. Forage brassica (cv. 'Hunter') sown at the same time as maize still reduced maize and total silage DM yields regardless of sowing rate, but perennial ryegrass (cv. 'Aries') and other sowing dates did not. Only forage brassica sown at the same time as the maize gave a viable intercrop stand that grew during the subsequent winter. The highest yields were achieved when maize alone was grown, over summer and followed by Italian ryegrass in the winter (36.7 t DM ha^{-1} $year^{-1}$).

Additional keywords: silage DM yield, intercrop yield, Italian ryegrass, kale, forage brassica, balansa clover, *Zea mays*, *Brassica campestris* x *Brassica napus*, *Brassica oleracea*. ssp. *acephala*, *Lolium multiflorum*, *Trifolium balansae*

Introduction

Intercropping involves growing two or more crops in close proximity simultaneously in the same paddock, such that they interact (Papendick *et al*., 1976; Sullivan, 2003). Intercropping is an established practice in many developing countries, and is gaining interest in developed countries as growers seek to adopt more environmentally sustainable farming methods whilst improving profitability.

Variations in intercropping are based on the timing of sowing and harvesting, and the degree of mixing/separation of the crops. Maize (*Zea mays* L.) is grown in rows, and therefore maize intercropping systems fall in the category of row-intercropping (Papendick *et al*., 1976). Relay-

[1]Revised 2010

intercropping occurs when two or more crops grow simultaneously but only during part of the life cycle of each crop (Papendick *et al*., 1976). For example, a second crop might be sown after the first crop but before the first crop is ready to harvest. This example is of particular relevance to New Zealand maize-silage growers aiming to reduce the time lost between the maize harvest and sowing and establishment of a subsequent winter crop.

New Zealand maize-silage growers are interested in intercropping for several reasons: to increase total annual biomass production and economic returns, minimise nutrient (e.g. N) leaching, improve soil structure and productivity, improve resilience to vehicle movements, manipulate maize crop silage quality, and to provide further options for winter grazing or silage (Carey *et al*., 2006). While potential benefits can be gained from intercropping, growers are also aware of some of the likely disadvantages, such as increased input costs and management time, competition between the intercrop and the maize for water and nutrients, and changes in cultivation and other management practices (Carey *et al*., 2006).

The aim of this research was to provide answers to two fundamental questions before New Zealand maize-silage growers trial intercropping:

(1) what are the most suitable plant species for intercropping with maize? and
(2) when should intercrops be sown?

Materials and Methods

Site and experimental details

Experiments were undertaken during 2006-07 and 2007-08 at Plant & Food Research, Hastings (39 ° 36′ 30.74 "S, 176 ° 54′ 46.26 "E). The soil was a Mangateretere silty-clay loam. Key soil test results are summarised in Table 1.

Table 1: Soil test results for the two seasons. The depth of soil sampled was 0-15 cm for all test variables except mineral-N where the sampling depth was 0-30 cm.

Soil test	2006-07	2007-08
pH	5.8	6.3
Olsen P (µg ml^{-1})	37	23.0
Exchangeable cations (me 100 g^{-1})		
Ca	11.7	12.3
Mg	2.3	1.7
K	0.8	1.0
Na	0.2	0.1
CEC (me 100 g^{-1})	21.5	19.0
Mineral N (kg N ha^{-1})	38.0	18.0

The 2006-07 experiment was a randomised complete-block design with 4 replicates and 13 treatments (4 intercrop species, three sowing dates, and a no-intercrop control). Plots were 4.56 m wide (six 76 cm maize rows) x 10 m long. Maize (Pioneer hybrid 36H36) was sown on 21 October 2006 at

90,000 seeds ha^{-1}. Intercrops were sown by broadcasting and light raking at various intervals: at maize sowing (SD_1), 52 days after maize sowing (SD_2) and 147 days after maize sowing (SD_3, which was 11 days after the maize silage harvest). Intercrop species and sowing rates used were forage brassica (*Brassica campestris* L. x *Brassica napus* L. cv. Hunter; 5 kg ha^{-1}), kale (*Brassica oleracea* L. ssp. *acephala* DC. cv. Grunner; 5 kg ha^{-1}), Italian ryegrass (*Lolium multiflorum* Lam. cv. Moata; 25 kg ha^{-1}) and balansa clover (*Trifolium balansae* Boiss. cv. Bolta; 25 kg ha^{-1}); abbreviated henceforth as FB, K, IR and BC respectively.

All plots received 18 kg N ha^{-1} and 20 kg P ha^{-1} as di-ammonium phosphate at maize sowing and 145 kg N ha^{-1} as a urea side dressing (48 days after maize sowing). Approximately 20 mm of irrigation was applied in November and 50 mm in January to assist the establishment of the SD_1 and SD_2 intercrops respectively (Figure 1). SD_3 intercrops received no irrigation.

In 2007-08 the experiment was also a randomised complete-block design with 4 replicates. Individual plots were again 4.56 m wide by 10 m long. Maize (Pioneer hybrid 34D71) was sown on 21 October 2007 at 100,000 seeds ha^{-1}. The intercrops were FB (cv. Hunter), IR (cv. Moata) and perennial ryegrass (PR; *Lolium perenne* L. cv. Aries). FB and PR were sown at 50 and 100% of the recommended sowing rate if these crops were sown by themselves (i.e. 2.5 and 5.0 kg ha^{-1}, and 12.5 and 25 kg ha^{-1} respectively), and at two intervals (at maize sowing, and 26 days after maize sowing; SD_1 and SD_2 respectively). Control (maize only) plots were also established giving a total of nine treatments. Italian ryegrass was sown on 9 April 2008 (177 days after maize sowing; 22 days after the silage harvest), at 25 kg ha^{-1} in an area adjacent to the main experiment. Yield measurements from this area over winter were used to estimate the dry matter (DM) production that could be expected under a common system in New Zealand of cultivating and then sowing an annual ryegrass crop soon after maize silage harvest. The necessary cultivation for this could not be achieved on the control plots without disturbing the other treatments.

All plots received 92 kg N ha^{-1}, as urea, broadcast and incorporated prior to sowing; 36 kg N ha^{-1} and 40 kg P ha^{-1} as di-ammonium phosphate banded down the spout at sowing; and 138 kg N ha^{-1} as urea broadcast on 26 November 2007. A total of 175 mm of irrigation water was applied during the season (Figure 1).

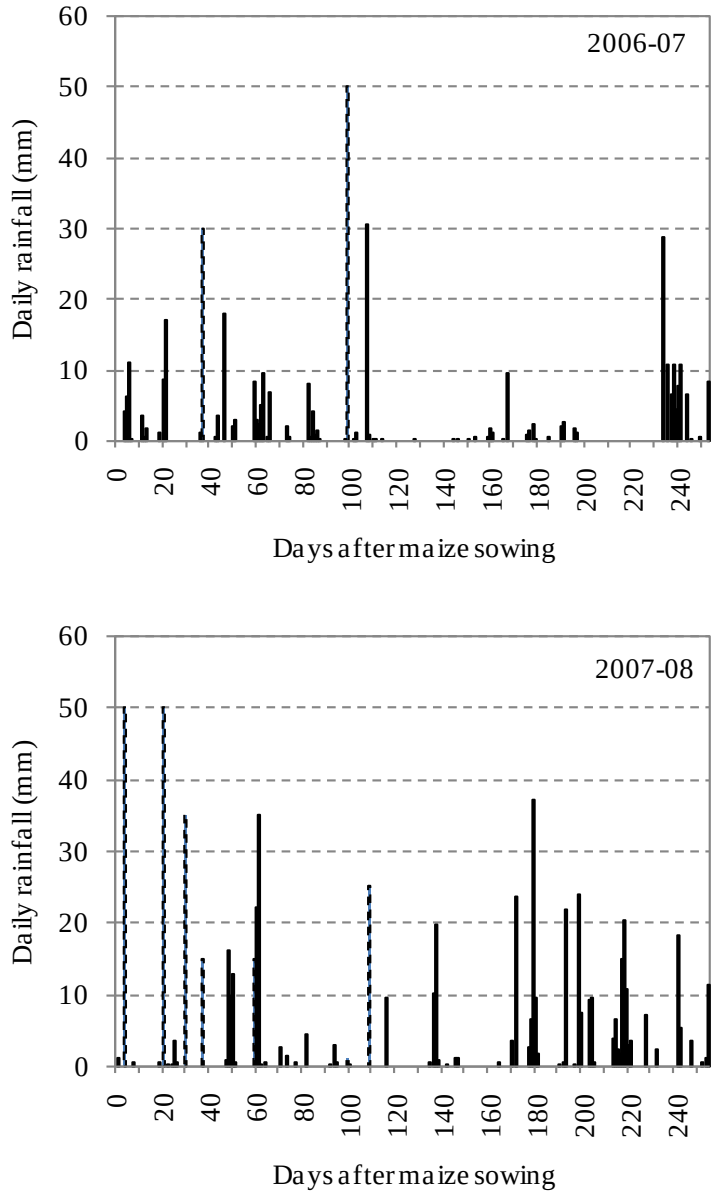

Figure 1: Daily rainfall (solid bars) and irrigation (dashed bars) from days after maize sowing (21 October) until the end of June. SD_2 intercrops in 2006-07 were sown 52 days after maize sowing and SD_3 intercrops 147 days after maize sowing. Respective sowing times for 2007-08 were 26 and 177 days after maize sowing. Seasonal rainfall and irrigation totals were 370 mm and 626 mm in 2006-07 and 2007-08, respectively.

Measurements

In 2006-07 measurements included: soil temperature (6 December 2006; control and SD_1 plots); maize shoot biomass, leaf counts and vigour scores (greenness and size relative to the control) (11 December 2006; all plots except SD_3); radiation interception (12 December 2006; control and SD_1 plots); visual weed assessments (11 December 2006; all plots); and intercrop plant population density (various dates; all

plots except the control). The main silage harvest was taken on 6 March 2007 (136 days after maize sowing). From each plot all plant material 10 cm above ground level was harvested from a 4.5 m^2 quadrat (which included two 3 m lengths of maize row).

Plant material was separated into maize and intercrop components which were weighed and sub-sampled and then oven-dried at 70 °C for 7 days. The remaining plant material on each plot was then removed using a forage harvester. However, this process damaged much of the intercrop plant material that would have otherwise promoted rapid re-growth in SD_1 and SD_2 plots.

In 2007-08 there was greater emphasis on monitoring intercrop death during the maize growing season. Intercrop plant counts (plants m^{-2}) were taken approximately three weeks after intercrop sowing in both the early and late sown intercrops; and at approximately 15 and 11 weeks after intercrop sowing in the SD_1 and SD_2 intercrops respectively.

At each sampling date plant counts were taken in 3 randomly selected, permanently located, 0.375 m^2 quadrats $plot^{-1}$. The main silage harvest was taken on 18 March 2008 (155 days after maize sowing).

Maize and intercrop material was hand harvested from a quadrat, as in the previous year, except the quadrat size was 3.75 m^2. Remaining plant material was removed by hand in the SD_1-FB plots (the only plots to have significant amounts of intercrop still growing in them). Winter season biomass accumulation in these SD_1-FB plots was assessed on 2 September 2008 by harvesting a 3.75 m^2 quadrat at ground level (to simulate livestock grazing). The SD_3-IR plot, sown adjacent to the experimental area, had four 1 m^2 samples collected from random locations on the same date.

A commercial maize grain harvester was used to harvest grain from all plots on 16 June 2008, ensuring that SD_1-FB and SD_3-IR were not shaded by the standing maize crop over the winter.

Weed control

In 2006-07 weed control was a major concern and was performed on several dates using a combination of herbicides and hand weeding. In 2007-08 weed control with herbicides was more effective.

Data analysis

Data was analysed by Genstat V9 using ANOVA. There were no significant interactions among main treatments (i.e. sowing time or intercrop/species). Therefore only the main effects are reported. Contrast analysis was used where appropriate.

Results

2006-07

Maize silage yield in control plots at 23.9 t DM ha^{-1} was typical for a New Zealand maize-silage crop but well below the usual potential of more than 30 t ha^{-1} at this site (see results from 2007-8 below, and Pearson *et al*. (2004)). All SD_1 intercrops reduced maize silage yield, with SD_1-K and SD_1-FB having a greater effect than SD_1-BC and SD_1-IR (Table 2). None of the SD_2 intercrop treatments affected maize

yield, and of the SD_3 intercrop treatments only the BC and FB treatments reduced maize silage yield.

Maize-silage yields in SD_3-BC and SD_3-FB were significantly less than the control even though the SD_3 intercrops were not sown until after the maize harvest. The use of maize biomass estimates (10 plants plot^{-1}, 11 December 2006) as a covariate when analysing the maize-silage yields indicated that maize yields in SD_3 intercrop treatments were not significantly different from the control. This supports the notion that the reduction in maize yield in these plots was probably due to less than ideal weed-control during the maize growth.

At the time of maize silage harvest, the SD_1 intercrop yields ranged from 1.6 t DM ha^{-1} (IR and FB) to 4.1 t DM ha^{-1} (K) (Table 2). In all cases SD_1 intercrop yields were well short of the corresponding reduction in maize yield in these treatments. The SD_2 and SD_3 intercrops yielded no harvestable DM because they were below the 10 cm cutting height. Maize was the main contributor to total annual DM yield, therefore all SD_1 intercrops had significantly less total annual yield than the control.

Table 2: Maize and intercrop yields (t DM ha^{-1}) for 2006-07. Control = maize only (no intercrop); BC = balansa clover; IR = Italian ryegrass; FB = forage brassica; K = kale. SD_1 = intercrop sown at maize planting; SD_2 = 8 weeks after maize sowing; and SD_3 = 11 days after silage-harvest. Combined silage yield = maize yield + intercrop yield. Intercrop winter yield = yield accumulated by the intercrops over winter. Total annual yield = combined silage yield + intercrop winter yield.

Intercrop	Sowing date	Maize-silage yield	Intercrop silage yield	Combined silage yield	Intercrop winter yield	Total annual yield
Control	-	23.9	0.0	23.9	0.0	23.9
BC	SD_1	14.6	2.1	16.7	0.7	17.4
BC	SD_2	20.9	0.0	20.9	0.1	20.9
BC	SD_3	19.7	0.0	19.7	0.4	20.1
IR	SD_1	15.7	1.6	17.3	0.6	17.9
IR	SD_2	23.6	0.0	23.6	1.3	24.9
IR	SD_3	20.7	0.0	20.7	1.8	22.5
FB	SD_1	10.9	1.6	12.5	0.3	12.8
FB	SD_2	22.3	0.0	22.3	0.5	22.8
FB	SD_3	15.7	0.0	15.7	2.4	18.1
K	SD_1	10.7	4.1	14.8	1.4	16.1
K	SD_2	21.9	0.0	21.9	0.8	22.6
K	SD_3	20.9	0.0	20.9	1.8	22.7
	LSD (5%)	3.9	0.8	4.0	0.6	4.1
	P	<0.001	<0.001	<0.001	<0.001	<0.001

The SD_1 intercrops established well and were vigorous and fast-growing. By 7 December 2006 (47 days after sowing) SD_1-IR had 218 (± 60) plantsm^{-2}, SD_1-BC 601 (± 169) plants m^{-2}, SD_1-K 63 (± 37) plants m^{-2}, and SD_1-FB 67 (± 48) plants m^{-2}. Although repeat plant counts were not made in the SD_1 intercrops, it appears that plant population density declined throughout the season in them all except in SD_1-K. Nevertheless, complete ground cover was attained in most areas approximately 1 month after sowing. At that time, the fraction of radiation intercepted (*f*) was in the order of SD_1-BC (0.65), -IR (0.60), -K (0.57), -FB (0.56); all significantly higher than the control (0.40) ($P<0.001$; LSD = 0.03).

Soil shading by the SD_1 intercrops influenced soil temperature and maize performance. On 6 December 2006 in the SD_1 treatments the average soil temperature at 5 cm depth was 13.6 ºC compared to 14.0 ºC in control plots ($P=0.085$; df = 7). Contrast analysis indicated that soil temperature in the SD_1-IR plots (13.7 ºC) was not different from the control ($P=0.714$; df = 19) whereas SD_1-BC (13.2 ºC; $P=0.063$), -FB (13.2 ºC; $P=0.055$) and -K (13.0 ºC; $P=0.064$) were lower.

These temperature differences were correlated with maize leaf counts taken on the same day, such that maize plants on SD_1 intercrop plots had, on average, 6 fully-expanded leaves compared to 7 on the control plots. Further soil temperature, as measured on 6 December 2006, accounted for 55% of the variance in the final maize yield ($P<0.001$).

In SD_2 intercrops, establishment was similar to the SD_1 intercrops. Thirty six days after SD_2 intercrop sowing SD_2-IR had 226 (± 75) plants m^{-2}, SD_1-BC 421 (± 166) plants m^{-2}, SD_1-K 89 (± 41) plants m^{-2}, and SD_1-FB 167 (± 37) plants m^{-2}.

In SD_2 intercrops plant death rates increased during the season (Figure 2). The SD_2 intercrops did not flower, and winter production of these intercrops was from the few viable plants that persisted over the summer months and possibly from new plants germinating in autumn from the seed that did not germinate soon after sowing.

In SD_3 intercrops, germination was slow due to very dry soil conditions. Significant rain did not fall until about 20 days after SD_3 intercrop sowing (Figure 1). On 3 May 2007 (47 days after SD_3 intercrop sowing) SD_3-IR had 189 (± 92) plants m^{-2}, SD_3-BC had 112 (± 108) plants m^{-2} SD_3-FB had 72 (± 28) plants m^{-2} and SD_3-K had 41 (± 14) plants m^{-2}, indicating poorer establishment than in the SD_1 and SD_2 intercrops.

The SD_1-IR and SD_1-BC intercrops died mid-way through the season after they had flowered, whereas SD_1-K, and to a lesser extent, SD_1-FB maintained a viable stand throughout the season. Both BC and IR are annual (self-regenerating) crops by nature and there was evidence of self-seeding in autumn given that SD_1-BC and -IR managed to produce some fresh harvestable biomass during the winter. However, re-establishment of these crops after silage-harvest was not helped because the experimental design prevented soil re-cultivation on those plots after silage harvest. It is also possible that any seed set, over summer, may have had poor vigour due to poor irradiance of the intercrops during seed filling.

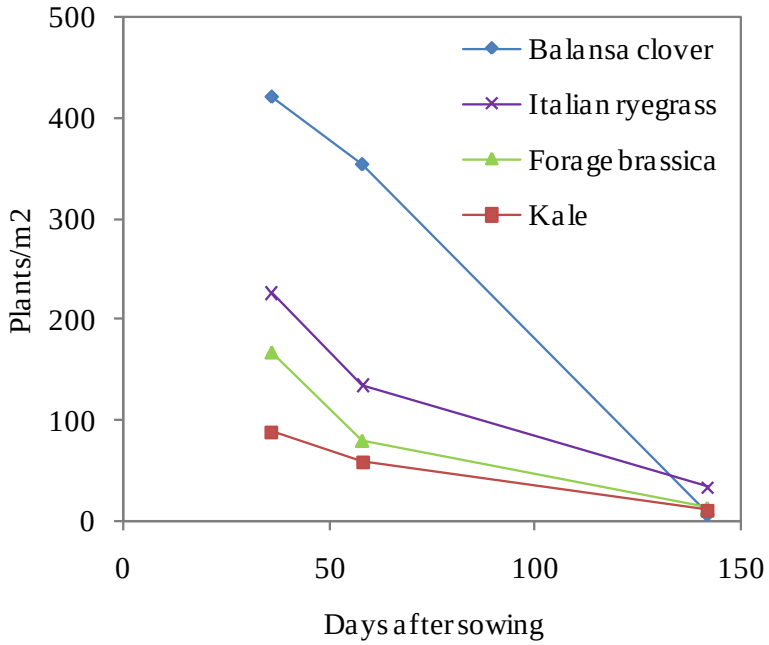

Figure 2: The decline in intercrop plant population density over time from sowing date 2 (SD_2) (day zero is the day SD_2 intercrops were sown; 12 December 2006). At 142 days after sowing (3 May 2007) clover had 6 plants m^{-2}, kale 10 plants m^{-2}, ryegrass 33 plants m^{-2} and forage brassica 12 plants m^{-2}.

2007-08

Maize silage yield was substantially higher than in 2006-7 (Tables 2 and 3). It was unaffected by the PR intercrops, irrespective of time of sowing and the SD_2 FB intercrops (Table 3). However, compared to the controls, maize-silage yield was reduced to 80% in SD_1-FB_{50} and 57% in SD_1-FB_{100}. Maize-silage yields in SD_2-FB plots (both sowing rates) were significantly higher than in SD_1-FB plots.

Maize-silage DM % was not affected by any treatment. There were no significant differences in N % of the maize-silage material between the control, SD_1-FB_{100} and SD_1-PR_{100} (mean = 1.03 % N), indicating that N did not limit the maize component at silage-harvest.

Only SD_1-FB intercrops had any viable plants remaining at silage-harvest. Although SD_1-PR had full ground cover at silage harvest, it was senesced material and the amount of biomass was not measured because it was below harvestable height. A thatch was present at silage harvest in SD_2-PR but it was not as dense as in SD_1-PR. SD_1-FB_{50} had one plot with viable plant material in the harvest area, as did all four plots of SD_1-FB_{100}. Considering only these five plots the maize-silage yield had a negative linear relationship with intercrop silage yield ($R^2 = 0.90$; $y = -14.869x + 22.107$), suggesting strong competition between the FB-intercrops and maize.

Total silage yield showed the same patterns of treatment differences as the maize silage yield, because only the SD_1-FB intercrops gave a silage yield, and these were too small to offset the maize yield reductions (Table 3). This same pattern was evident in the total

annual yield. Total annual yield was highest in the control treatment due to the additional DM yield of the winter (annual) ryegrass. Total annual yield was not enhanced by winter production in SD_1-FB_{50} (P=0.229) but it was in SD_1-FB_{100} (P=0.006).

Table 3: Maize and intercrop yields (t DM ha^{-1}). Combined silage yield = maize yield + intercrop yield. Intercrop winter yield = yield accumulated by the intercrops over winter. Total annual yield = combined silage yield + intercrop winter yield. The "intercrop winter yield" for the control is that measured for Italian ryegrass sown soon after the maize harvest (see methods).

Treatment	Maize-silage yield	Intercrop silage yield	Total silage yield	Intercrop winter yield	Total annual yield
Control	31.5	-	31.5	5.2	36.7
SD_1-FB_{50}	25.1	0.1	25.2	1.0	26.2
SD_1-FB_{100}	18.1	0.3	18.4	2.2	20.6
SD_2-FB_{100}	32.9	-	32.9	-	32.9
SD_2-FB_{50}	32.8	-	32.8	-	32.8
SD_1-PR_{100}	29.5	-	29.5	-	29.5
SD_1-PR_{50}	29.7	-	29.7	-	29.7
SD_2-PR_{100}	34.2	-	34.2	-	34.2
SD_2-PR_{50}	29.3	-	29.3	-	29.3
P	<0.001	0.171	<0.001	<0.001	<0.001
LSD	5.0	0.4	4.9	1.24	4.8

The SD_1 and SD_2 intercrops established well (Figure 3) and grew quickly usually achieving greater than or equal to 50% ground cover around three weeks after sowing. The SD_2 intercrops had slightly lower plant populations than SD_1 intercrops. Contrast analysis indicated that at approximately three weeks after sowing intercrop plant population was significantly higher in the 100% than in the 50% sowing rates in both SD_1 and SD_2 and also that the intercrop plant populations in SD_1 and SD_2 at this time were similar for each sowing rate by species combination.

By 11 weeks after intercrop sowing SD_2-PR was in the dying off (Figure 3). Measurements were not taken in SD_1-PR at the same time because the sward was too thick to count individual plants, but observations indicated that the health and vigour of the SD_1-PR intercrops was also in decline.

Leaf counts at approximately six weeks after maize sowing indicated no differences among treatments, so soil temperature was assumed to be the same in all treatments and was not measured. Both SD_1 and SD_2 intercrops experienced severe shading as the maize canopy closed (six to eight weeks after maize sowing). Shading had less of an impact on SD_1-FB crops because the expansive nature of the FB canopy meant that it converged on the intercrop-free strip and competed with the maize, reducing the size and vigour of the maize canopy.

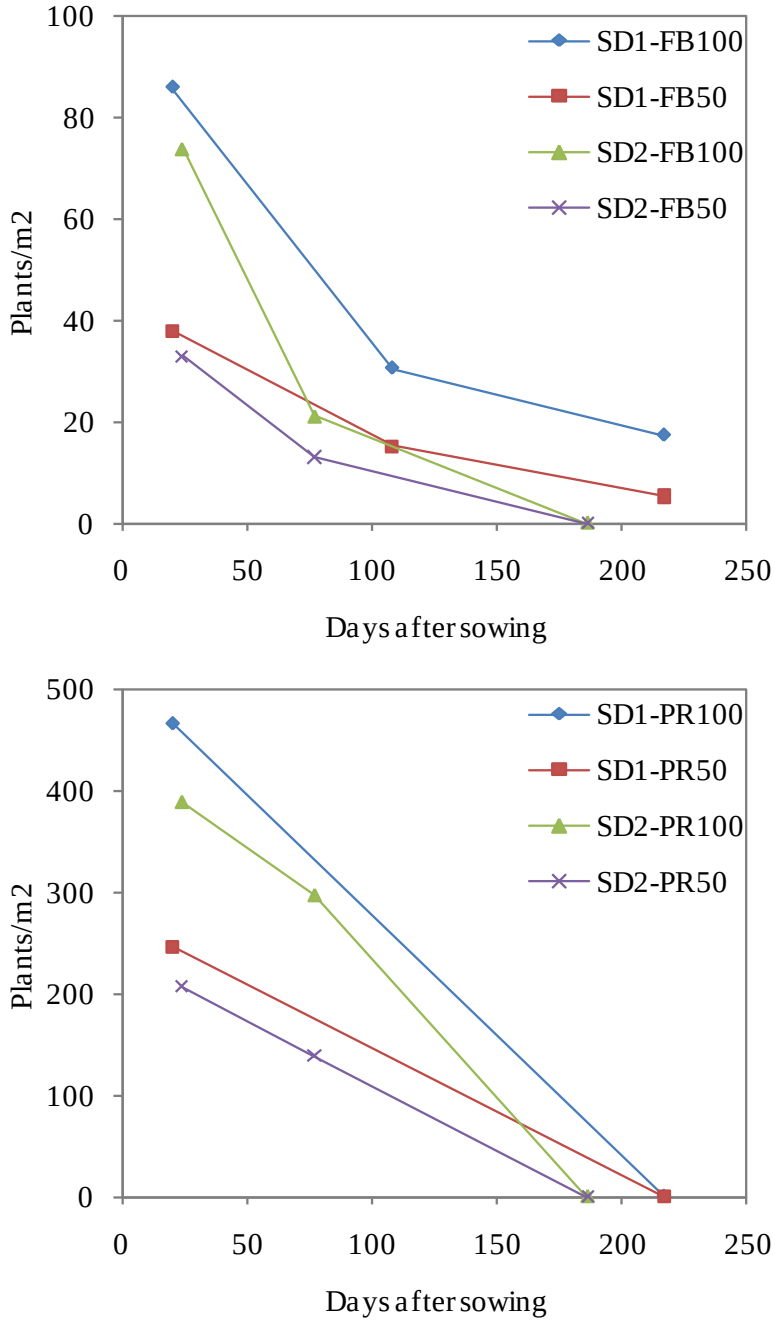

Figure 3: The decline in plant population density of forage brassica (FB; left) and perennial ryegrass (PR; right) intercrops over time in 2007-08. Sowing dates (SD_1 and SD_2) were at maize sowing and 26 days after maize sowing respectively, and the two sowing rates (treatment suffixes 50 and 100) were respectively 50 and 100% of recommended commercial sowing rates for pure stands. Final sampling was at silage-harvest.

Discussion

In 2006-7 all SD_1 intercrops reduced maize yield. Maize was the major component of silage yield and SD_1 intercrop growth was minimal over the winter months, and so total annual DM yield was also reduced by the intercrops. SD_2 intercrops did not affect maize yields nor did they increase total annual DM yield. This was primarily due to poor intercrop survival under the maize canopy and poor winter production. Reduced competition for light and water, achieved through wider maize row spacing and/or lower maize population density may have reduced the death of SD_1 and SD_2 intercrops during summer (Semere and Froud-Williams, 2001; Ghanbari *et al*., 2010). The SD_2 intercrops did not flower, and so their winter production was from the few viable plants that persisted over the summer months and possibly from delayed (autumn) germination of some seeds from the original sowing. The SD_3 intercrops (sown after maize-silage was harvested) also failed to increase total annual yield, but this was probably due to the dry conditions and the broadcast sowing (with no cultivation) used to sow the crops. Drilling and irrigation might have greatly enhanced productivity.

The negative effect of SD_1 intercrops on maize yield in 2006-7 was probably due to cooler soil temperatures and competition for water, N and light. Our results show a clear relationship between shading by the intercrops, soil temperature and maize performance. Ghanbari *et al*. (2010) also found that intercrops reduced soil temperature in maize intercropping systems, and Stone *et al*. (1999) showed an influence of soil temperature on maize leaf appearance rates in Hawke's Bay. Use of the maize model, AmaizeN (Li *et al*., 2006), indicated that the measured maize yield in the control plots (23.9 t DM ha^{-1}) was slightly lower than the simulated yield if water and N were not limiting (25.2 t DM ha^{-1}). The required amount of fertiliser N for this simulated yield was 154 kg N ha^{-1}. At maize sowing the mean amount of soil mineral N was 38 kg N ha^{-1} in the top 30 cm soil and less than 4 kg N ha^{-1} between 30 and 120 cm depth (data not shown). Fertiliser N applications totalled 163 kg N ha^{-1} during the season, and so there was very little N that was surplus to maize requirements.

In 2007-08, significant improvements were made on the previous season's systems. Total annual yields and maize yields were much higher, although the intercrop yields were still poor. The only intercrop treatment to yield significantly was the FB at SD_1, and even then there was a much greater loss in maize yield. Winter yield from IR was significantly higher than any of the intercrop treatments, suggesting that the existing system of following the maize-silage harvest by planting IR was the most productive under these conditions.

The 2007-08 experiment highlighted problems that will need to be overcome with intercrop persistence. Perennial ryegrass had poor persistence under the maize canopy, probably the result of an inability to cope with low light and possibly low soil moisture levels. Ryegrass species are not as deep rooting as forage brassicas (Kristensen and Thorup-Kristensen, 2004) which may make forage brassicas more drought tolerant. This would contribute to their better persistence and productivity in

intercropping systems. However, a high sowing rates of forage brassica was more persistent than a lower sowing rate, so other factors may also be involved.

Intercrops may bring benefits not directly related to total DM production. The dense thatch observed here in the PR intercrops may enhance ability of the soil to withstand vehicle movements during silage harvest, particularly under wet conditions. If allowed to persist, such thatches may reduce the risk and severity of erosion if maize or winter crops such as Italian ryegrass or oats are direct drilled into them.

Conclusions

This work has shown only limited viability and persistence of intercrops grown in maize crops established using standard maize sowing rates (90,000-100,000 plants ha^{-1}) and row spacing (76 cm). This was probably mainly due to the low light and soil moisture levels under the maize canopy. Brassica species seem to be more persistent and competitive when intercropped with maize than ryegrass and clover. Based on the systems used in this research, the most productive system is the standard practice of growing maize silage over summer followed by Italian ryegrass in winter. If soil cover to enhance resilience to traffic and/or reduce erosion is the primary goal then either annual or perennial ryegrass sown in 45 cm swaths between maize rows should be beneficial, although it is unlikely there will be significant winter regrowth.

For maize intercropping to be viable and sustainable in New Zealand more detailed work needs to be done to determine ways of enhancing intercrop persistence. Variables to be investigated should include wider maize row spacing and lower maize seeding rates.

Acknowledgements

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Crop architecture and light interception in forage rape (*Brassica napus* L.) grown for seed

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Abstract

In New Zealand, forage rape is typically grown as an alternative feed in animal production systems. Detailed investigations on the growth and reproductive development of forage rape grown for seed are limited. Maximum light interception by photosynthetic tissues throughout a canopy is important for achieving optimum seed yields. Factors such as water availability and crop management can influence plant growth and, as a consequence, light interception. Changes in crop architecture and light penetration during reproductive development in forage rape grown with and without irrigation were investigated. Trials were established in grower fields at two locations with forage rape cv. Greenland. Crops were monitored from early flower head emergence (growth stage 54) through to harvest. Photosynthetically active radiation was measured regularly at four different heights throughout the canopy. Individual plants were also investigated further for various reproductive characteristics. The irrigated crop was 70 cm taller and had more secondary racemes than the non-irrigated crop. Light penetration at different levels varied considerably, with the non-irrigated crop allowing more light to penetrate into the various canopy levels. However, better light penetration did not give higher seed yield as the seed yield of the non-irrigated crop (455 kg ha^{-1}) was only 22% that of the irrigated crop; (2025 kg ha^{-1}). Results are discussed in terms of crop architecture, light penetration through the canopy and water stress and their effect of on these on seed yield.

Additional keywords: irrigation, photosynthetically active radiation, seed yield, canopy architecture

Introduction

In New Zealand, forage rape (*Brassica napus* L.) is typically grown for green feed to fill gaps in the feed supply of pasture-based animal production systems. Consequently, detailed investigations on the growth and reproductive development of forage rape, grown for seed, are limited. Seed yield potential is determined by the ability of a plant to produce biomass and the partitioning of biomass in the plant to seed. Biomass accumulation depends on crop architecture and the ability of the canopy to intercept photosynthetically active radiation (PAR) (Sinclair and Muchow, 1999). In some brassicas, including forage rape, as biomass

accumulation continues to maturity, crop architecture and the amount of PAR intercepted by the crop are important for optimum seed yield (Rose *et al*., 2007).

Water is vital for many plant physiological processes including photosynthesis (Lawlor and Tezara, 2009). Water stress can alter the proportion of dry matter (DM) partitioned among organs (Taylor *et al*., 1991) and can reduce seed sink size (Anderson *et al*., 1996). Water stress at flowering has negatively influences seed pod formation resulting in lower seed yields (Johnston *et al*., 2002). Further, the timing of water stress may have more of an effect on seed yield than the intensity of the stress (Korte *et al*., 1983). The aim of this research was to investigate changes in crop architecture and light interception in forage rape grown for seed with, and without. irrigation.

Materials and Methods

Plant material

Trials were positioned in established crops of forage rape (cv. Greenland) at two locations in Canterbury, New Zealand.

Location one (Long Beach, Ashburton) at 20 m above sea level was irrigated with a total water application, including rain, of 170 mm. The soil type was a Lowcliffe silt loam.

Location 2 (Methven) at 280 m above sea level was non-irrigated (dryland) but received 15 of rain. The soil type was a Lyndhurst silt loam. The dryland site was exposed to strong Northwest winds during seed fill. Both crops received approximately 200 kg ha^{-1} of nitrogen in spring.

Sampling

At both locations 15 individual plants were tagged on 17 October 2008 when single flower buds on the main inflorescence were visible but still closed (growth stage 54) (Bayer CropScience, 2008). Crops monitored regularly through to harvest (7 January 2009). PAR was measured at four different canopy heights (75% of canopy height, mid-canopy, 25% of canopy height, canopy base) using a Decagon AccuPAR LP-80 linear PAR Ceptometer. Individual plant heights and the number of secondary racemes were also recorded.

At harvest (approximately 40% seed moisture content) tagged plants were divided into 12 different seed fractions (Figure 1). Based on pod position, primary racemes were divided into upper, middle and lower fractions (Fractions 1 to 3). Based on the position of secondary racemes, secondary racemes were also divided into upper, middle and lower fractions. Individual racemes within the fractions were further divided into upper, middle and lower fractions. Each seed fraction was hand threshed, sieved and cleaned on a small scale Westrup air-screen cleaner. Dry matter was assessed by taking the weight of plants both before and after drying at 80 °C for 18 h.

Tin foil trays (207 cm^2) were placed at soil level underneath the crops on 27 December 2009 before windrowing to assess the amount of seed loss. GenStat (Version 10) was used for statistical analysis using a general ANOVA model for a direct comparison between irrigated and dryland Greenland forage rape and the difference between harvest components. Individual and combined

measurements were designated as treatments and replicates and individual plants designated as blocks.

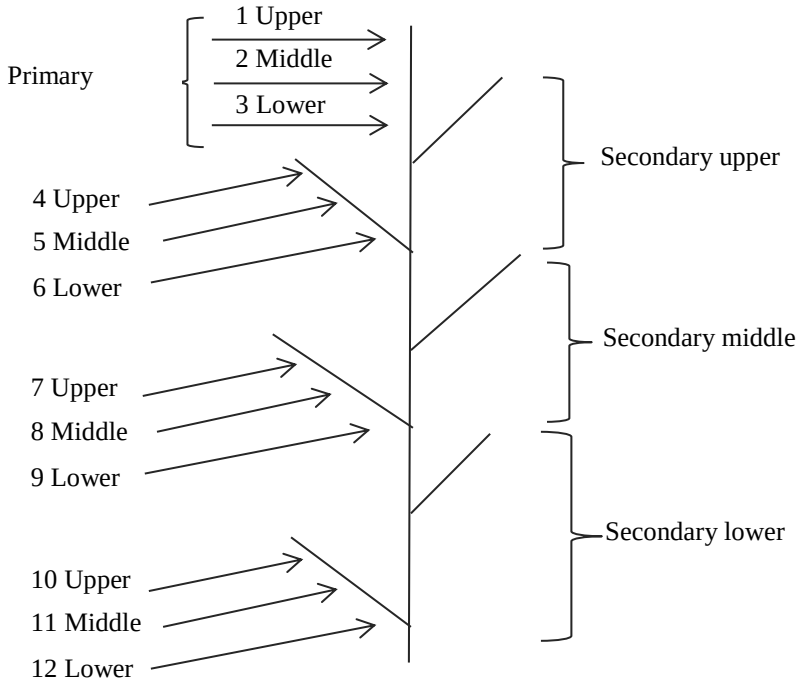

Figure 1: Dissection of tagged plants for seed yield analysis. The total number of secondary racemes was divided into upper, middle and upper fractions. Individual racemes within fractions were further divided into upper, middle and lower fractions.

Results

Plant height and biomass

At the beginning of the trial crop heights were similar between the irrigated and dryland sites. There was no significant difference until one week after flowering (Figure 2). Compared with the dryland crop, flowering in the irrigated crop was delayed by approximately four days. Associated with flowering and pod (silique) formation, for both irrigated and dryland crops, there was a decline in the rate at which crop height increased. In the irrigated crop this decline coincided with flowering and pod formation and lasted approximately three days. The average daily increase in crop height fell by 38% at flowering and 57% at pod formation. In the dryland crop, this decline was delayed until four days after flowering and pod formation (Figure 2) with the average daily increase in crop height declining by 68% at flowering and 73% at pod formation. From pod formation to harvest the irrigated and dryland crops increased in height by 37% and 21% respectively.

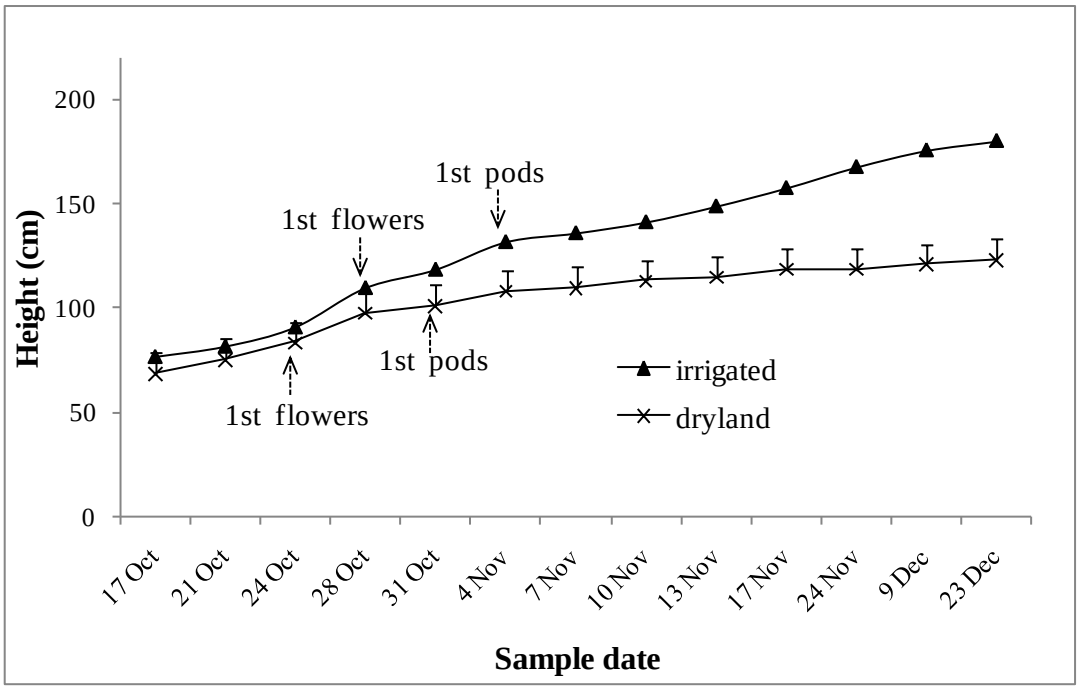

Figure 2: Average height of irrigated and dryland crops from early flower emergence through to harvest. First flowers and first pods are indicated. Bars = 5% LSD.

There was a significant difference in average plant biomass. Irrigated plants had 3.5 times more biomass than plants from the dryland site (data not shown). The dry weight % of plants at both the irrigated and dryland site were similar at 27% and 29%, respectively.

Secondary racemes

The dryland site had significantly more plants m^{-2} (55) than the irrigated site (37) (Figure 3a). However, the number of secondary racemes $plant^{-1}$ was lower at the dryland site (Figure 3b). These results combined, emphasize differences in crop architecture between the irrigated site (fewer larger plants with more secondary racemes) and the dryland site (smaller plants with fewer secondary racemes). Although both sites had different crop architectures the total number of secondary racemes per unit area was similar (Figure 3c).

Light interception

Differences in crop architecture between the two sites resulted in differences in light interception at different levels in the canopy. At the start of the experiment the % PAR (% relative to the canopy top), measured at 75% crop height, was similar for both the irrigated (74%) and dryland (78%) sites (Figure 4). In the irrigated crop this increased to 90% at the start of flowering with a subsequent decrease to 77% at the start of pod formation (Figure 4a). During pod development and seed fill through to harvest the amount of PAR at 75% crop height steadily declined to 10%.

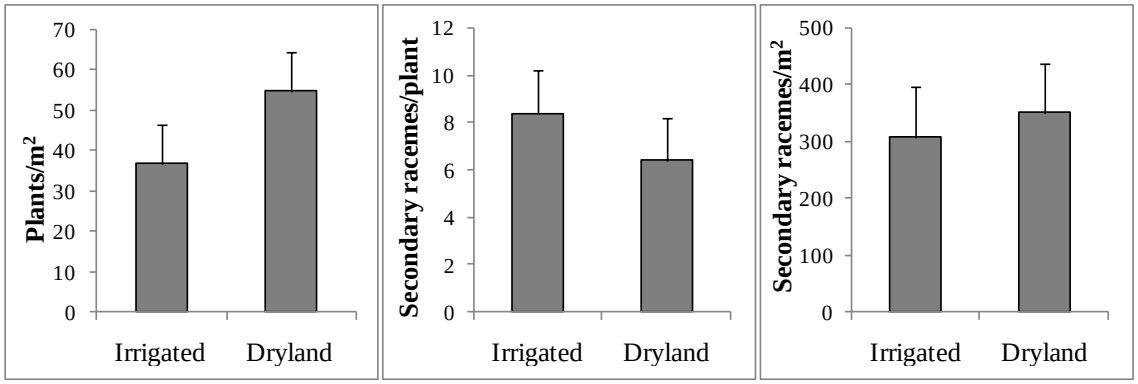

Figure 3: Number of plants (a), secondary racemes plant^{-1} (b) and total number of secondary racemes for irrigated and dryland crops. Bars = 5% LSD.

By comparison, at 75% crop height, in the dryland crop there was little change from early flower development through to the start of pod formation (Figure 4b). During pod development through to harvest % PAR only decreased from 78% to 69%.

At 50% crop height the initial amount of PAR (% relative to the canopy) was substantially lower for the irrigated crop (12%) compared with the dryland crop (36%) (Figure 4). In the irrigated crop this increased to 42% at the start of flowering with a decrease to 23% at the start of pod development with a continued decrease to 3% at harvest (Figure 4a). By comparison, in the dryland crop, there was a decrease from early flowering (36%) to the start of pod formation (22%). However, during pod development and seed fill through to harvest the % PAR increased to 31% (Figure 4b).

In the irrigated crop at 25% crop height and at the base of the canopy (0% crop height) % PAR was initially 9% and 4%, respectively. Both of these decreased to 1% by the start of flowering and remained low until harvest (Figure 4a). In the dryland crop at 25% crop height and at the base of the canopy, % PAR was initially 20% and 8%, respectively. These decreased to 4% and 2% respectively, by the start of pod formation. However, these values increased during pod development and seed fill and continued to increase to 25% and 20%, respectively, at harvest (Figure 4b).

Flower and pod number

At both sites the number of flowers and pods on primary racemes were similar (Table 1). However, there were large differences in the number of pods secondary raceme^{-1} between the two sites with over five times as many pods secondary raceme^{-1} on irrigated plants.

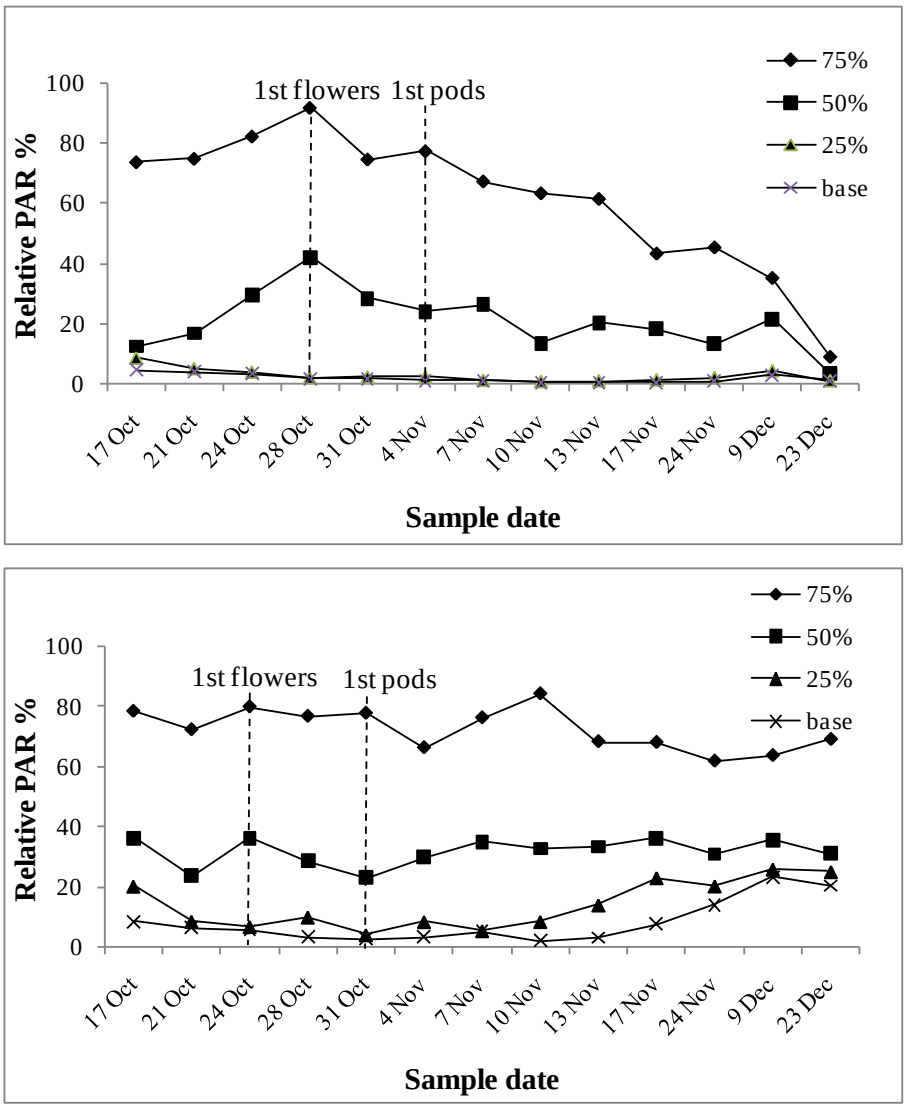

Figure 4: Photosynthetically active radiation (PAR) at different levels throughout the canopy of irrigated (a) and dryland (b) crops from early flower emergence through to harvest. First flowers and first pods are indicated.

Table 1: Number of pods raceme^{-1} for irrigated and dryland sites.

Site	Pods 1^{o} raceme^{-1}	Pods 2^{o} raceme^{-1}	Pods from 1^{o} raceme (%)
Irrigated	55	36	12
Dryland	61	7	60
LSD (5%)	13	15.6	13
Pr > F	0.246	0.006	<0.001

This resulted in 60% of the total number of pods plant^{-1} coming from the primary raceme at the dryland site compared with only 12% at the irrigated site. There was a strong linear relationship between pod density and DM (R^2 = 0.89) (Figure 5).

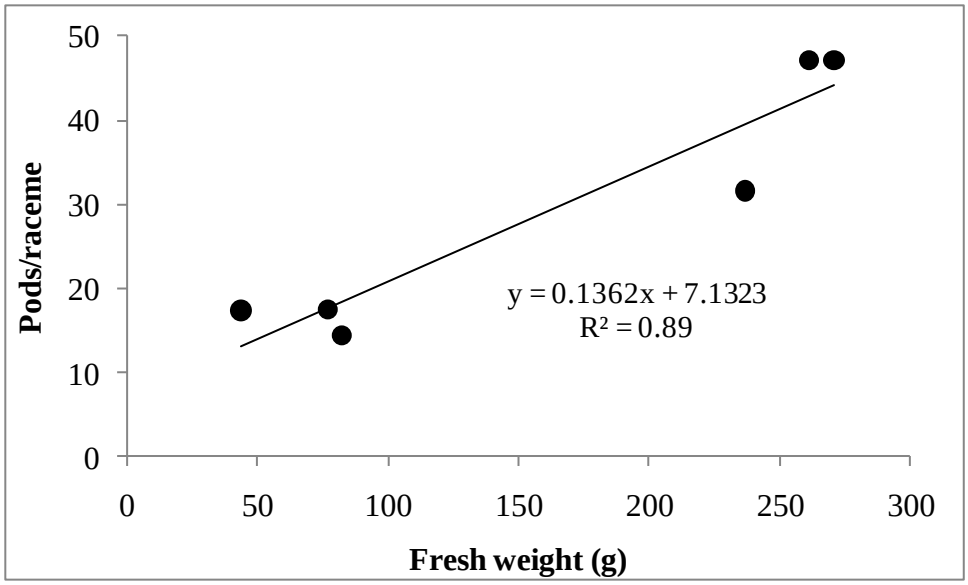

Figure 5: Relationship between the number of pods per secondary raceme and biomass.

Seed yield

There was a large difference in the final dressed seed yield between the irrigated crop (2,025 kg ha^{-1}) and the dryland crop (455 kg ha^{-1}). Seed loss trays beneath the crops indicated that in the irrigated crop approximately 200 kg ha^{-1} of dressed seed was not recovered compared to 1,000 kg ha^{-1} of dressed seed in the dryland crop. The poor plant water status and the strong northwest winds, at Methven, during late seed fill and harvest accounted for much of the seed loss at the dryland site.

Compared with the irrigated site, the dryland site had a recovered seed yield of 22% (455 kg ha^{-1} versus 2,025 kg ha^{-1}). There was a seed shatter yield loss of 49% (1,000 kg ha^{-1} from 2,025 kg ha^{-1}) leaving a 28% seed loss which may be attributed to moisture stress.

At the irrigated site seed yield was mainly driven by the secondary racemes with over 85% of the seed coming from pods on the secondary racemes (Figure 6). Also, over 60% of the seed could be accounted for by the middle and lower secondary racemes.

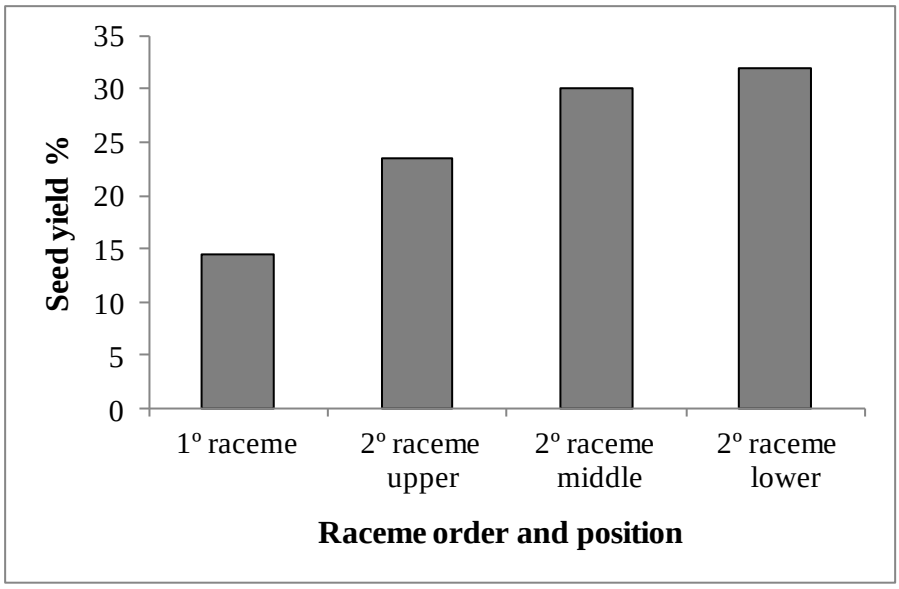

Figure 6: Seed yield (%) from primary and secondary racemes for the irrigated crop.

In the primary and upper secondary racemes seed yield decreased from the top of the raceme towards the base (Figure 7). In contrast, in the middle and lower secondary racemes, seed yield was highest in the middle of the raceme (Figure 7) with more seed from the lower part of the raceme compared with the primary and upper secondary racemes.

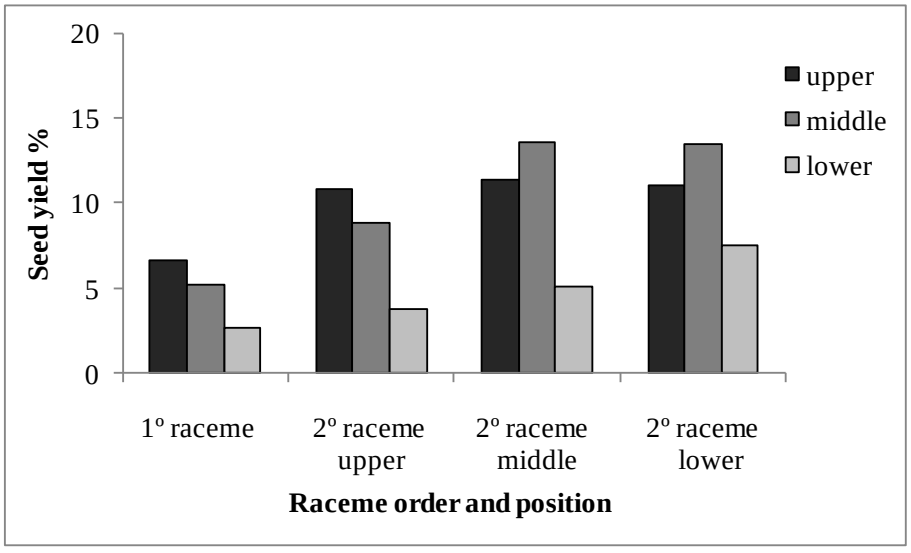

Figure 7: Seed yield (%) from different fractions of primary and secondary racemes for the irrigated crop.

Discussion

In New Zealand, forage rape is typically grown as an alternative feed in animal production systems. As a result detailed investigations on the growth and reproductive development of forage rape grown for seed are limited. This study, compared plants at an irrigated site, plants at a dryland site. The latter were shorter with less biomass, had fewer secondary racemes with fewer pods raceme^{-1}, intercepted less PAR throughout the canopy and had a lower seed yield. In a year with severe droughtat a dryland site there was a lower recovered seed yield and higher seed loss from shattering and moisture loss.

Crop architecture has a major influence on light penetration through the canopy. In this study the amount of PAR intercepted by the canopy differed between the irrigated and dryland sites. Plants at the irrigated site were larger with higher biomass and more secondary racemes. As a result the percentage of PAR intercepted by the canopy was higher than at the dryland site. However, during flowering much of the PAR is reflected by the floral canopy rather than being absorbed by the leaf canopy. In oil seed rape it has been estimated that between 7 and 22% of PAR reached the leaf canopy with the floral canopy absorbing 64% of PAR (Evans, 1984; Fray *et al*., 1996). In this study, from flowering to harvest, PAR interception did not change throughout the canopy in the dryland crop. In comparison, in the irrigated crop, floral canopy PAR absorption increased from 10% to 90% from flowering to harvest.

The dryland crop received only 15 mm of rain and although the soil moisture was not measured, the Lyndhurst soil is a shallower soil than the Lowcliffe soil at the irrigated site. Therefore, the soil water holding capacity at the dryland site should be lower compared with the irrigated site.

Water deficit can reduce seed yields and the stress response can depend on the crop developmental stage. Negative effects on seed yield have been observed with water stress during flowering and seed fill (Stoker and Carter, 1984; Nielsen, 1997). Johnston *et al*. (2002) also showed that, in canola, once minimum water use was achieved (approximately 130 mm) seed yield increased from 1,550 kg ha^{-1} by 7 kg ha^{-1} for every 1 mm of water. Minimum water use for Greenland forage rape, grown under New Zealand conditions, is unknown. However, the total amount of seed (recovered plus unrecovered) at the dryland site was 1,450 kg ha^{-1}, which is similar to the calculated seed yield using 130 mm water (1,550 kg ha^{-1}). Using the dryland site as the base measurement for water use, seed yield increased 3.7 kg ha^{-1} for every mm of water above 15 mm. However, seed shedding and seed abortion due to adverse growing conditions, such as low water availability and extreme weather, can severely reduce potential seed yields. In New Zealand, especially on dryland sites, early flowering cultivars of forage rape may be better suited for seed to take advantage of lower temperatures and increased water availability early in the season, although the risk of late spring frosts at flowering is also increased.

The irrigated crop produced larger plants, with more secondary racemes, during the yield establishment period (stem elongation through to and including flowering). Faraji *et al*. (2009) emphasized the contribution of photoassimilates to seed yield in canola showing that increased accumulated above ground DM resulted in increased seed yield. At the irrigated site the majority of the seed was from middle and lower secondary racemes. Pod density and seed density maybe fully determined at the end of flowering and Habekotté (1993) showed that actual pod density in canola was linearly related to cumulative DM production until the end of flowering. This is consistent with the strong linear relationship between pod density and DM observed in this study (Figure 5). During flowering, the irrigated plants intercepted more PAR and continued to produce more DM than plants at the dryland site.

Conclusion

An irrigation effect on seed yield in forage rape was clearly observed. Reduced irrigation affected crop architecture, light interception, biomass and seed yield components. Early flowering cultivars which take advantage of lower temperatures and increased water availability during flowering and seed fill may improve forage rape seed production on dryland sites in New Zealand.

Acknowledgements

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Kale dry matter yield responses to nitrogen and phosphorus application

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Abstract

Forage brassica crop establishment and subsequent growth are affected by nutrient availability, particularly of nitrogen (N) and phosphorus (P). The effects of P and N applications on kale dry matter (DM) accumulation were examined in three field experiments in Canterbury and one in the Central North Island region of New Zealand. Nitrogen, as urea (46%), was applied at sowing and mid-season and P as triple superphosphate (P = 21 %) was hand broadcast, hand broadcast and soil incorporated or banded at 0 or 50 kg P ha^{-1} at sowing. Nitrogen fertiliser doubled kale yields at Te Pirita, from 5 to 10 t DM ha^{-1} but there was no difference between the 100 and 200 kg N ha^{-1} rates. Total DM increased with P supply from 5 t DM ha^{-1} in the control to a mean of 8 t DM ha^{-1} with 50 kg P ha^{-1}. At Fairlie, total DM yield increased with P supply and with N application when P was applied. Total DM at Methven increased more than 2 t ha^{-1} when 170 kg N ha^{-1} was applied compared with the 70 kg N ha^{-1} for kale crops. There was also an effect of background soil P at Methven, mostly affecting the stem DM accumulation. Because of the nature of the treatments (nested) at Te Pirita and Fairlie, it was not possible to determine whether the effect of N was due to the total N applied or the time of application. The lack of response, to all the treatments, at Lochinvar was probably due to moisture stress meaning the initial soil N (mean 220 kg N ha^{-1}) and P (Olsen P = 22) levels were adequate for the 4-6 t DM ha^{-1} crops grown. For most situations a P application of up to 50 kg ha^{-1} is recommended at establishment with N managed more dynamically throughout the growing season based on soil N and crop yield potential.

Additional keywords: Banded, broadcast, *Brassica oleracea* var. *acephala*, establishment, Gruner kale, independent, interaction, leaching, metabolisable energy

Introduction

The New Zealand dairy industry has set two goals to achieve by 2015; to increase metabolisable energy (ME) by 50 % and to reduce N leaching losses by 50 % (FoRST, 2007). This will require a higher proportion of farms growing high producing specialist forage crops (de Ruiter *et al.*, 2009a) such as kale (*Brassica oleracea* var. *acephala* L.). Kale establishment and subsequent growth are affected by availability of key nutrients such as nitrogen (N) and phosphorus (P). Phosphorus affects crop

establishment (Grant *et al.,* 2000), as it is associated with improved root development (Claridge, 1972) while N affects kale growth throughout the season (Fletcher *et al.,* 2007). Kale crops respond strongly to N and P application, especially if they are sown after depletive crops like cereals. Previous research with kale has shown a higher response to banded than broadcast P fertiliser (Wilson *et al.,* 2006). These authors also reported that kale was more efficient at utilising fertiliser P than soil P, irrespective of the method of P application.

Kale is an important forage crop in the southern parts of New Zealand, occupying over 25,000 ha (Gowers and Armstrong, 1994) and can produce dry matter (DM) yields over 20 t ha^{-1} (Zyskowski *et al.,* 2004; Fletcher *et al.,* 2007). Despite this potential, kale yields are often variable as it is grown in a range of climates and soil fertility situations (Wilson *et al.,* 2006) with varying levels of management expertise. Kale crops have high nutrient requirements. For example, Wilson *et al*. (2006) estimated that an 18 t ha^{-1} kale crop removes about 360 kg N ha^{-1} and 50 kg P ha^{-1}.

The high kale N requirement (Wilson and Maley, 2006; Fletcher *et al.,* 2007) may lead to adverse animal health effects and create a potential environmental risk from N leaching into ground water. The environmental effects may be exacerbated by urine returns after grazing, especially under wet conditions. Kale, like most forage brassica species, is inefficient at N uptake compared with other crops (Wilson *et al.,* 2006), which accentuates the need for appropriate rates and times of application.

There are also likely to be strong interactions between P and N supply that influence kale yields. For example, lower responses to P fertiliser are expected on soils with a low N supply and when little fertiliser N is applied at establishment. To make the most efficient and economic use of applied P and N fertilisers it is necessary to quantify the extent of these interactions.

This paper reports four experiments that aimed to refine N and P fertiliser recommendations for kale crops. They investigated the effects of method of P application, rate of P and N application and time of N application on kale DM accumulation. The specific objectives were to:

(1) measure the yield response to different rates of N and P,
(2) confirm the yield response to P application method and
(3) quantify any interactions between N and P application.

Materials and methods

The four experiments are grouped based on sowing year: Experiment A (2004) and Experiment B (2007). All trials were located in farmers' fields and none of the crops were irrigated. One of the Experiment A sites was at Te Pirita (43 ° 43 'S, 171 ° 45 'E) on a stony Lismore soil (Haynes, 2000). Another was at Fairlie (44 ° 10 'S, 170 ° 83 'E) on a yellow grey earth with gravelly subsoil (McLaren and Cameron, 1996), in Canterbury. The third site was at Lochinvar (38 ° 58 'S, 176 ° 21 'E) on a yellow brown pumice soil (Toxopeus and Gordon, 1985), in the Central North Island. Experiment B was at Methven (43.38 ^{o} S, 171.4 ^{o}E) on a Lyndhurst silt loam soil (Martin, 1986), in Canterbury. Gruner kale seed was drilled into cultivated soils at Te Pirita and direct

drilled at the three other sites. Kale crops followed a rape crop at Fairlie and long term pasture at Methven, Lochinvar and Te Pirita.

Treatments and experimental design

The design for the three Experiment A sites was a randomised complete block with three replicates of 12 treatments. Triple superphosphate (TSP; 21% P) was either hand broadcast, hand broadcast and incorporated or banded (Table 1) below the seed at sowing at 0 or 50 kg P ha^{-1}. Nitrogen, as urea (46%), was broadcast and incorporated into the soil at 0, 50 and 100 kg ha^{-1} at sowing (Table 1). Mid-season N was applied after the first sampling and was broadcast onto the soil surface.

A soil test to 150 mm depth was taken from each of the 36 plots at each site before sowing. Average 'Quick test' result for each site and available N results are shown in Table 2.

Table 1: Fertiliser treatments for experiments at Te Pirira, Fairlie and Lochinvar, 2004-05.

Treatment	Phosphate at sowing			Nitrogen	
	[1]Band	[2]Broadcast	[3]Incorporated	[4]At sowing	[5]Mid-season
F_1	0	0	0	0	0
F_2	0	0	0	50	50
F_3	0	0	0	100	100
F_4	50	0	0	0	0
F_5	0	50	0	0	0
F_6	0	0	50	0	0
F_7	50	0	0	50	50
F_8	0	50	0	50	50
F_9	0	0	50	50	50
F_{10}	50	0	0	100	100
F_{11}	0	50	0	100	100
F_{12}	0	0	50	100	100

[1]Triple superphosphate (TSP; P = 21%) placed below seed, at sowing. [2]TSP on the surface just after sowing. [3]TSP on the surface and incorporated by a surface cultivation just before sowing. [4]Urea (N = 46%) on the surface and incorporated by surface cultivation just before sowing. [5]Urea broadcast on the surface mid-season.

Table 2: Average soil test results and optimum quick test for Te Pirita, Lochinvar and Fairlie (2004-05) and Methven sites (2007-08) and optimum nutrient requirements (McLaren and Cameron, 1996).

Site	pH	Olsen P (µg kg^{-1})	Potassium (K)	Calcium (Ca)	Magnesium (Mg)	Available N (kg ha^{-1})
Te Pirita[1]	5.7 (6.2-6.6)[2]	11 (6-18)	6 (3-6)	5.0 (7-9)	15 (7-12)	65 (51-86)
Fairlie[1]	5.6 (5.5-5.9)	31 (26-36)	7 (4-11)	6.0 (4-7)	6 (4-8)	126 (85-176)
Lochinvar[1,3]	6.1 (5.9-6.2)	22.0 (10-46)	4 (3-5)	2.0 (1-4)	4 (2-6)	220 (108-310)
Methven[1]	5.9 (5.8-6.1)	7.0 (5-11)	3 (11-21)	6 (5-8)	7 (5-9)	187 (143-225)
Optimum	5.8-6.0	20-25	5-7	4-10	8-10	200-300

[1]Average values from all plots. [2]Numbers in parentheses are the ranges of each nutrient on a per plot basis. [3]P retention of 62%.

Base fertiliser was applied at 1.5 kg ha^{-1} boron, 50 kg K ha^{-1} as potassium chloride. Seed was direct drilled with an 11 row cone seeder in 150 mm rows at a depth of approximately 20 mm (Lamp, 1962) at all sites. Sowing rate was 3.5 kg ha^{-1} of viable seed, pelleted with 'Superstrike®' which contains systemic insecticides to control springtails (*Bourletiella* species) and fungicides to control *Pythium* and *Fusarium* diseases (Salmon and Dumbleton, 2006). Karate (a.i. 250 g l^{-1} lambda-cyhalothrin) at 0.04 l ha^{-1} and Contact at 0.1 l ha^{-1} were applied on 10 January and 17 February 2005 at Te Pirita and at the same rates for Karate and Contact on 10 January and 3 March 2005 at Fairlie to control insect pests. Details of key activities at each site are summarised in Table 3

Table 3: Key dates and activities for Gruner kale crops grown at four experimental sites.

Site	Year	Sowing date	Sampling Date		Area harvested (m^2)
			1	2	
Te Pirita	2004-05	1 December	4 April	2 June	2
Fairlie	2004-05	30 November	4 April	2 June	2
Lochinvar	2004-05	13 December	6 April	21 June	2
Methven[1]	2007-08	26 November	-	26 May	2

[1]Harvested once at the end of the season.

Experiment B

The design at Methven was a randomised complete block with three replicates of 16 treatments. The TSP was either broadcast by hand before sowing and soil incorporated or banded below the seed at sowing at 0, 25, 50 or 75 kg P ha^{-1}. N, as urea, was broadcast at 70 and 170 kg ha^{-1} with the higher rate split and applied at 100 kg and 70 kg N ha^{-1} at 8 and 14 weeks after sowing, respectively. The low rate of N was applied 14 weeks after sowing. Gruner kale seed treated with 'Superstrike®' was direct drilled with a 13 row cone seeder at 4 kg ha^{-1} of viable seed.

A soil test to 150 mm depth was taken from all 24 plots before sowing. Average Quick test results are shown in Table 2. Base fertiliser was applied at 1.5 kg ha^{-1} boron, 25 kg K ha^{-1} applied as potassium chloride 30 kg Mg ha^{-1} was applied from a commercial calcium/magnesium fertiliser. The crop was managed using best practices (de Ruiter *et al.,* 2009b) to minimise the risk of weeds, pests and diseases. Pre emergent Treflan® (a.i. 480 g l^{-1} trifluralin EC) was the only herbicide used for weed control.

Measurements

Herbage yield and partitioning.

At each harvest plant counts and crop fresh weights were determined. A representative 10 plant sub-sample was kept for DM determination and leaf and stem partitioning. Samples were dried in a forced air oven at 60 ^{o}C to constant weight.

Meteorological conditions

No site-specific weather data were available for Experiment A. Results from

the nearest weather station are shown in Table 4. The closest recorded weather data for the Lochinvar site was Taupo; about 40 km west. Weather data for Experiment B were obtained on site. Total rainfall was lower than the long term mean (403 mm), a third (115 mm) of which fell in February. Temperatures were similar to the long term mean (12.2 ^{o}C) except for a low of 4.2 ^{o}C in May.

Table 4: Mean weather data for the three Experiment A sites (NIWA, 2010) and Methven site.

Site	Weather Station	Location	Rainfall (mm)	Temp (^{o}C)
Te Pirita	4722	43 ° 69 'S, 171 ° 90 'E	423	13.6
Fairlie	7726	44 ° 12 'S, 170 ° 88 'E	373	13.6
Lochinvar (Taupo)	25040	38 ° 68 'S, 176 ° 10 'E	442	13.9
Methven		43 ^{o} 38 'S, 171 ^{o} 40 'E	338	11.8

Data analysis

Leaf, stem and total DM yields at each site were analysed using analysis of variance (ANOVA) fitted with least squares in GenStat version 12. This was followed by a meta-analysis of the data from all three Experiment A sites; using a mixed model fitted with the restricted maximum likelihood (REML) programme in GenStat version 12. An estimate of the variation associated with treatment means was given by least significant difference ($LSD_{5\%}$) with associated degrees of freedom (df). Sum of squares were partitioned to allow for treatment structure and enable direct comparison of the control with treatment means. For the Methven site, background soil P and N levels were used as covariates in the analysis because they had a significant effect.

Results

Experiment A

There was no interaction of N, P and method of P application for any of the variables measured at Te Pirita (Figure 1). The total DM yield increased ($P<0.001$) with application of N from a mean of 5 t ha^{-1} for the unfertilised crops to 10 t ha^{-1} with applied N. There was no difference in yield between 100 and 200 kg N ha^{-1}. There was some evidence that adding P increased ($P=0.025$) total DM yield (Figure 1) but application method had no effect ($P=0.723$).

Both leaf and stem DM increased ($P<0.001$) with N application. The leaf ($P=0.014$) and stem ($P=0.034$) DM yields were also increased with P application but application method had no effect on either component.

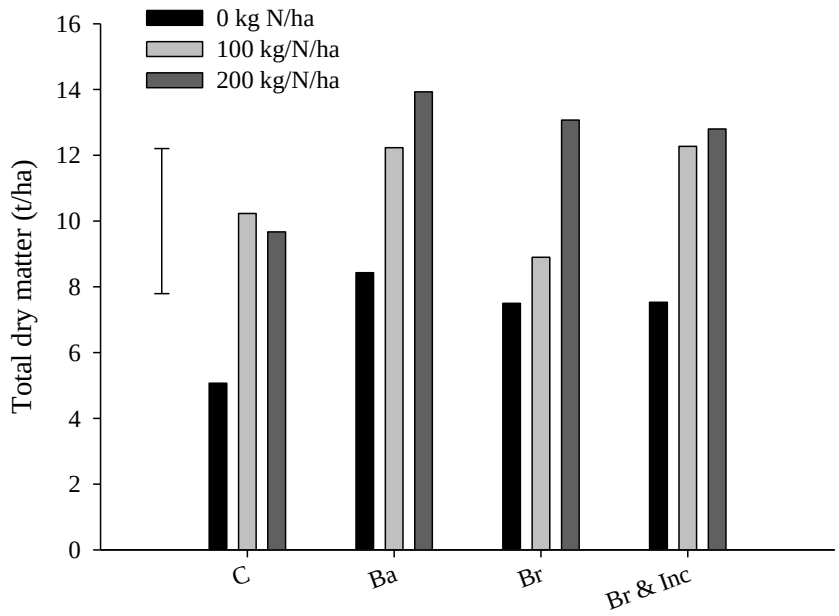

Figure 1: Total dry matter yield (t ha^{-1}) for kale crops grown with three rates of nitrogen (N = 0, 100 & 200 kg ha^{-1}), three methods of phosphorus (P) application (Ba = Banding, Br = Broadcast, Br & Inc = Broadcast & Incorporated) and two rates of P (Control or 50 kg ha^{-1} for Ba, Br or Br & Inc) at Te Pirita, Canterbury in 2005. Bar represents 5% LSD with 22 df.

There was a significant interaction (P=0.034) between N and P rate for total DM yield at Fairlie (Figure 2). Specifically, application of 50 kg P ha^{-1} had little impact when no N was applied. Equally when no P was applied (control) there was no response to 100 or 200 kg ha^{-1} of N. However, when 50 kg P ha^{-1} was banded or broadcast both N levels improved the yield with a maximum of 15 t ha^{-1}. This yield was only achieved for broadcast and incorporated P when 200 kg N ha^{-1} was applied.

There were also interactions of N and P rate for stem (P=0.038) and leaf (P=0.048) DM yield at Fairlie. However, P application method had no effect on either leaf or stem DM yield.

At Lochinvar, leaf, stem and total DM yield were unaffected by rate of N or P application or the method of P application (Figure 3). Overall yield was lowest at 4-6 t ha^{-1} with a high degree of variability.

Meta-analysis of the three Experiment A sites showed an interaction (P=0.017) between P rate and N rate. This indicated that overall the total DM yield only increased with application of 200 kg N ha^{-1} when P had been applied at establishment (Figure 4).

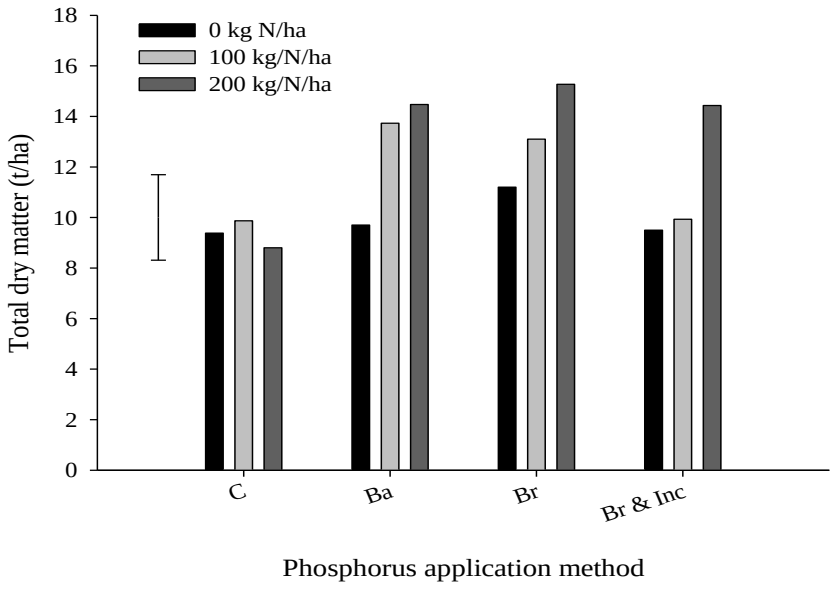

Figure 2: Total dry matter yield (t ha^{-1}) for kale crops grown with three rates of nitrogen (N = 0, 100 & 200 kg ha^{-1}), three methods of phosphorus (P) application (Ba = Banding, Br = Broadcast, Br & Inc = Broadcast & Incorporated) and two rates of P (Control or 50 kg ha^{-1} for Ba, Br or Br & Inc) at Fairlie, Canterbury in 2005. Bar represents 5% LSD with 22 df.

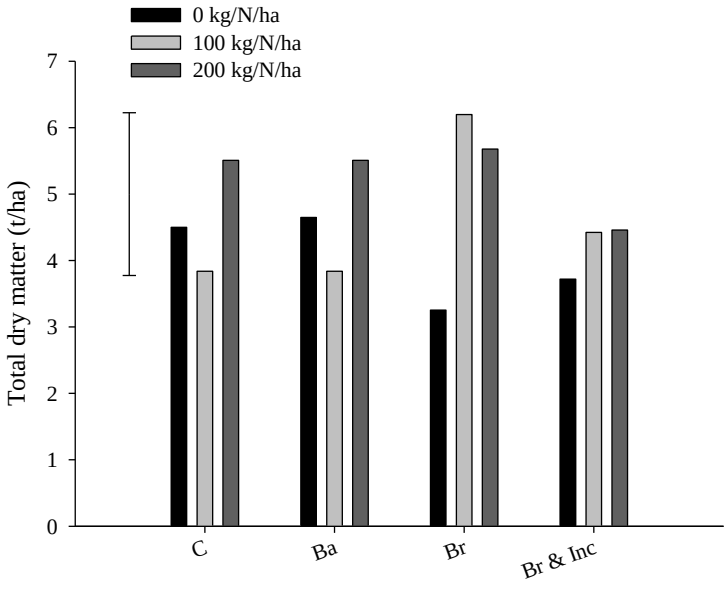

Figure 3: Total dry matter yield (t ha^{-1}) for kale crops grown with three rates of nitrogen (N = 0, 100 & 200 kg ha^{-1}), three methods of phosphorus (P) application (Ba = Banding, Br = Broadcast, Br & Inc = Broadcast & Incorporated) and two rates of P (Control or 50 kg ha^{-1} for Ba, Br or Br & Inc) at Lochnivar, Central North Island in 2005. Bar represents 5% LSD with 22 df.

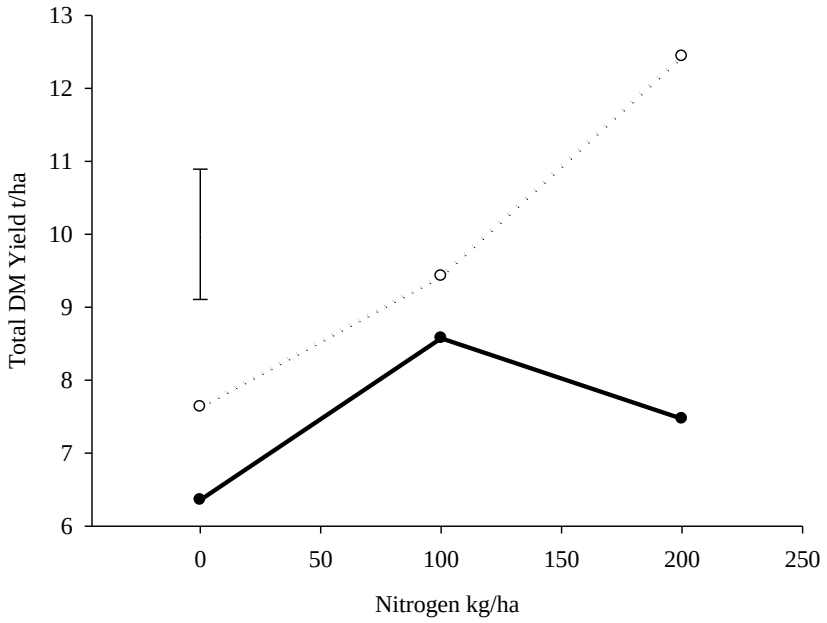

Figure 4: Total dry matter yield of kale crops grown with two rates of phosphorus, 0 (-●-) and 50 (--○--) kg P ha^{-1} at three nitrogen levels (0, 100, 200 kg ha^{-1}), at three sites in New Zealand (Experiment A). Bar represents 5% LSD with t = 2.

Experiment B (Methven)

Mean total DM yield across treatments increased (P<0.001) by 2.5 t ha^{-1} to 14.7 t ha^{-1} when 170 kg N ha^{-1} was applied compared with 70 kg N ha^{-1} (Figure 5, Table 5).There was some evidence of an interaction (P=0.064) among the rate of P and methods of P application at 170 kg N ha^{-1} (Figure 5b). Specifically, banded P crops yielded more than the broadcast P crops when 25 or 50 kg P ha^{-1} was applied at 170 kg N ha^{-1} but this was reversed at 75 kg P ha^{-1}. Background N had no effect on total DM yield.

Mean leaf DM increased (P<0.001) by 0.4 t ha^{-1} to 3.6 t ha^{-1} when 170 kg N ha^{-1} was applied compared with 70 kg N ha^{-1}. However, there was no evidence that adding any P had an effect on leaf yield at any rate (25, 50 and 75 kg ha^{-1}) or method of application (Banded or Broadcast).

Mean total stem DM increased (P=0.002) by 2 t ha^{-1} to approximately 11 t ha^{-1} when 170 kg N ha^{-1} was applied compared with 70 kg N ha^{-1}. However, there was no evidence that the unfertilised crops were different from the average of P treated crops (P=0.391). However, once the initial soil P status was used as a covariate, there was some evidence (P=0.086) that the 75 kg P ha^{-1} treatment was different from the others. However there was evidence (P=0.036) that the effects of P rate, P application method and N rate were not consistent for stem DM production; signified by the 3-way interaction. Stem DM also responded (P=0.01) to the interaction of background soil P and N.

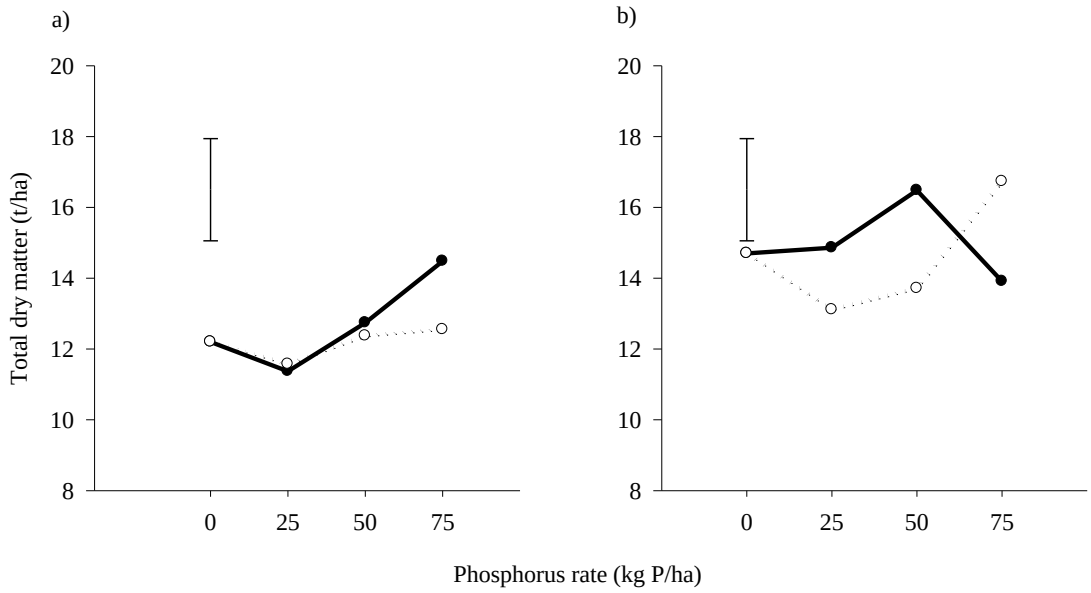

Figure 5: Total dry matter yield (t ha^{-1}) for kale crops grown with two methods of phosphorus (P) application; Banding (-●-) and Broadcast (--○--) and four rates of P, at (a) 70 kg N ha^{-1} and (b)170 kg N ha^{-1} at Methven, in 2008. Bar represents average 5% LSD with 32 df.

Table 5: Summary of kale dry matter yield responses to nitrogen and phosphorus application at four sites across New Zealand.

Site	Yield (t DM ha^{-1})			[1]Response to:			
	No fertiliser	Highest	Range	N rate	P rate	P method	Interaction
Te Pirita	5.0	14.0	5-14	√	√	x	x
Fairlie	9.4	15.3	8-15.3	√	√	x	√
Lochinvar	4.5	6.2	3.2-6.2	x	x	x	x
Methven							
(a) 70 kg N ha^{-1}	12.2	14.5	11-14.5	-	x	x	x
(b) 170kg Nha^{-1}	14.7	16.7	13-16.7	√	x	x	√

[1]√ = responded, x = no response

Discussion

The DM yield at Lochinvar, in the Central North Island, did not respond to any of the treatments (Figure 3, Table 5). The highest yield of 6 t ha^{-1} (Table 5) was lower than at the other three sites and lower than the optimum yields of 18-20 t ha^{-1} reported in literature (Wilson *et al.*, 2006; Fletcher *et al.*, 2007). This may indicate that nutrients were not the limiting factor at this site. The low yield potential meant that background N and P gave adequate nutrition (Table 2). The overall mean yields when both N and P were applied ranged from 9 to 12 t DM ha^{-1} in Experiment A (Figure 4) and 13.6 t DM ha^{-1} in Experiment B (Figure 5). These are medium yields for kale as well grown irrigated kale crops can produce more than 18 t DM ha^{-1} (Wilson *et al.*, 2006; Fletcher *et al.*, 2007). The lack of irrigation at all sites probably limited

yields. The mean leaf yield of 3.3 t DM ha^{-1} at Fairlie, Lochinvar and Methven was consistent with reports in the literature (Stephen 1976; Adams *et al.*, 2005; Fletcher *et al.*, 2007). However, the mean leaf yield of 2.6 t DM ha^{-1} at Te Pirita was lower.

Experiment A

The response to N application at Te Pirita (Figure 1) and Fairlie (Figure 2) was expected as the background soil N was low to medium (Table 2). De Ruiter *et al*. (2009b) state that a response to N is unlikely when soil N is greater than or equal to 150 kg ha^{-1}. The treatments at Te Pirita and Fairlie were nested and therefore it was not possible to determine whether the responses were due to total N applied or time of application. However, most of the yield increase at Te Pirita was from stems this could potentially reduce feed quality (Chakwizira, 2008). Total DM yield also increased with P application at Te Pirita and Fairlie (Table 5) but was unaffected at Lochinvar. A response to P at Fairlie was unlikely, due to a high soil P (Olsen P = 31), but was expected at Te Pirita (Olsen P = 11) (de Ruiter *et al.,* 2009b) This was an inconsistent result as Lochinvar had a moderate soil P level (Olsen P = 22) compared with Fairlie. This anomaly could possibly be attributed to a high soil N and moderate P retention (Table 2) at Lochinvar. Fertiliser application at Lochinvar (Figure 3) was not economic. At all four sites method of P application had no effect on total DM yield.

Experiment B

Total kale DM yield did not respond to either application method or rate of P (Figure 5). This, together with the no response to method of P application at Te Pirita (Experiment A), was a surprising result because the soil P background levels were low (Olsen P < 11). The results are inconsistent with the literature, for both method and rate of P application (Wilson *et al.*, 2006) and rate of P (Chakwizira, 2008). However, the failure to respond to method of application was similar to findings for both kale (Chakwizira, 2008) and Pasja (Chakwizira *et al.,* 2009). This was attributed to low soil P retention capacity and hence most of the P was available to the crop irrespective of application method. Kale crops have a more extensive root system than other brassicas and therefore access P from a larger soil volume and possibly satisfy growth requirements despite soil P tests indicating available soil P was low.

These experiments (Wilson *et al.,* 2006; Chakwizira, 2008; Chakwizira *et al.,* 2009) were carried out in Canterbury at mean Olsen P levels of 13, and therefore the differences in yield responses to P with the current experiments are unlikely to be attributed to either background soil P or P retention because the soils are similar. The background soil P was a significant covariate affecting yield. It is proposed that the total amount of P supply (both background P and applied P fertiliser) is an important determinant of yield.

There was a strong response to fertiliser N application at this site despite the high concentration of available soil N (186 kg ha^{-1}, Table 2) which was higher the 150 kg N ha^{-1} proposed by de Ruiter *et al*. (2009b). Yield increased by 2.5 t DM ha^{-1} (Figure 5) when 170 kg N ha^{-1} was applied compared with 70 kg N ha^{-1}.

This result highlights the depth limitation of the readily available N test, as it indicates available N only in the top 150 mm. Deep and extensively rooted crops, like kale, can access additional N from a greater soil volume. However, if subsoil N is low, N applied and incorporated near the soil surface may still give yield responses even if N tests show an adequate soil N concentration.

Conclusion

Nitrogen increased DM yield by more than 2 t DM ha^{-1} at Methven and doubled DM yield to 10 t DM ha^{-1} at Te Pirita but had no effect on kale yield at Fairlie or Lochinvar. The response to N was more pronounced in the presence of P. The non-responses to method and rate of P application may have been due to adequate available soil N at Methven and Fairlie and soil P at Lochinvar. The effects of P may be manifested only under low available N as it is proposed that P influences the rate of N uptake.

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Dry matter accumulation of oats sown at five different sowing dates

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Abstract

In crop rotations the harvest date of the first crop affects the sowing date of the succeeding crop which then influences the potential annual yield of the rotation. This study measured the dry matter accumulation and growth rate of oats, cv Milton, sown on five different dates 4 March (S_1), 28 March (S_2), 21 April (S_3), 12 May (S_4) and 3 June (S_5) in 2008. Each sowing was sequentially harvested until October. More than 15 t DM ha^{-1} was obtained from oats sown in March but the yield declined to 7.7 t DM ha^{-1} in the June sowing. Using a base soil temperature of 0 °C Milton accumulated yield at between 8 and 13 kg DM °Cd^{-1}. The earlier autumn sowings accumulated more heat units and therefore had higher dry matter production. Winter growth of S_4 and S_5 was < 19 kg DM ha^{-1} d^{-1}. Low growth rates in these treatments occurred because they failed to reach a critical leaf area index before cool temperatures restricted canopy development. However, these later sown crops responded rapidly to warm spring temperatures. The final yield from the October harvest reflects the yield potential prior to sowing a maize or kale crop for summer.

Additional keywords: *Avena sativa*, harvest date, thermal time, forage

Introduction

In New Zealand oats (*Avena sativa* L.) are used as supplementary forage in pasture and crop rotations (Moot *et al*., 2007). Oats have better growth than other crops in declining autumn temperatures and also have good seedling vigour (Forsberg and Reeves, 1995). They are therefore more suited to late sowing than most other annual forage crops. Oat crops are often sown after summer forages such as rape (*Brassica napus* L.) and maize (*Zea mays* L.) and are sown into cultivated soils or are direct drilled into seedbeds that would be unsuitable for other crops, such as annual ryegrass (*Lolium multiflorum* Lam.).

Planting an oat crop is often the best option if sowing has been delayed or seedbed preparation is not ideal. However, the onset of cool autumn temperatures can be expected to decrease potential growth rates.

Thus, determining how late in autumn a crop can be successfully sown is an important management decision for growers. If crops are sown too late they may fail to reach canopy closure before cool autumn and winter temperatures restrict leaf appearance and consequently crop growth is compromised. Subsequently, the time of final crop harvest may depend on whether the crop is to be grazed, ensiled or taken for seed. This paper reports on an experiment that studied crop growth from each sowing date through to mid spring when the next crop in a rotation may need to be sown. In this study, to determine the effect of sowing and harvest date on crop yield, light interception was monitored and growth rates were related to temperature using thermal time (Mills *et al*., 2006).

Materials and Methods

Experimental site

The study was conducted at Block H14, Lincoln University, Canterbury, New Zealand. The soil was a Tempelton silt loam (Typic Ustochrept, USDA soil taxonomy). The experiment site had been in a barley trial the previous year. A Ministry of Agriculture and Fisheries (MAF) soil quick test was done and soil test results are reported in Table 1. In this study, the oat (*Avena sativa* L.) cultivar 'Milton', was sown on five different dates (4 March (S_1), 28 March (S_2), 21 April (S_3), 12 May (S_4) and 3 June (S_5) of 2008) as part of an experiment that also included tick bean (V*icia faba* L.) and Italian ryegrass (*Lolium multiflorum*). This paper, only reports the results for oats.

Experimental design and management

The experiment was a split-plot design with four replicates. The five sowing dates were main plots and crop species were sub-plots. The oats were sown with an Oyjørd cone seeder at 240 plants m^{-2}. The target sowing depth was 20 mm. Experimental sub-plots were 14 x 2.1 m with 150 mm between rows. All five sowings received 500 kg N ha^{-1} in 10 split equal applications of 50 kg N ha^{-1} as urea during the growing season. The rate of 50 kg N ha^{-1} was based on standard farm practise. Irrigation was applied when the soil moisture was 20% below field capacity as measured by a plug-in Hydrosense probe about 27 cm deep in the soil. Monitoring was to avoid water stress during the growing season. Temperature probes (Hobo shuttle) were placed in the plots to measure soil and air temperature. For weed control, MCPA (375 g l^{-1} MCPA) was applied at 3 l ha^{-1} on 3 April 2008. Pirimor 50 insecticide (500 g kg^{-1} pirimicarb) was applied for aphid control at 250 g ha^{-1} on 8 April, 29 May and 28 August 2008.

Measurements

Dry matter accumulation and thermal time

Dry matter (DM) accumulation, was measured at approximately fortnightly intervals until October 2008. Sampling was done three weeks after the crop was sown using two 0.1 m^2 quadrats. Oats were cut to ground level from each of the three rows across the plot. Samples were weighed and oven-dried at 50-60 °C to constant weight. At final harvest a 0.5 m^2 quadrat was used. Daily mean soil temperatures from temperature sensors placed at 25 mm depth in the experimental plots were used for thermal time (Tt) calculations with a base temperature of 0 °C.

Radiation interception and leaf area index

Leaf area index (LAI) and the amount of radiation transmitted through the canopy were measured using a plant canopy analyser LAI-2000 (LI-COR Inc., Lincoln, Nebraska, USA). Measurements were made weekly in March, April and May, once every two weeks in June, July and August and weekly again in September and October.

Data analysis

Results were analysed using analysis of variance (Genstat 11) across all sowing dates. Mean separation was by Fisher's protected least significant difference method. Linear regressions were performed for DM and leaf area index against Julian days. Points for the regression were excluded from late winter or when DM yield started to increase in early spring (Figure 1) due to a loss of linearity in the data set. In contrast, all points up to maximum DM for all sowing dates were included in the regression against thermal time.

Table 1: Soil test results (0-15 cm) for Block H14 Horticulture Research Area, Lincoln University, Canterbury, New Zealand.

Year	pH	Olsen-soluble P (μg ml^{-1})	Ca MAF	Mg MAF	K MAF	Na MAF	Sulphate (μg g^{-1})	Anaerobic mineralisable N (kg ha^{-1})
2008	5.9	23	8	20	7	8	2	42

Results

Dry matter yield

The maximum DM accumulation for autumn sowings was higher than for winter sowings with 14,620 kg ha^{-1} and 15,390 kg ha^{-1} for crops sown in March. Yields declined successively to 12,840 kg ha^{-1} for the April sowing to 7,730 kg ha^{-1} for the June sowing (Figure 1). In this study, oat DM yield did not increase after the end of October and in some instances the yield declined with time. Respective March-sown oats had faster early growth rates with 71 and 47 kg DM ha^{-1} d^{-1} than sowings in April, May and June. In the latter sowings, winter growth rates never exceeded 17 kg DM ha^{-1} d^{-1}. However, growth rates recovered to approximately 148 kg DM ha^{-1} d^{-1} during the September to October spring period (Figure 1).

Accumulated thermal time

Oats accumulated DM at about 9 kg DM °Cd^{-1} for the season when sown in March and averaged 12 kg DM °Cd^{-1} for the three final sowings (Figure 2). For all sowings the results showed a strong linear relationship between accumulated DM and accumulated thermal time. The earlier autumn sowings accumulated more heat units which allowed higher maximum DM yields. Specifically, the duration of growth was 1773 °Cd for the 28 March sowing (S_2) and this was associated with the highest DM yield accumulation.

Radiation interception, leaf area index and accumulated thermal time

Figure 3 shows that critical LAI ($LAI_{(crit)}$) for Milton oats was about 2.6. Virtually all sowing dates achieved $LAI_{(crit)}$. However, the time when this occurred differed among sowing dates.

For the 4 March sowing this was achieved by 9 June compared with a month later in S_2 on 6 July which was sown three weeks later. Delaying sowing a further three weeks to 21 April meant canopy closure was not achieved until 26 August. In the last two sowings, canopy closure did not occur until the following spring on 14 and 17 October 2008 respectively, (Figure 4). Figure 5 shows that the leaf expansion rate that drives canopy expansion, as measured by leaf area index, was related to thermal time. Based on the regression equations the accumulated thermal time was about the same (approximately 1029 °Cd for the March sowing, approximately 999 °Cd for the April and May sowing and 967 °Cd for the last June sowing) across all sowing dates.

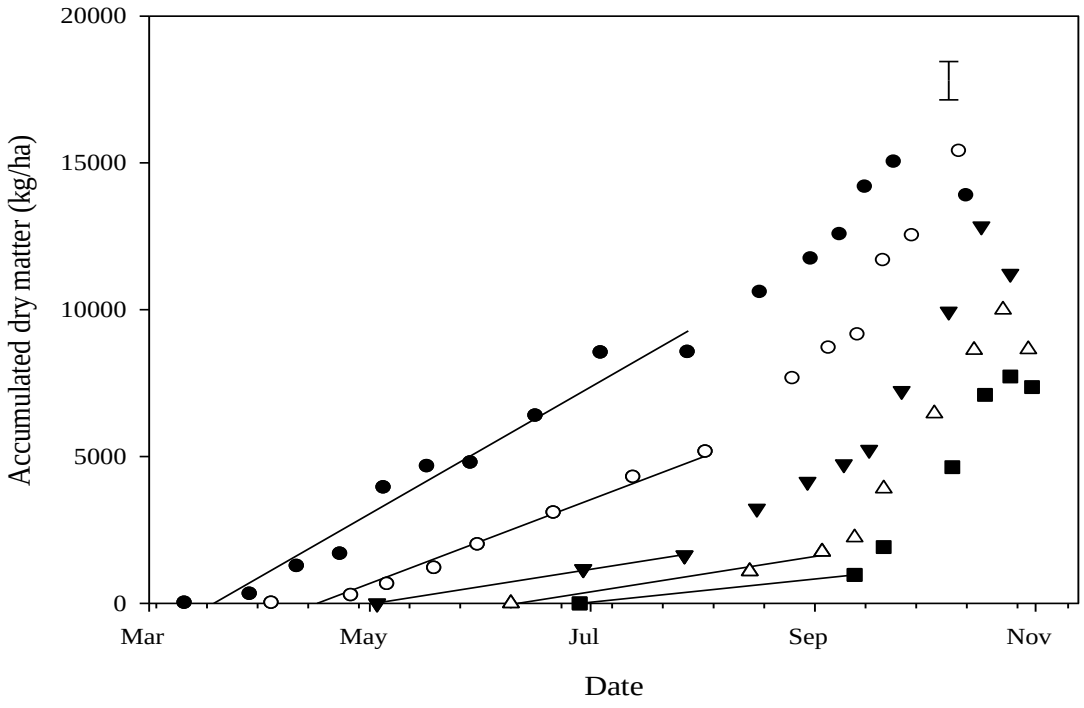

Figure 1: Dry matter accumulation from different sowing dates of Milton oats sown on 4 March (S_1) (●), 28 March (S_2) (■), 21 April (S_3) (▲), 12 May (S_4) (◆) and 3 June (S_5) (▼) 2008 at Lincoln University, Canterbury, New Zealand. Regressions which show winter growth rates are:
S_1 y = -5582 (± 699) + 70.8 (± 4.93)x (R^2 = 0.96),
S_2; y = -5023 (± 468) + 46.8 (± 2.10)x (R^2 = 0.97),
S_3, y = -2391 (± 162) + 19.4 (± 0.92)x (R^2 = 0.99),
S_4, y = -3158 (± 675) + 19.4 (± 3.14)x (R^2 = 0.95),
S_5, y = 12.7x - 2294 (*n*=2).
S.E.M presented means of maximum dry matter yield of five sowing dates.

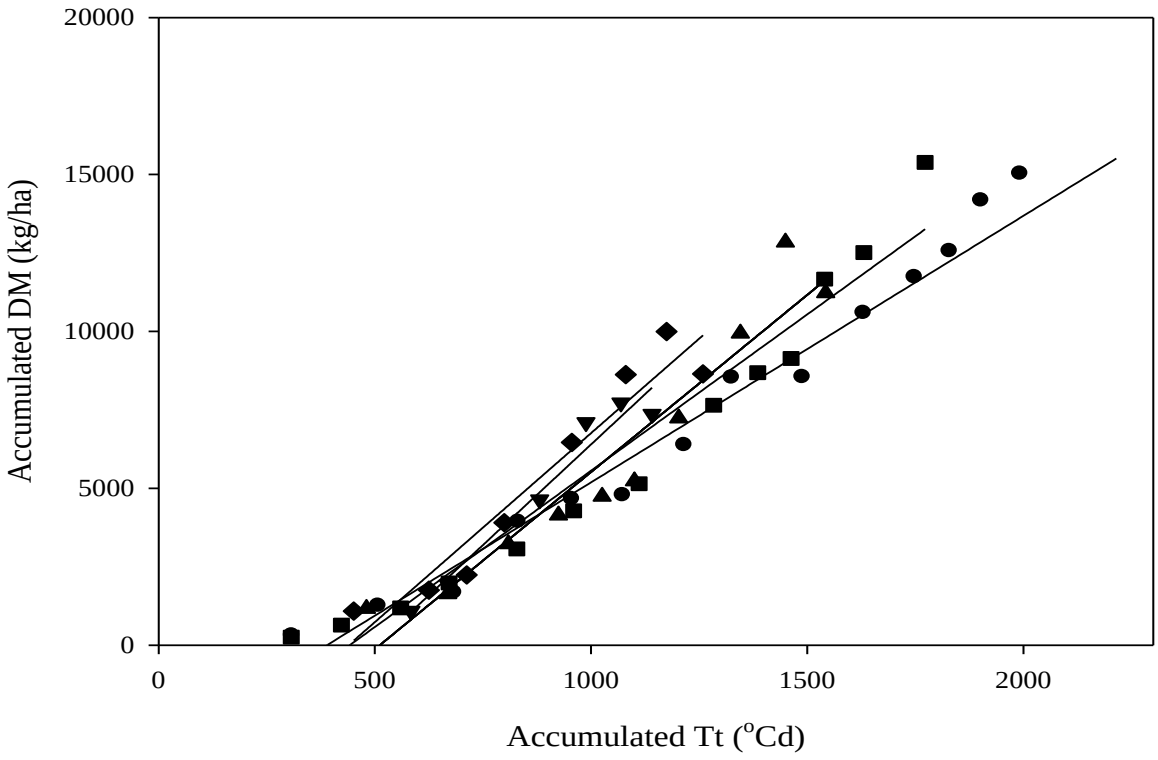

Figure 2: Dry matter accumulation against accumulated thermal time (Tt) with a base temperature 0 °C for 'Milton' oats sown on 4 March (S_1) (●), 28 March (S_2) (■), 21 April (S_3) (▲), 12 May (S_4) (◆) and 3 June (S_5) (▼) in 2008 at Lincoln University, Canterbury, New Zealand. Regressions are:
S_1, y = -3305 (± 599) + 8.49 (± 0.42)x, (R^2 = 0.97),
S_2, y = -440 (± 803) + 9.96 (± 0.69)x, (R^2 = 0.95),
S_3, y = -5774 (± 129) +11.3 (± 1.17)x, (R^2 = 0.91),
S_4, y= -5287 (± 124) +12.0 (± 1.34)x, (R^2 = 0.92),
S_5, y= -6424(± 121) +12.8 (± 1. 33)x, (R^2 = 0.95).

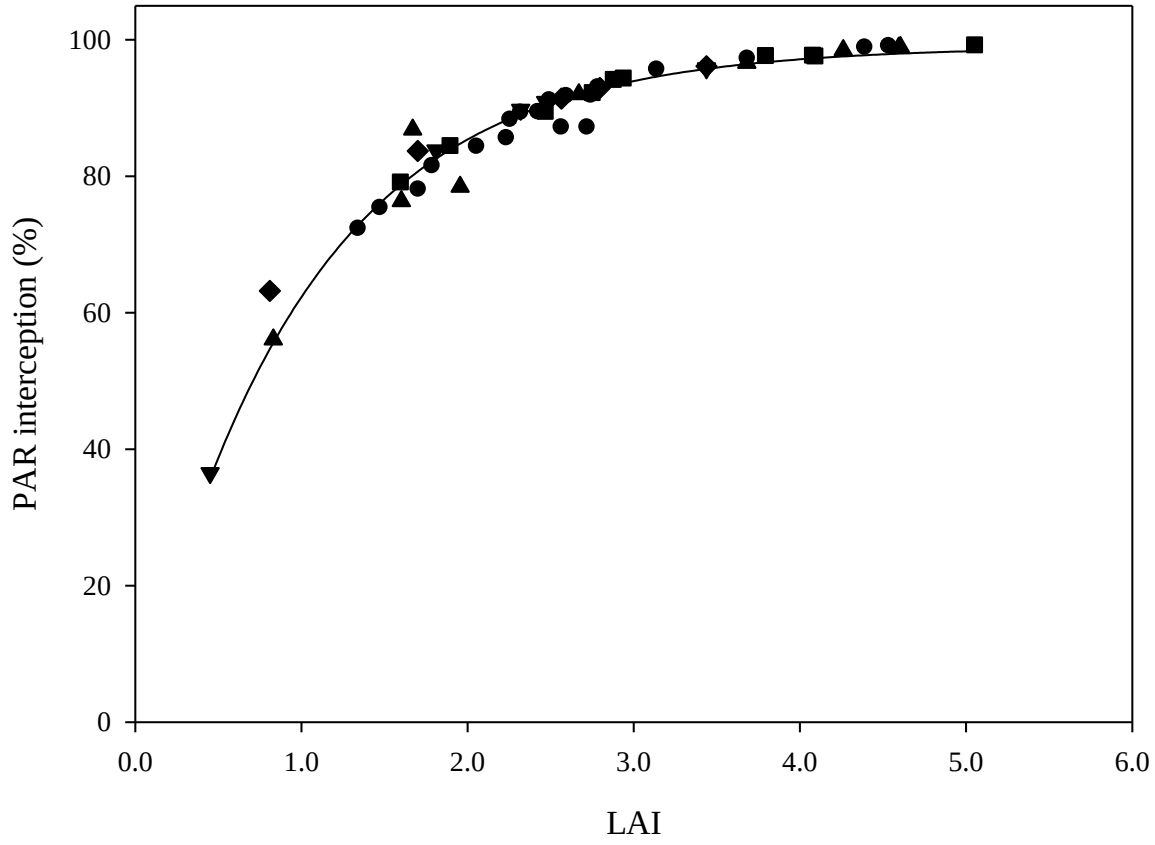

Figure 3: Intercepted photosynthetically active radiation (PAR) against leaf area index (LAI) for Milton oats sown on 4 March (S_1) (●), 28 March (S_2) (■), 21 April (S_3) (▲), 12 May (S_4) (◆) and 3 June (S_5) (▼) in 2008 at Lincoln University, Canterbury New Zealand. Form of the curve is:
$y= 99.0 (\pm 0.68)x (1-0.(\pm 0.010)^x)$ ($R^2 = 0.96$).

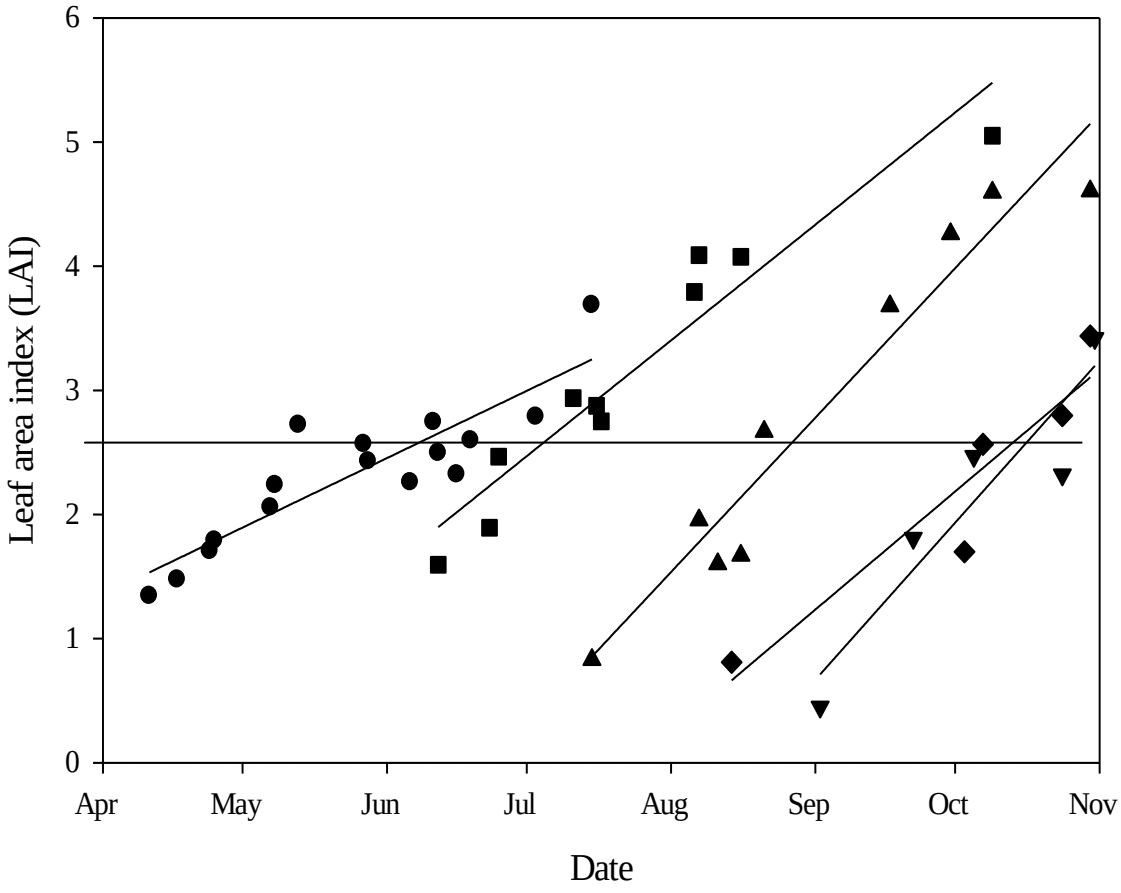

Figure 4: Leaf area index (LAI) of different sown dates for Milton oat crops sown on 4 March (S_1) (●), 28 March (S_2) (■), 21 April (S_3) (▲), 12 May (S_4) (◆) and 3 June (S_5) (▼) in 2008 at Lincoln University, Canterbury, New Zealand. Regressions are:
S_1, y = -0.3254 (± 0.3704) + 0.0182 (± 0.0025)x, (R^2 = 0.78),
S_2, y = -4.7840 (±0.6624) + 0.0392 (± 0.0033)x, (R^2 = 0.94),
S_3, y = -7.0485 (± 0.9657) + 0.0401 (± 0.0039)x, (R^2 = 0.93),
S_4, y = -6.5307 (± 1.8419) + 0.0317 (± 0.0066)x, (R^2 = 0.85),
S_5, y = -9.6560 (± 2.7340) + 0.0421 (± 0.098)x, (R^2 = 0.81).

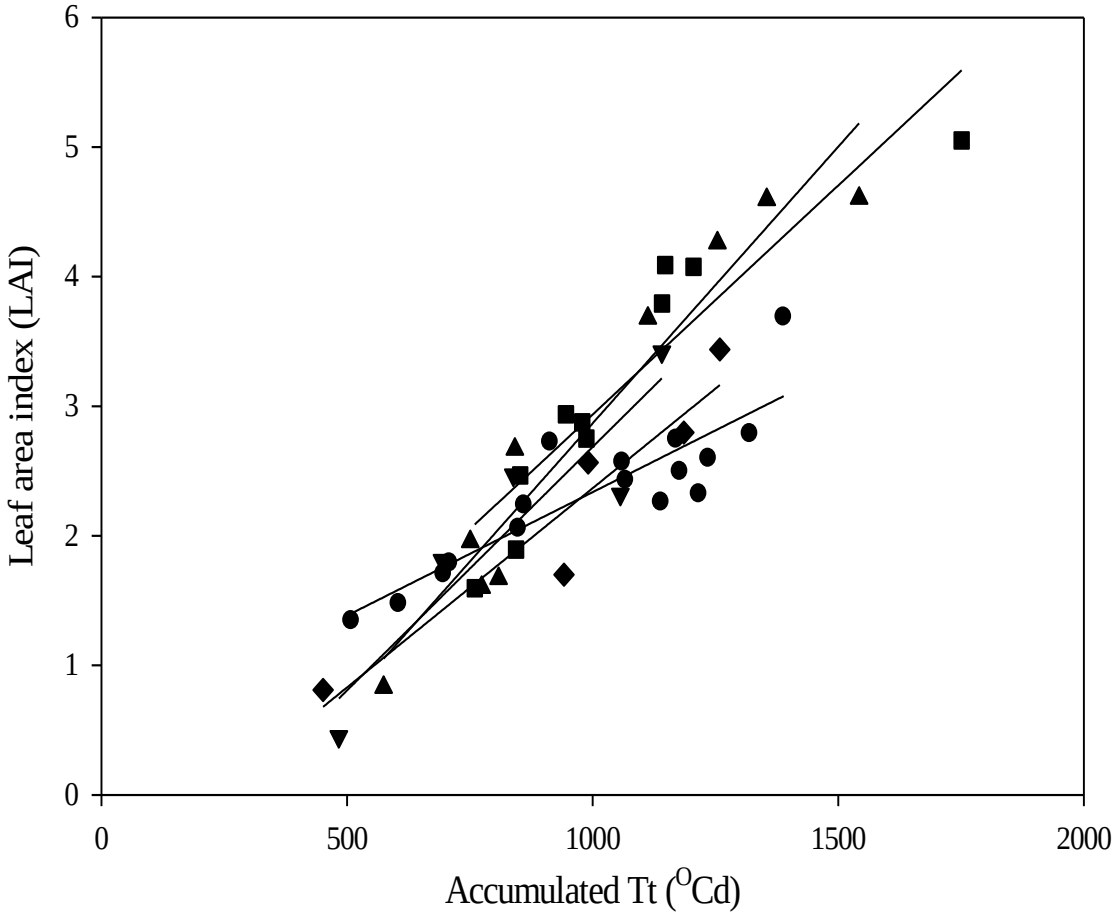

Figure 5: Leaf area index (LAI) against accumulated thermal time (Tt) with a base soil temperature of 0°C for Milton oat crops sown on 4 March (S_1) (●), 28 March (S_2) (■), 21 April (S_3) (▲), 12 May (S_4) (◆) and 3 June (S_5) (▼) in 2008 at Lincoln University, Canterbury, New Zealand. Regressions are:
S_1, y = 0.431 (± 0.28) + 0.002 (± 0.0003)x (R^2 = 0.76),
S_2, y = -0.601 (± 0.57) + 0.004 (± 0.0005)x (R^2 = 0.84),
S_3, y = -1.402 (± 0.45) + 0.004 (± 0.0004)x (R^2 = 0.92),
S_4, y = -0.708 (± 0.58) + 0.003 (± 0.0006)x (R^2 = 0.87),
S_5; y = -1.073 (± 0.79) + 0.004 (± 0 .0001)x (R^2 = 0.81).

Discussion

Early autumn sowing, on 4 and 28 March 2008, gave maximum growth rates of 71 kg DM ha^{-1} d^{-1} and 47 kg DM ha^{-1} d^{-1}, respectively. These results support those of de Ruiter *et al*. (2002) who reported that forage cereals (oats, triticale and barley) could give a yield of 50 to 60 kg DM ha^{-1} d^{-1} over winter from an early March sowing.

The maximum DM in S_1 (14,620 kg ha^{-1}) was lower than in S_2 (15,390 kg ha^{-1}) probably because of an outbreak of barley yellow dwarf virus in August and

September. The maximum yield, in this study, was slightly higher than the 10 t ha^{-1} reported by McDondald and Stephen (1979) and Jacobs *et al*. (2009) in New Zealand and Australia, respectively. The two New Zealand studies were similar. However, the Australian work examined whole crop cereal silage. In another study conducted from 1975 to 1977 in the Manawatu, New Zealand, Eagles *et al*. (1979) reported a higher mean yield of 16.3 t ha^{-1} DM of 4 cultivars of winter oats harvested in spring.

In most cases, an early autumn sown oat crop has a shorter emergence period and higher vegetative growth rate than oats sown in late autumn and winter. In this study, early autumn sown oats (S_1 and S_2) had higher winter growth rates than later sown oats. The differences in yield across the different sowing dates was associated with the early autumn sown oats receiving higher incident radiation and higher accumulated temperature sums over the duration of their growth. Both of these factors influence the rate of leaf appearance and canopy expansion.

The earlier sown oats achieved 90% light interception and $LAI_{(crit)}$ earlier than the later sown oats. The failure of later sown oats to obtain high yields was due to their low LAI and their delay in reaching canopy closure through most of the growing season. Canopy closure did not occur until the end of winter (S_3) or early October (S_4 and S_5). Low temperature reduced the rate of crop leaf appearance and expansion. Hay and Porter (2006) stated that the rate of leaf appearance in crop plants depended mainly on the temperature of the expanding leaves. This agrees with McMaster *et al*. (2003) who found temperature was the primary environmental factor controlling the phyllochron, or rate of leaf appearance in wheat (*Triticum aestivum* L.). However, after reaching LAI_{crit}, the growth rate of the later sown oats was rapid. This occurred in spring with high incident light and temperatures.

This study demonstrated the dependence of oat DM accumulation on the time available for growth between sowing and harvest. The determination of harvest date would depend on the purpose the crop was sown for, whether it was to be cut for green feed, grazed or ensiled. It has been reported that different times of harvest affect DM accumulation and are associated with a decline in nutritive value (metabolisable energy and crude protein content) of the forage (Filya, 2003; Jacobs *et al*., 2009). Late sowing (early June) resulted in low DM production because of the long duration to canopy closure followed by a shorter spring growth period. However, if the oats were sown too early, the yield may be reduced if barley yellow dwarf virus incidence was high as occurred in S_1 of this study.

Conclusions

Oats sown between early March and the middle of April reached canopy closure and therefore had longer before growth was limited by declining temperatures and radiation levels in the winter. Oats were ready for harvest in September or October as would be the case for late winter green feed or for making silage. The results highlighted the importance of selecting the appropriate sowing and harvest date for oats to produce a high DM yield. The choice of sowing and harvest times

offers some flexibility to match with summer crops to maximise total annual yield.

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Spring water use efficiency of six dryland pastures in Canterbury

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Abstract

The spring water use efficiency (WUE) of six pasture combinations was calculated from the 'MaxClover' grazing experiment at Lincoln University. Pastures have been established for six years and are grazed by best management practices for each combination. Measurements were from individual plots of four replicates of cocksfoot (CF)/subterranean clover (Sub); CF/balansa clover (Bal); CF/white clover (Wc); CF/Caucasian clover (Cc); perennial ryegrass (RG)/Wc or lucerne pastures. Actual water use was measured by time domain reflectometry (0-0.2 m) and a neutron probe (0.2-2.3 m). Dry matter yield, botanical composition and herbage quality were measured at the end of seven regrowth cycles between 1 July 2008 and 30 June 2009 (33-85 d duration). The results highlight differences in spring WUE amongst species and these were related to legume contribution and grass nitrogen (N) yield. Lucerne had the highest spring WUE at 30 kg DM ha^{-1} mm^{-1} of actual water use. This was produced at a rate of 5.7 kg DM ha^{-1} $°Cd^{-1}$. For grass based pastures CF/Sub clover produced 18 kg DM ha^{-1} mm^{-1} at a rate of 5.9 kg DM ha^{-1} $°Cd^{-1}$ compared with 14 kg DM ha^{-1} mm^{-1} for the other pastures at rates of 3.2 to 4.1 kg DM ha^{-1} $°Cd^{-1}$. These results highlight the importance of the spring period for dryland pasture production when soil temperatures are rising and moisture levels are high. The spring pasture WUE of dryland pastures was higher than in summer and autumn and therefore it is important that farmers maximise pasture production through combinations of pasture species that maximise spring legume content.

***Additional keywords**: Dactylis glomerata, Lolium perenne, Medicago sativa, Trifolium ambiguum, T. michelianum* var. balansae, *T. repens, T. subterraneum*

Introduction

In eastern districts of New Zealand moisture stress of dryland pastures is common over summer (Salinger, 2003). At Lincoln, Canterbury, monthly potential evapotranspiration generally exceeds rainfall from September to April. This produces a long term (1975-2007) average potential soil moisture deficit of approximately 430 mm yr^{-1} in April. Stress is relieved by autumn rain which re-establishes the sward before cool winter temperatures restrict pasture growth (Mills *et al.*, 2008a). On an annual basis the majority of pasture production in these regions occurs in the

spring when soil moisture is at, or near, field capacity and soil temperatures begin to rise. The efficiency with which pastures utilise this available soil water in spring is therefore an important contributor to annual pasture yields. Agronomically, water use efficiency (WUE) can be defined as the ratio of the total dry matter (DM) produced to the total water used for growth (Moot *et al.*, 2008), or as DM accumulation against potential or measured evapotranspiration (ET). This can be done on a seasonal or annual scale and is important for understanding how to manage dryland pastures. Enhancements in agricultural WUE depend on productivity gains at the field level, and are quantified by consistent increases in outputs per unit of input. For dryland farmers this can be equated to greater pasture and animal production per unit of water input.

For irrigated dairy pastures Martin *et al*. (2006) reported a mean WUE of 20 kg DM ha^{-1} mm^{-1} of potential evapotranspiration (PET). In dryland pastures, where actual evapotranspiration (Martin, 1990) or water use, was measured, Moot *et al*. (2008) reported a range of values from 7 kg DM ha^{-1} mm^{-1}, for a severely N deficient (*Dactylis glomerata* L.) dominant sward, to 40 kg DM $ha^{-1}mm^{-1}$ of water for lucerne (*Medicago sativa* L.).

In most cases they suggested that pastures which contained high legume content or had received applied N had higher water use efficiency than those with low N. Thus, at the pasture level, differences in water use efficiency were related to the N content of the pasture grown. A difficulty with their comparisons of pasture water use efficiency was that a range of experiments were interpreted from across different soil types. In the present study the spring water use efficiency of six dryland pastures are compared from within the 'MaxClover' grazing experiment. Four of these pastures have cocksfoot as the dominant grass because it is a persistent species commonly used in dryland pastures. However pastures are often N deficient (Peri *et al*., 2002), because of its competitive ability in water extraction that restricts the growth of companion legumes (Evans, 1978; Lee and Cho, 1985). Therefore the 'MaxClover' experiment was designed to identify legume species that may persist in cocksfoot swards to enhance overall pasture productivity (Mills *et al*., 2008a).

The present study compares WUE of cocksfoot (CF) pastures grown with

(1) subterranean (Sub) (*Trifolium subterraneum* L.), or
(2) balansa (Bal) (*T. michelianum* Savi var. balansae Boiss.) annual clovers, or
(3) white (Wc) (*T. repens* L.), or
(4) Caucasian (Cc) (*Trifolium ambiguum* M. Bieb.) perennial clovers with a
(5) perennial ryegrass (*Lolium perenne* L.)/white clover (RG/Wc) control and
(6) a lucerne (Luc) monoculture.

Materials and Methods

Full details of the experimental design, establishment and measurements of the 'MaxClover' experiment were reported by Mills *et al.* (2008a). Details related to the present experiment are included. Specifically, the experiment was at Lincoln University, Canterbury with 36 plots (6 pasture treatments x 6 replicates)

of 0.05 ha. Four replicates were established in February 2002 and were utilised for a measurement period of 1 July 2008 to 31 March 2009. Meteorological data for rainfall, used in the calculations of actual spring soil water use, and soil temperature, used to calculate thermal time (Moot *et al.*, 2000) were recorded at the Broadfields station located 2 km north of the site. Broadfields daily rainfall data is comparable (± 3%) to rainfall data collected closer (approximately 300 m) to the experimental area but has the advantage of having a complete set of other environmental variables including temperature, potential evapotranspiration, solar radiation and wind run.

Environmental conditions

During the experimental period reported annual rainfall was 767 mm which was 23% above the long-term mean (LTM) (Table 1). Specifically rainfall in July 2007 was more than double the long-term mean of 64 mm and in May 2009 rainfall was 171 mm compared with the LTM monthly rainfall of 50 mm. Soil temperature (0.1 m) was 11% higher than the LTM. Monthly mean soil temperatures were 9-19% warmer than the LTM from October to January.

Table 1: Monthly rainfall (mm) and 0.1 m soil temperature (°C) recorded at the Broadfields Meteorological Station located 2 km north of the experimental site. Long-term monthly means (LTM) are for the period 1975-2002.

	Rainfall (mm)		Soil temperature (°C)	
Month	LTM	Actual	LTM	Actual
July	64	145	4.0	5.8
August	62	94	5.4	6.1
September	43	39	8.1	9.8
October	51	22	11.2	12.3
November	52	11	14.0	16.6
December	50	77	16.5	18.0
January	51	46	17.6	20.9
February	41	59	17.1	17.4
March	50	36	14.9	15.1
April	46	53	11.1	12.2
May	50	171	7.4	7.2
June	64	14	4.7	5.4
Annual	624	767	11.0	12.2

Pasture production

Grass based pasture production and botanical composition were measured at 33-85 day intervals from 0.2 m^2 quadrats cut from exclosure cages which were shifted to a new site after each harvest. The herbage, cut to a height of approximately 30 mm, was then sub-sampled and sorted into sown grass; sown legume; other grass, other legume, weeds and dead matter before drying at 65 °C to constant weight. Sown clover and grass samples were ground through a 1 mm sieve and tested by near infrared

spectroscopy (NIRS) for N content. The N percentage of the grass and clover herbage and their DM yield were then used to calculate total N yield (kg N ha^{-1}) of the sown species in each plot. Lucerne samples were processed in the same manner but harvests were from 5 x 0.2 m^2 quadrats $plot^{-1}$ immediately prior to grazing.

Soil water measurements

Soil water content was measured by time domain reflectometry (0-0.2 m; Trace Systems 6050X1) and neutron probe (Troxler 4300) at 0.2 m intervals (0.2-2.3 m). Measurements were made at 5-41 d intervals, with the maximum interval occurring in winter. The drained lower limit (DLL) was defined as the lowest volumetric soil water content (Brown, 2004) in each 0.2 m soil layer recorded when soil water content was stable during a known period of water stress in summer. For example, Figure 1a shows little change in soil water content for lucerne in the 0.5-0.7 m soil layer from February to April which coincided with a period of no growth. For this layer the DLL was quantified as 10.1% v/v from a measurement on 4 March 2009. Similar analyses were undertaken for each soil layer in each plot. To define field capacity, or the drained upper limit (DUL), the average of the second and third highest volumetric water contents recorded, when soil moisture profiles were fully recharged, in winter was used. The DUL was calculated from measurements made when soil water content was stable (Robertson *et al*., 1993), prior to the start of root water extraction during active growth, in each of the 12 individual soil layers. The measured volumetric water content in the 2.2-2.3 m soil layer under lucerne grown in plot 19 is shown in Figure 1b. The absolute value of 7.7% indicates a high gravel content which was apparent at 0.5-2.1 m across plots. The consistency of the measured values indicated no water extraction at this lowest depth for lucerne. Slight variations in reading can occur and thus the DUL was taken as the average of the 2nd and 3rd highest volumetric water content measured. The difference between DUL and DLL is a measure of plant available water content in each soil layer. These were summed (0-2.3 m soil depths) for each individual plot.

Analysis of variance indicated the plant available water content was 280 ± 19.8 mm for all pastures and was unaffected by pasture type (Tommukayakul, 2009).

For spring grazed pastures the assumption of a full canopy used in the calculation of potential evapotranspiration was not always fulfilled, particularly under set-stocked conditions. Therefore, actual soil water use was calculated for each individual plot. Actual soil water use was calculated from a total soil water (0-2.3 m) budget which made daily interpolations of soil water content (SWC, Equation 1) and water use (WU, Equation 2). Water use was then accumulated for individual regrowth periods in the spring period.

Equation 1 $$SWC = \sum_{bottom}^{top} \theta \times d$$

Where θ is the volumetric water content (% v/v) and d is depth (mm) of the soil layer measured and *top* is the 0-0.2 m soil layer and *bottom* is the 2.2-2.3 m soil layer.

Equation 2 $WU = P - \Delta SWC - D$

Where P is precipitation or rainfall measured at the Broadfields Meteorological Station, ΔSWC is the change in SWC between successive measurements and D is drainage. Drainage occurs on a daily basis when precipitation causes the SWC to exceed the drained upper limit of the profile. A WU factor was calculated as the ratio between actual evapotranspiration and Penman potential evapotranspiration. This factor was applied to daily PET to estimate daily water use between successive measurements.

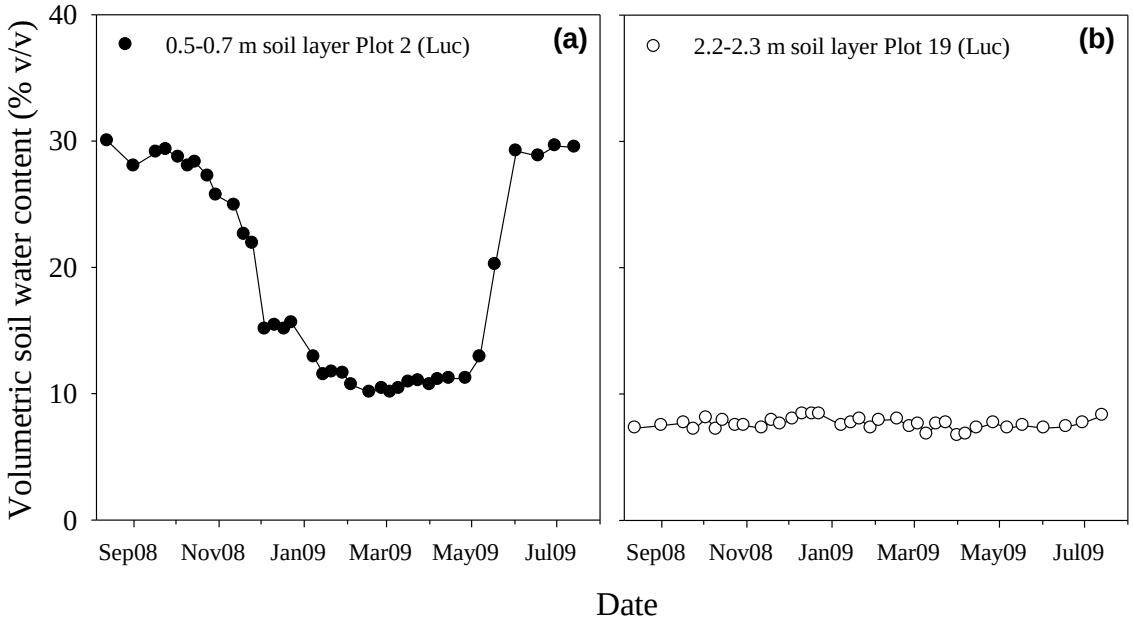

Figure 1: Soil moisture content (a) in the 0.5-0.7 m soil layer in plot 2 (lucerne) and (b) in the 2.2-2.3 m soil layer in plot 19 (lucerne) throughout the 2008-09 growth season at the 'MaxClover' grazing experiment at Lincoln University, Canterbury.

Results and Discussion

The main period of pasture production with the highest pasture growth rates for all species was in the spring (Figure 2). Growth rates for lucerne are shown for reference but were excluded from the analysis of variance as harvests were made at different times from the grass based pastures. During the winter period CF/Sub pastures grew at 21 kg DM ha^{-1} d^{-1} which was almost double ($P<0.001$) the 11 ± 1.4 kg DM ha^{-1} d^{-1} produced by all other grass-based pastures.

In early spring (8 October 2008) a trend ($P<0.10$) suggested that CF/Sub pastures grew faster (57 kg DM ha^{-1} d^{-1}) than CF/Bal, CF/Wc or CF/Cc pastures. As spring progressed the CF/Sub pastures showed superior production ($P<0.01$) and grew at 74 kg DM ha^{-1} d^{-1} (10 November 2008) compared with 43 ± 6.0 kg DM ha^{-1} d^{-1} for all other grass based pastures. Lucerne grew at a rate of approximately 100 kg DM ha^{-1} d^{-1} in November and 75 kg DM ha^{-1} d^{-1} 38 d later in December. Growth, in grass based pastures slowed after the November harvest and they were next

harvested 56 d later (5 January 2009) during which period all grass based pastures had grown at 24 ± 6.5 kg DM ha^{-1} d^{-1}. Lucerne, harvested 12 d later, after 38 d of regrowth, had grown at 77 kg DM ha^{-1} d^{-1}.

Late summer/autumn (2 March 2009) rains alleviated soil water stress conditions and annual clover seedlings began to germinate. The cocksfoot pastures established with Sub clover grew at 16 kg DM ha^{-1} d^{-1} compared ($P<0.05$) with 9 kg DM ha^{-1} d^{-1} for CF/Cc pastures. By mid-autumn (6 April 2009) the CF/Sub pasture production of 21 kg DM ha^{-1} d^{-1} was double ($P<0.1$) the 10 ± 2.7 kg DM ha^{-1} d^{-1} from perennial clover based pastures. The CF/Bal pasture was intermediate at 13.8 kg DM ha^{-1} d^{-1}. Early autumn production by lucerne was > 30 kg DM ha^{-1} d^{-1} and this decreased to 7 kg DM ha^{-1} d^{-1} when the last lucerne harvest of was taken on 27 May 2009.

For the late autumn/early winter period (30 June 2009) the maximum ($P<0.05$) growth rate of the grass based pastures was 7 kg DM ha^{-1} d^{-1} by the CF/Sub pastures and lowest in RG/Wc pastures (4 kg DM ha^{-1} d^{-1}).

The duration of the spring phase, where moisture was non-limiting, was quantified as the period before a significant reduction in daily growth rates of each pasture occurred. For the grass treatments this reduction was on 10 November 2008 compared with one month later on 9 December 2008 for lucerne. During these periods the growth rate of pastures can be related to thermal time until a lack of soil moisture restricts growth (Mills *et al.*, 2006).

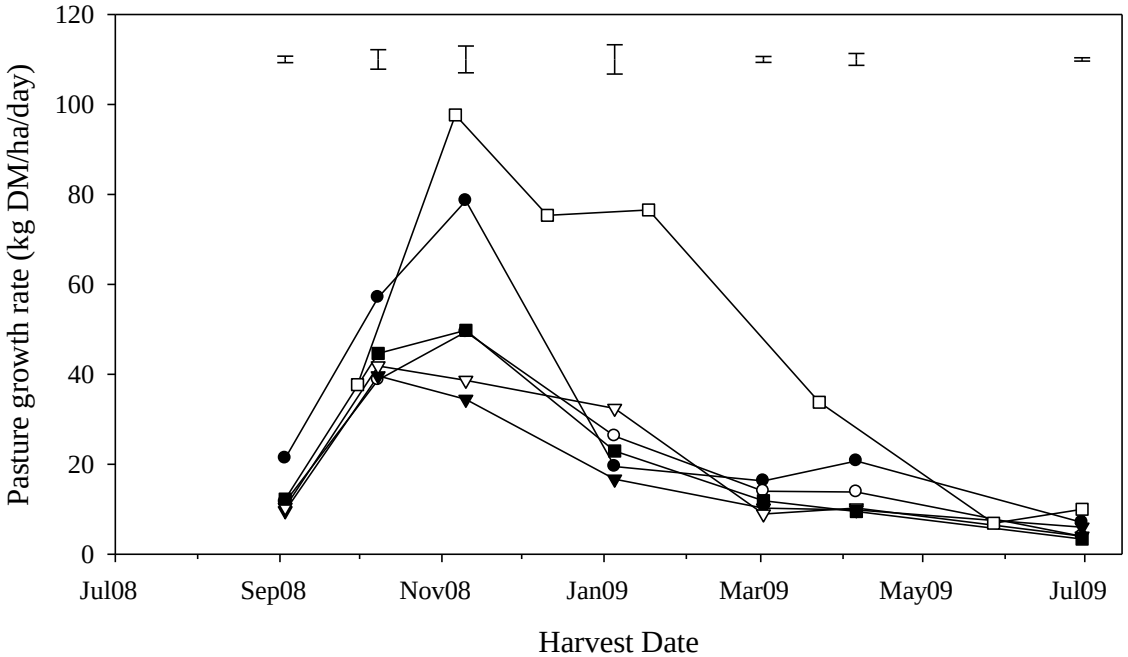

Figure 2: Daily growth rates of CF/Sub (●), CF/Bal (○), CF/Wc (▼), CF/Cc (▽), RG/Wc (■) and Luc (□) pastures at Lincoln University, Canterbury for regrowth cycles between 1 July 2008 and 30 June 2009. Mean daily growth rates of lucerne are shown for reference but were excluded from the analysis as harvests were not made at the same time as those of grass based pastures. Error bars are SEM for grass based pastures.

Figure 3 shows the accumulated pasture DM against accumulated thermal time calculated from 0.1 m soil temperatures with a base temperature of 0 ºC. For the period before water stress compromised growth the relationship was linear for all pasture combinations. In each case the fitted regression equation indicated an x-axis intercept of around 200 ºCd, which translated to 3 August 2008. This value differed from zero and this suggests that pasture accumulation during winter (from 1 July 2008) was not linearly related to temperature. This probably reflects the low pasture covers at this time with the hard autumn grazing removing herbage to below the critical leaf area index. This apparent lag phase was also reported by Fasi *et al*. (2008) for dryland pastures growing in the Lees Valley of Canterbury. This suggests further work is required to identify the mechanism responsible for the lag period, to enable the trigger point to commence linear accumulation with thermal time to enable it to be used in a predictive manner.

A feature of the thermal time approach was the consistency of response within a species. For the grass based pastures the CF/Sub pasture had the highest spring growth rate ($P<0.001$) at 5.9 kg DM $ºCd^{-1}$ which was similar to the 5.7 kg DM $ºCd^{-1}$ found for lucerne, but higher than those found for all other grass combinations (3.2 to 4.1 kg DM $ºCd^{-1}$).

For the grass based pastures the higher rate for the CF/Sub pasture led to a spring DM yield of 6,100 ± 270 kg DM ha^{-1} which was 50-90% greater ($P<0.001$) than the other grass based pastures (Figure 3). Surprisingly, the lucerne grew at a rate comparable to the CF/Sub pastures throughout the early spring growth period despite its reputation for slow early spring growth. Of note was the extended linear duration of the lucerne pastures for 400 ºCd later than grass based pastures. This led to a spring yield from this linear phase of 8,730 kg DM ha^{-1} or > 44% more ($P<0.001$) than the next highest yielding pasture (CF/Sub). This additional yield of high quality feed (Brown and Moot, 2004) would support higher live-weight gain and consequently yield more meat per hectare (Mills *et al*., 2008b) than traditional pasture combinations. Equally, the higher yield from the CF/Sub pastures supports the recommendation for this combination to be used in dryland pastures to compliment lucerne productivity (Brown and Moot, 2004; Mills *et al*., 2008a).

A feature of soils used for dryland pastures in Canterbury is their variability in depth to gravel which consequently affects soil water holding capacity. This is apparent in Figure 4 where the calculation of plant available water for a CF/Sub pasture in plot 5 of replicate 1 was 223 mm (gravels at approximately 1.0 m) compared with 340 mm for the nearby lucerne in plot 2 of replicate 1 (gravels at approximately 1.5 m). Also when analysing water over the winter-spring period in temperate regions some drainage may occur which is difficult to account for. Figure 4 also shows the water holding capacity of these soils changed markedly with depth. In the top 0.2 m the top soil had a drained upper limit of over 30% and lower limits around 8%, which are consistent with these silt loam soils (McLaren and Cameron, 1996). Below depths of

approximately 1.0 m the drained upper limit was between 10 and 15% indicating the presence of stones and a lot less silt with a consequence of lower plant available water in each layer. This variability is common amongst such soils and is one of the reasons the actual water use was measured and quantified for individual plots. The analysis requires assessment of how much water is available and also how much the plant roots can access at lower depths.

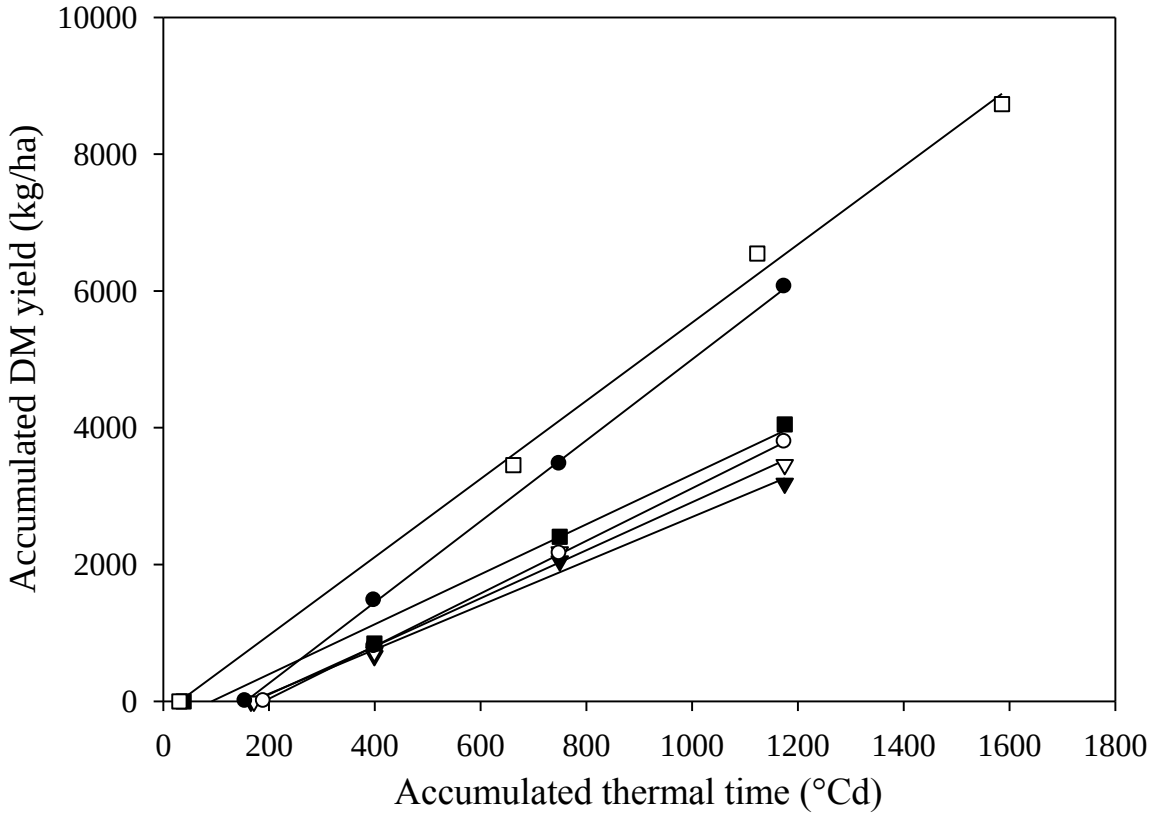

Figure 3: Dry matter (DM) accumulation from 1 July 2008 to 10 November 2008 for CF/Sub (●), CF/Bal (○), CF/Wc (▼), CF/Cc (▽), RG/Wc (■) and from 1 July 2008 to 10 December 2008 for Luc (□) pastures at Lincoln University, Canterbury against accumulated thermal time (Tt) calculated using 0.1 m soil temperature with a base temperature of 0 °C. The regression equation of:
CF/Sub was y = 5.9 (± 0.11)x-922 (± 95.5) (R^2 = 0.99),
CF/Bal was y = 3.9 (± 0.01)x-733 (± 8.6) (R^2 = 0.99),
CF/Wc was y = 3.2 (± 0.37)x-536 (± 307.0) (R^2 = 0.98),
CF/Cc was y = 3.5 (± 0.34)x-602 (± 282.0) (R^2 = 0.98),
RG/Wc was y = 4.1 (± 0.17)x-759 (± 142.0) (R^2 = 0.99) and
Luc was y = 5.7 (± 0.57)x-175 (± 679.0) (R^2 = 0.98).
Standard errors of the slope and intercept are reported in the regression equations.

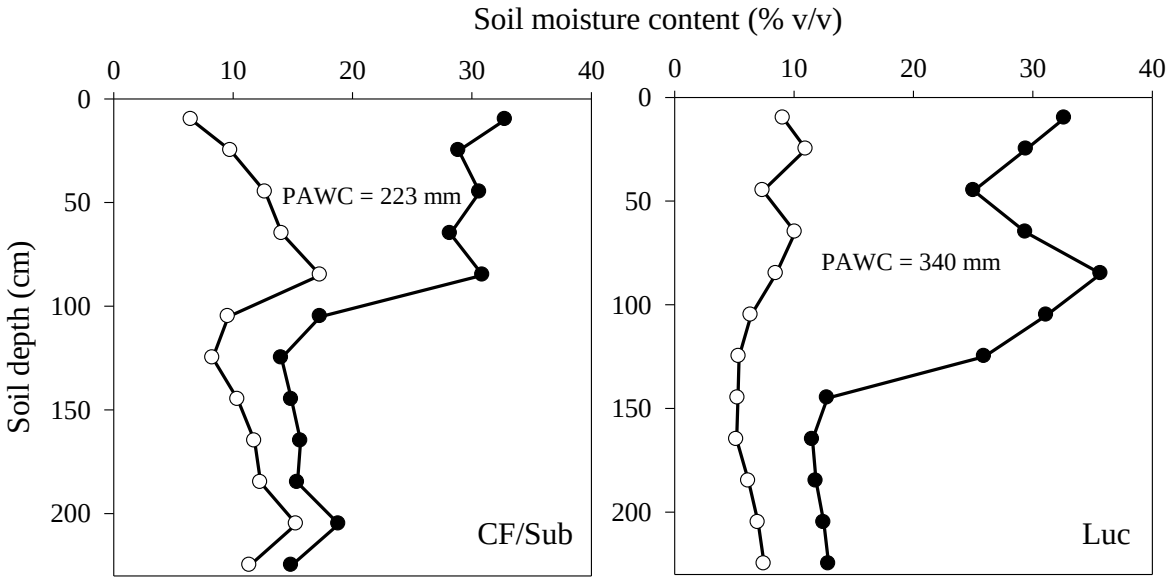

Figure 4: Water storage capacity (% v/v) for each 0.2 m soil layer from 0-2.3 m depth under a CF/Sub (plot 5) and a lucerne (plot 2) pasture grown on a variable depth Templeton silt loam soil at Lincoln University, Canterbury. Where DUL (●) is the drained upper limit and LL (○) is the lower limit to field based extraction measured from 1 July 2008 to 18 June 2009.

The higher yield of the lucerne and CF/Sub pastures (Figure 5) probably resulted from their having access to more moisture in the profile or utilising that moisture more efficiently. Specifically, lucerne produced 8,730 kg DM ha^{-1} using 310 mm of water in spring. A trend ($P<0.1$) indicated lucerne used about 60 mm more water than grass based pastures.

In contrast, the CF/Sub pastures used the same amount of water as the other grass based pastures (approximately 280 mm) but produced a yield that was 50-90% higher than other pastures. Thus, the CF/Sub used a similar amount of water in to produce more DM indicating a more efficient use of the available water to produce yield. For the lucerne pastures higher yields were produced through a combination of access to more water and greater efficiency of that water to produce DM.

The total accumulated water use in spring shows some differences among pasture species (Figure 5). The regression relationships were forced through the origin on the basis that water use and yield are intrinsically linked. Of the grass-based pastures, total accumulated water used by the CF/Wc and CF/Cc pastures in spring was < 246 mm which was less ($P<0.1$) than the 310 mm used by lucerne. The relationship between this actual water use and DM yield gave a water use efficiency of approximately 14 kg DM ha^{-1} mm^{-1} for the CF/Wc, CF/Cc, CF/Bal and RG/Wc pastures. The variation in total accumulated yield among these pastures was proportional to the additional water used. For the CF/Sub plots the total

accumulated water use was comparable to the RG/Wc pastures (approximately 280 mm) but the higher yield gave a calculated WUE of 18 kg DM ha^{-1} mm^{-1} of water used. For lucerne the WUE was 30 kg DM ha^{-1} mm^{-1} of water and it also had the highest total accumulated water use of 310 mm. This combination of a higher WUE and greater access to water, due to a deep tap root (Moot *et al*., 2008) explains the higher spring yields for the lucerne.

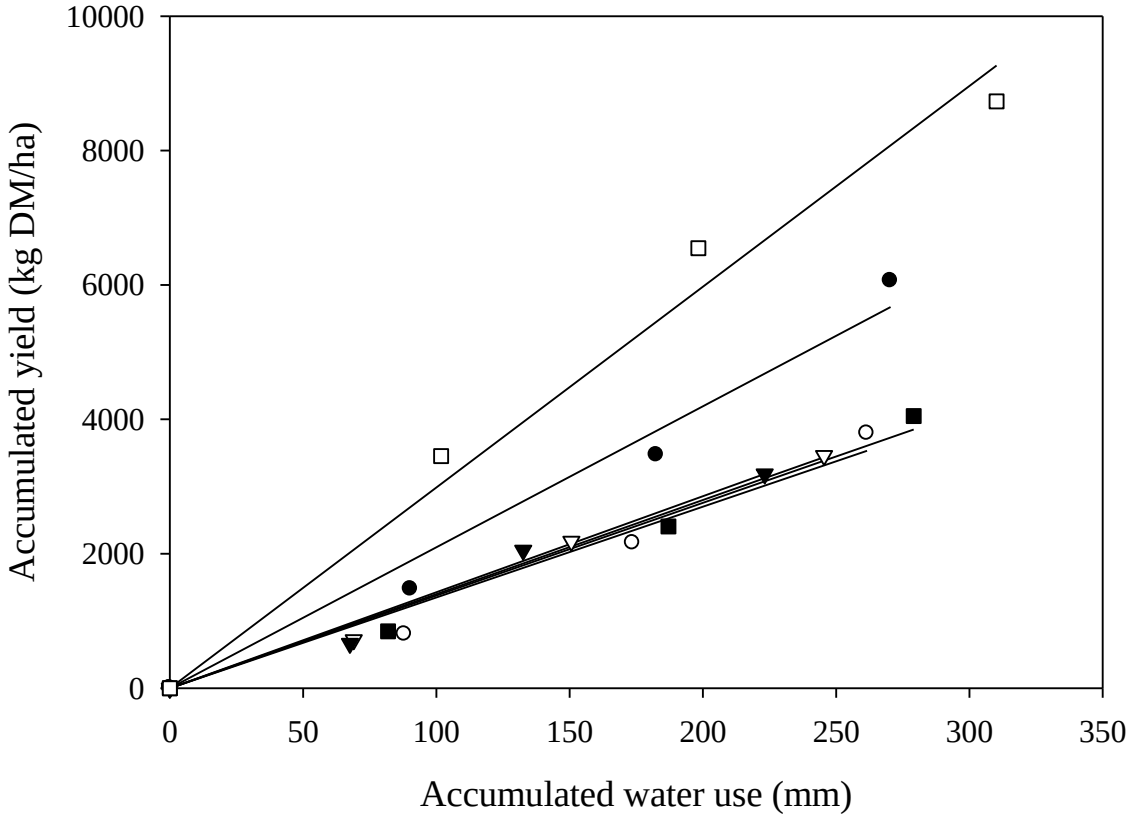

Figure 5: Relationship between accumulated yield (kg DM ha^{-1}) and water use (mm) over spring season for CF/Sub (●), CF/Bal (○), CF/Wc (▼), CF/Cc (▽), RG/Wc (■) and Luc (□) pastures. The regression equation of
CF/Sub was y = 21.0 (± 1.16)x (R^2 = 0.98),
CF/Bal was y = 13.5 (± 0.89)x (R^2 = 0.97),
CF/Wc was y = 14.3 (± 0.73)x (R^2 = 0.98),
CF/Cc was y = 14.0 (± 0.51)x (R^2 = 0.99),
RG/Wc was y = 13.8 (± 0.65)x (R^2 = 0.98) and
Luc was y = 29.9 (± 1.39)x (R^2 = 0.98).
Standard error of the slope is included for the regression equations.

These differences in spring WUE of the grass-based pastures may be explained by differences in their botanical composition which contributed to differences in the total N yield. Table 2 shows that the sown grass component of these six-year-old pastures ranged from 25% for the RG/Wc pastures to 58% for the CF/Wc. The legume component of the grass pastures ranged

from a maximum of 49% in the CF/Sub to < 20% in all other grass plots. The balance was predominantly from dicotyledonous (dicot) weed species and unsown grasses, especially in the ryegrass plots. These results show the continued decline in the ryegrass pastures and the relative superiority of the cocksfoot after seven years (Mills *et al.*, 2008a). Combining the botanical composition results and the herbage N percentage (N %) allowed the total N yield from each pasture to be determined (Table 3).

Table 2: Botanical composition of six dryland pastures at Lincoln University, Canterbury during the spring period of year 7 (2008-09). Legume content (%) in grass based pastures shows the contributions of volunteer (unsown) white clover in brackets for each treatment. For lucerne monocultures the total weed content is reported and this includes contributions from volunteer white clover, grass weeds and dicot weeds. Values may not sum to 100 due to rounding.

				Weeds (%)	
Treatment	Sown grass (%)	Legume (%)	Dead (%)	Grass	Dicots
CF/Sub	30	49 (<1)	3	17	1
CF/Bal	36	17 (17)	2	18	9
CF/Wc	58	14	3	22	3
CF/Cc	40	12 (11)	3	24	10
RG/Wc	25	16	3	43	14
Luc	-	95	<1	0	4

Table 3: Nitrogen content (% N) and corresponding N yields of the sown grass and legume components of the six dryland pastures at Lincoln University, Canterbury in spring. The sown species % N is the weighted N concentration based on botanical composition from the sown grass and legume components.

Treatment	Grass %N	Legume %N	Grass N yield (kg ha^{-1})	Legume N yield (kg ha^{-1})	Sown species N%	Sown species N yield (kg ha^{-1})
CF/Sub	3.8a	4.4	74.2a	45.3b	4.1a	119.5b
CF/Bal	3.3ab	3.0	65.0a	9.3b	3.4abc	74.3cd
CF/Wc	3.5a	4.2	74.2a	16.3b	3.6ab	91.0bc
CF/Cc	3.5a	4.8	58.3a	15.1b	3.7ab	73.4cd
RG/Wc	1.9b	3.6	24.4b	19.1b	2.4c	43.5d
Luc	-	4.0	-	288.3a	4.0ab	288.3a
Grand mean	3.2	4.0	59.3	65.6	3.5	115.0
SEM	0.30	0.68	6.66	13.1	0.34	14.45
Significance	<0.01	NS	<0.01	<0.01	<0.05	<0 .01

Note: Separations were made with Fishers' Protected LSD. Means followed by the same letter are similar at the P<0.05 level. NS = non-significant.

For all of the cocksfoot pastures the N percentage in the sown grass was between 3.3 and 3.8%. These values are consistent with those found by Peri *et al.* (2002) which were required to give at least 80% of the maximum potential

photosynthetic capacity in cocksfoot. Once values fell below 2.6% the rate of photosynthesis was severely compromised. This appears to have been the case for the ryegrass which had the lowest herbage N of 1.9% and a consequent N yield of only 24 kg N ha^{-1}. It was therefore unexpected that the total DM yield and water use efficiency of the RG/Wc pasture was similar to that of several of the cocksfoot based pastures. This suggests that the annual weed grasses (predominantly barley grass (*Hordeum murinum* L.) and *Bromus* spp.) that had invaded these pastures were producing DM at a similar rate to the cocksfoot. Without determination of the N percentage of these components it is difficult to know exactly how much N was harvested from this treatment. The total of 44 kg N ha^{-1} calculated from sown species probably underestimates the total N yield.

In contrast, the superior clover content (49%) in the CF/Sub pastures resulted in the highest total N yield of 120 kg ha^{-1} from grass based pastures. These results highlight the importance of N availability to maximise the WUE of dryland pastures. In most cases, spring DM production of dryland pastures is N limited and the highest response of yield to applied N can be expected at this time (Fasi *et al.*, 2008). The main impact of N deficiency is to reduce leaf area. Many species adjust their leaf size to maintain N concentrations above critical levels that affect photosynthesis (Lemaire *et al*., 2008). This probably explains why the herbage N percentage values are usually conservative within the range of 3-4% found in this study. On its own herbage N concentration does not reflect whether the pasture would respond to applied N.

The benefits of managing dryland pastures to maintain a legume in the system are frequently directly related to the herbage quality of feed on offer (Litherland and Lambert, 2007). Indirectly, the increased water use efficiency means each unit of water use results in a higher DM yield, particularly in spring. The additional benefit of a pure legume can be gauged from the lucerne pastures which yielded 288 kg N ha^{-1} or about 30 kg N t^{-1} DM produced. This is similar to the generalized figure for N fixation of 25 kg N t^{-1} DM produced (Peoples and Baldock, 2001). The higher value possibly represents the added input of soil N from these grazed pastures. Regardless of the source, the availability of N in spring pastures is crucial to maximise the limited water storage capacity of the soil in dryland regions. The resulting increase in water use efficiency leads to higher DM yields through a faster rate of DM accumulation per unit of thermal time before the dry summer.

Acknowledgements

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Cardinal temperatures and thermal time requirements for germination of annual and perennial temperate pasture species

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Abstract

Cardinal temperatures (base (T_b), optimum (T_o) and maximum (T_m)) and thermal time (Tt) requirements for germination of 21 temperate annual and perennial grass, legume and weed species were calculated from incubator experiments. Cardinal temperatures were defined using an iterative broken-stick linear regression model of development rate against temperature. Species specific maximum germination rates were all > 80% except for the 60% attained by 'Pawera' red clover. The maximums were stable from 5 to 20 °C with the exception of 'Arrotas' arrowleaf clover, 'Advance' tall fescue and 'Vision' cocksfoot which had < 20% germination at 5 °C. T_o was approximately 26 °C for 'Woogenellup' subterranean, 'Mihi' Persian, alsike, red and strawberry clovers but ≤ 20 °C for white clover and the other annual clover species tested. A base temperature of 0 °C was found for all species except ripgut brome (T_b = 4.0 °C) and T_m was ≥ 35 °C. Thermal time requirements for germination were generally lower for annual than perennial clovers which may reflect adaptation to avoid out of season germination. Annual weed grasses, showed rapid germination which aids their competitive ability to invade establishing pastures. Vulpia hair grass seed germination was over 95% at 25 °C and below; barley grass declined with increasing temperatures from 5 to 35 °C.

Additional keywords: growing degree days, heat units, *Bromus* spp., *Critesion glaucum, Trifolium* spp., *Vulpia myuros*

Introduction

The rate and time of germination of seeds are modulated by changes in environmental conditions and differ among years and geographic locations. To quantify germination across environments, species specific cardinal temperatures (minimum or base (T_b), optimum (T_o) and maximum (T_m)) are calculated (Angus *et al.*, 1981). The base temperature is the lowest temperature at which germination occurs, while the optimum represents the temperature at which the rate of germination is fastest. The maximum temperature is that above which no seeds germinate. These cardinal temperatures represent species specific response profiles that in ecological terms could be expected to align the time of germination and

subsequent emergence to favourable conditions for seedling growth and development. Thus, the cardinal temperatures are associated with the environmental range of each species' adaptation (del Pozo and Aronson, 2000; Alvarado and Bradford, 2002). Temperate-adapted species typically have a T_b below 4 °C (Angus *et al.*, 1981). The cardinal temperatures of several common temperate perennial pasture species have been determined previously, including perennial ryegrass and white clover (Black *et al*., 2006) but those for annuals species have not been reported.

Models which describe the pattern of germination against temperature are common and give satisfactory estimates of the thermal time requirements for a range of species (Angus *et al.*, 1981; Garcia-Huidoboro *et al.*, 1982). Thermal time (Tt) is a measure of thermal units, also known as heat units of growing degree days, accrued each day. Thermal time eliminates location-specific calendar day-based explanations. Thermal time requirements for germination have been reported for several temperate pasture legumes (Moot *et al.*, 2000; Black *et al.*, 2003; Boswell *et al.*, 2003; Lonati *et al.*, 2009). Overall, adventive annual species have a lower base temperature and/or a smaller thermal time requirement for germination than perennial species. In many cases adventive winter annual species have a lower optimum temperature than perennial species (Lonati *et al.*, 2009) which may inhibit germination of some of the seed population under warm, summer, conditions. This would prevent a 'false-break' which could generate a seedling population that subsequently dies in a dry autumn. Additional adaptations to avoid out of season germination may include hard-seededness or dormancy where the final germination percent is decreased at high temperatures (Knight, 1965).

In this study the germination requirements of a range of commercially available annual and perennial species used in dryland pastures are compared with those of some economically important winter annual grass weeds.

Materials and Methods

Three replicates of 50 seeds per cultivar were placed on moist standard blotting paper in Petri dishes in unlit incubators at constant set temperatures from 5.0 to 35.0 °C (± 0.5 °C) in 5 °C increments (Table 1). Supplementary data for selected species were also gathered at other temperatures (4, 12, 22, 28 and 40 °C) using the same experimental procedures. Seed of commercial cultivars was sourced directly from retailers (Table 1) while the winter annual weed grass seed was from hand harvested plants from an experimental block at Lincoln University, Canterbury. Species and cultivars within species are referred to as species and indicative species responses are given unless individual cultivars produced different results.

None of the seeds were coated or treated except 'Bolta' balansa clover (*Trifolium michelianum* Boiss.), which had a lime-based coat. This was washed from the seed immediately before the experiment began. Actual incubator temperatures were recorded using a 'Hobo 4-Channel External' (Onset Computer Corporation) data logger calibrated against a reference thermometer prior to the experiment. Legumes were scarified between sheets

of 80-grit sandpaper, but no other pre-conditioning treatments were used. Distilled water was added as required to ensure moisture was non-limiting for germination. Petri dishes were re-randomised on a single incubator shelf after each count. Seeds were defined as germinated when the emerged radicle was twice the length of the testa. Germinated seeds were measured and removed once or twice daily for up to 19 days or until five days after the last seed in a dish had germinated. The number of days to reach 75% of final germination was derived from a generalised logistic curve, using Genstat Tenth Edition (10.1.0.72) (Lawes Agricultural Trust) (Equation 1).

Equation 1 $$y = a + C/(-B^{(x \times -M)})$$

Where y is germination percentage, a is the lower asymptote, C is the upper asymptote which represents the final germination percentage, B depends on the values of y(0), x is time after sowing and M is the point of inflection which represents the time of maximum germination rate when 50% of the final germination has been achieved. Curves were initially fitted to individual replicates but ANOVA of coefficients showed no significant differences so data were pooled and curves fitted across replicates.

In this paper, species and cultivars within species are treated as being indicative of species responses unless individual cultivars produced different results.

Data analysis

Data for each species were plotted as the reciprocal of the duration (in days) to 75% germination against temperature, where a linear relationship between the rate of germination and temperature indicated that use of the thermal time model was appropriate (Angus *et al.*, 1981). Broken stick linear regressions were performed using an iterative process (Draper and Smith, 1998) to find the point of inflection as an indication of the optimum temperature. Least squares regression analysis was then used for the positive linear portion of the line where:

Equation 2 $$Rate = b_0 + b_1 x$$

The regression coefficients b_0 and b_1 were related to T_b (base temperature) and Tt (thermal time), when $T_b \geq T \leq T_o$, by Angus *et al.* (1981) as:

Equation 3 $$T_b = -b_0 / b_1$$

Equation 4 $$Tt = 1/b_1$$

Calculated T_b was considered to be different from 0 °C if the confidence interval (95%) did not include 0 °C. Thermal time was also calculated with T_b = 0 °C, by forcing the regression equations through the origin, to allow direct comparison among species (Moot *et al.*, 2000).

The maximum temperature at which germination occurred (T_m) was calculated as the x-axis intercept from a second linear regression for the decreasing portion of the regression at temperatures between the optimum (T_o), at which germination rate is the fastest, and T_m. Germination results were used to determine the final germination percentage and were analysed by ANOVA with means separated by least significant difference (5 %).

Table 1: Species and cultivars evaluated and incubator temperatures used.

Functional Group	Common name	Botanical name	Cultivar	Temperatures	Source
Annual clovers	Arrowleaf	*Trifolium vesiculosum*	Arrowtas	5, 10, 15, 20, 25, 30, 35	DLF
	Balansa	*T. michelianum*	Bolta	5, 10, 15, 20, 25, 30, 35	Agricom
			Frontier	5, 10, 12, 15, 20, 22, 25, 30, 35	Agricom
	Persian	*T. resupinatum*	Laser	5, 10, 15, 20, 25, 30, 35	PGGW
			Mihi	5, 10, 15, 20, 25, 28, 30, 35, 40	PGGW
			Nitro	5, 10, 12, 15, 20, 22, 25, 30, 35, 40	PGGW
	Subterranean	*T. subterraneum*	Dalkeith	4, 5, 10, 15, 20, 25, 30	Lincoln University
			Leura	5, 10, 15, 20, 25, 30, 35	AgResearch
			Mt Baker	5, 10, 15, 20, 25, 30, 35	Lincoln University
			Woogenellup	5, 10, 15, 20, 25, 28, 30, 35	Lincoln University
Perennial clovers	Alsike	*T. hybridum*	MAI302	5, 10, 15, 20, 25, 30, 35	Lincoln University
	Red	*T. pratense*	Pawera	5, 10, 15, 20, 25, 30, 35	PPGW
	Strawberry	*T. fragiferum*	Onward	5, 10, 15, 20, 25, 30, 35	Lincoln University
	White	*T. repens*	Demand	5, 10, 15, 20, 25, 30, 35, 40	PGGW
			Nomad	5, 10, 15, 20, 25, 28, 30, 35	Lincoln University
Annual grass weeds	Barley grass	*Critesion glaucum*		5, 10, 15, 20, 25, 30, 35	Lincoln University
	Goosegrass	*Bromus mollis*		5, 10, 15, 20, 25, 30, 35	Lincoln University
	Ripgut brome	*Bromus diandrus*		5, 10, 15, 20, 25, 30, 35	Lincoln University
	Vulpia hair grass	*Vulpia myuros*		5, 10, 15, 20, 25, 28, 35	Lincoln University
Perennial grasses	Cocksfoot	*Dactylis glomerata*	Vision	5, 10, 15, 20, 25, 30, 35, 40	Lincoln University
	Perennial ryegrass	*Lolium perenne*	Commando	5, 10, 15, 20, 25, 30, 35	PGGW
	Tall fescue	*Schedonorus phoenix*	Advance	5, 10, 15, 20, 25, 28, 30, 35	PGGW
		syn. *Festuca arundinacea*	Flecha	5, 10, 15, 20, 25, 30, 35	PGGW

Results

The rate and maximum cumulative germination percentage differed with temperature (Figure 1, 2). For annual legume species (Figure 2a), final germination percentage was constant between 5 and 20 °C and decreased to zero as temperatures increased. For example, the final germination percentage for 'Bolta' balansa clover (*Trifolium michelianum*) was 91 (± 2.5)% from 5 to 20 °C and then decreased linearly to 37% at 35 °C.

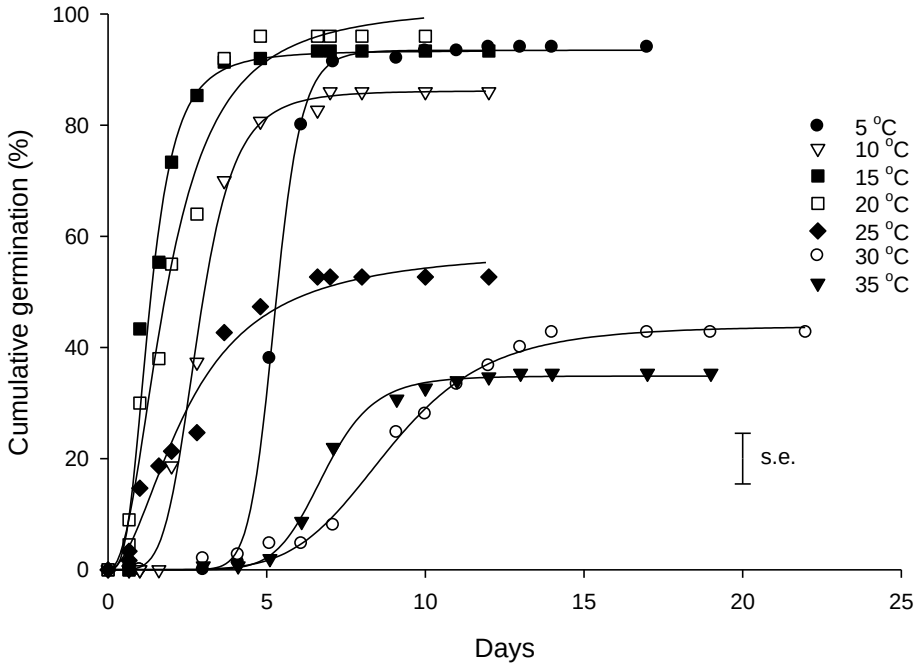

Figure 1: Cumulative germination of 'Bolta' balansa clover at 10 constant temperatures. Note: s.e. is maximum standard error for the final germination percent.

For perennial legumes (Figure 2b), the final germination percentage was constant across the entire temperature range and only declined at 35 °C. Maximum germination was only 65% for 'Pawera' red clover (*T. pratense* L.) compared with > 80% for all other species.

The maximum germination of the three annual grasses each responded differently to temperature (Figure 2c). The highest germination for barley grass (*Critesion glaucum* Steud.) was at 5 °C, it then decreased to 0% at 35 °C. For both vulpia hair grass (*Vulpia myuros* L.) and ripgut brome (*Bromus diandrus* Roth), the maximum germination percentage was > 90% from 5 to 25 °C, but declined above 25 °C in vulpia hair grass and 30 °C in ripgut brome.

The commercial perennial grasses all had their maximum germination at between 10 and 30 °C, but in 'Vision' cocksfoot (*Dactylis glomerata* L.) the maximum germination was only 60%.

The number of days to 75% germination differed among species and for temperatures (Figure 1). For

'Frontier' balansa clover, the time to 75% germination was less than five days at temperatures between 5 and 25 °C and more than six days at ≥ 30 °C (Figure 3).

The rate of germination increased as temperatures increased up to a temperature optimum and then decreased beyond that optimum (Figure 4). For 'Frontier', the germination rate increased linearly from approximately 20% germination per day at 5 °C, up to approximately 45% per day at 15 °C. Germination rate then decreased linearly to < 10 % per day at 40 °C. This pattern of linear increase and decrease in the rate of germination was uniform across species (except for 'Commando' perennial ryegrass (*Lolium perenne* L.) Figure 4) and was used to define the cardinal temperatures. Germination rate of 'Commando' increased from 4 to 10 °C but was then constant to 30 °C and 0 at 35 °C.

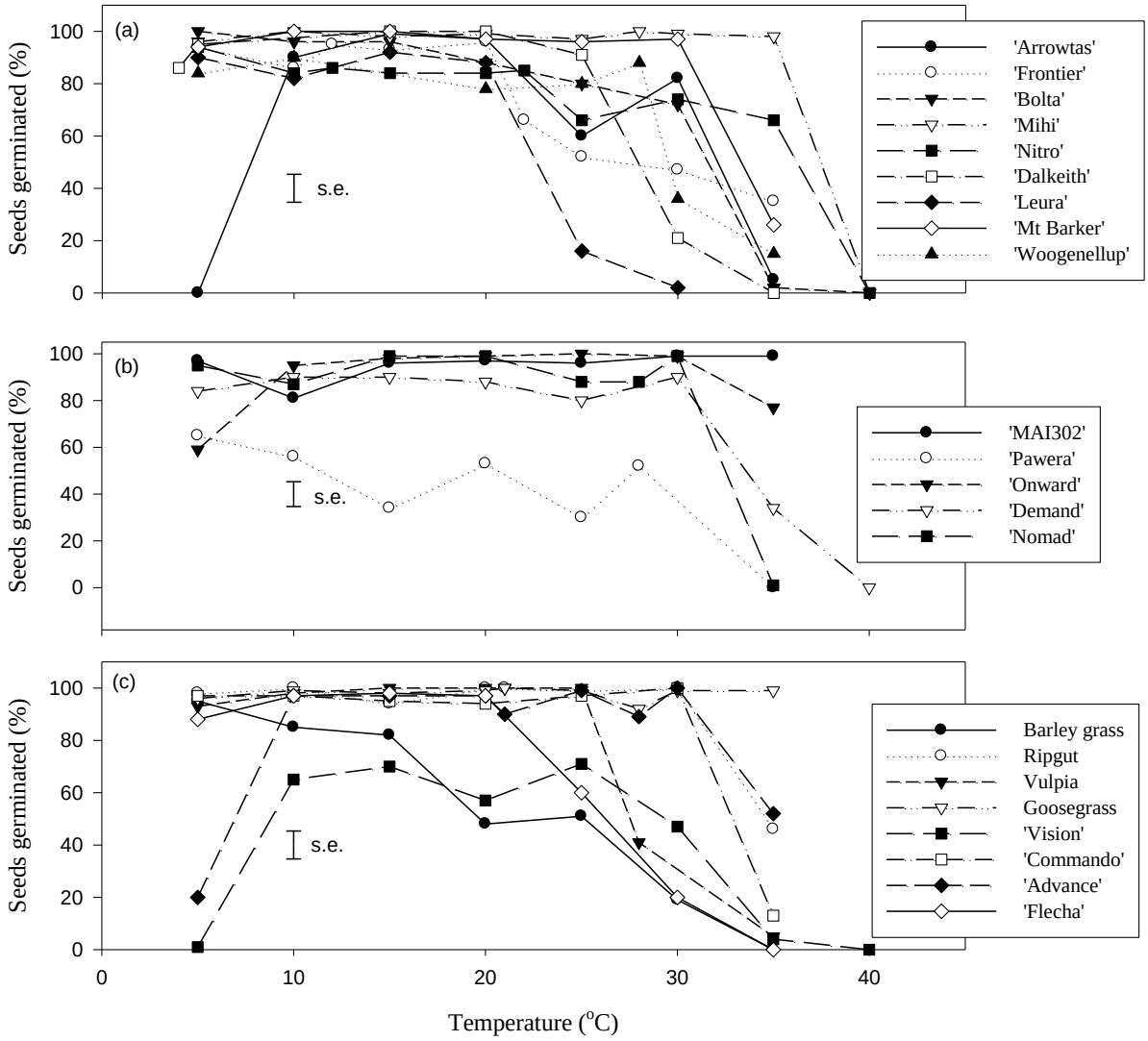

Figure 2: The maximum cumulative germination (%) of seeds from a range of temperate annual (a) and perennial (b) legumes and (c) grasses at different constant temperatures.

From regression analysis (Equation 2) the base temperature (T_b) for germination was not different from 0 °C (± 95% confidence intervals) (Table 2). The optimum temperature (T_o) for arrowleaf (*Trifolium vesiculosum* Savi), balansa, subterranean (*T. subterraneum* L.) and Persian (*T. resupinatum* L.) clovers was 12 to 20 °C except for 26 °C for 'Woogenellup' sub. clover and 25 °C for 'Mihi' Persian clover. For the perennial clovers, T_o was 18-20 °C for white clover (*T. repens* L.) and approximately 25 °C for the other three species. The T_o for ripgut brome was 10 °C compared with 16 °C for vulpia hair grass and 25-30 °C for barley grass and goosegrass (*Bromus mollis* L.).

When T_b was set to 0 °C, thermal time requirements for germination for the annual clovers arrowleaf, balansa and Persian ranged from 18-31 °Cd and the subterranean clovers ranged from 41-62 °Cd (Table 3). The perennial clovers ranged from 35-48 °Cd. For germination of the weed grasses, ripgut brome required 29 °Cd, vulpia hair grass 39 °Cd and barley grass, 77 °Cd.

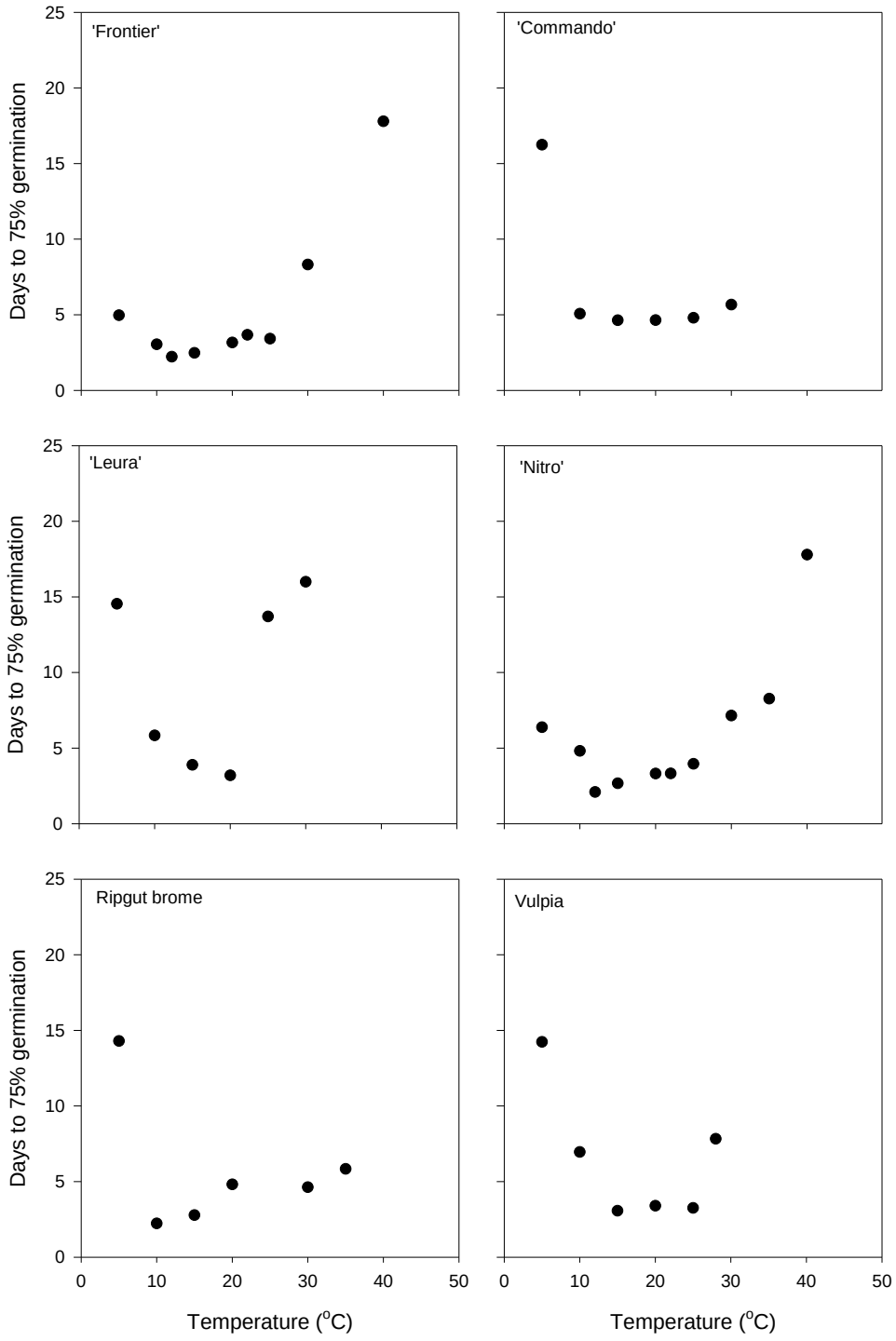

Figure 3: Days after sowing to 75% of final germination for ‘Frontier’ balansa clover, ‘Commando’ perennial ryegrass, ‘Leura’ subterranean clover, ‘Nitro’ Persian clover, ripgut brome and vulpia hair grass at different temperatures.

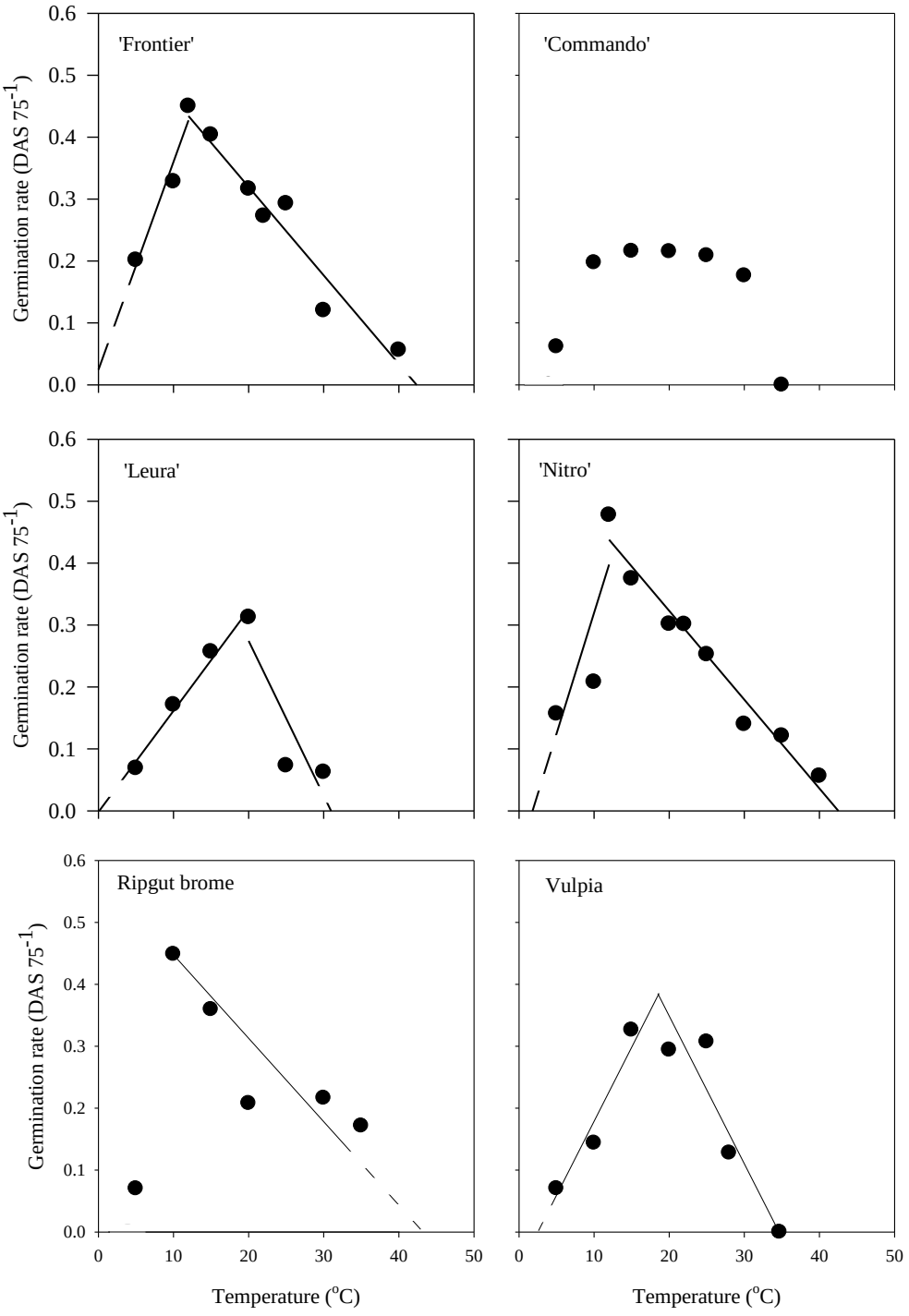

Figure 4: Germination rate of 'Frontier' balansa clover, 'Commando' perennial ryegrass, 'Leura' subterranean clover, 'Nitro' Persian clover, ripgut brome and vulpia hair grass at different temperatures.

Table 2: Estimates of base (T_b), optimum (T_o) and maximum (T_m) temperature and total thermal time (Tt) requirement for germination of a range of temperate pasture species.

Functional Group	Species	Cultivar	T_b (°C)	± 95% CI	T_o (°C)	R^2 (%) ($\leq T_o$)	T_m (°C)	± 95% CI	R^2 (%)($\geq T_o$)	Tt (°Cd)
Annual legumes	Arrowleaf	Arrowtas	3.7	6.6	14	96	30.3	7.1	72	12
	Balansa	Bolta	1.4	4.9	14	95	38	6.5	84	26
		Frontier	-0.7	14.2	12	95	42.4	6.4	92	30
	Persian	Mihi	0	9.1	25	92	34.2	4.3	88	22
		Nitro	1.8	16.4	12	66	41.9	6.3	97	26
	Subterranean	Dalkeith	0.7	1.1	19	100	31.9	8.1	93	39
		Leura	0.1	3.9	20	98	31	13.4	78	61
		Mt Baker	0.4	4.6	20	98	41.6	18.9	76	45
		Woogenellup	1.3	2.2	26	99	>35	-	-	52
Perennial	Alsike	MAI302	0	7.1	~25	90	~40	-	92	35
legumes	Red	Pawera	2.4	8.7	25	87	>28	-	99	46
	Strawberry	Onward	1.1	6.6	26	94	>35	-	86	47
	White	Demand	-0.6	6.6	20	93	43	3.4	99	49
		Nomad	0.2	8.1	18	93	31.5	3.7	96	38
Annual weed	Barley Grass		1	14.2	~25	72	~35	-	-	95
grasses	Goosegrass		-3.7	9.7	>30	94	>35	-	-	72
	Ripgut brome		4	0.2	10	100	43.9	29.9	79	13
	Vulpia hair grass		3.4	7.6	16	94	34.3	17	73	52
Perennial grasses	Cocksfoot	Vision	-0.8	6.5	18	96	48	14.7	89	181
	Perennial Ryegrass	Commando	3.2	5.9	10-30	87	>30	-	-	52
	Tall fescue	Advance	-	-	15-30	-	>35	-	-	-
		Flecha	4.6	6.2	17	80	35.8	3.8	97	38

Note: '-' = insufficient data to allow derivation, CI is confidence interval for the x-axis intercept. R^2 = coefficient of variation for linear regression.

Table 3: Summary of thermal time to 75% germination for temperate climate species at sub-optimal temperatures when T_b = 0°C.

Functional Group	Species	Cultivar	Tt (°Cd)	Minimum R^2 (%)
Annual legumes	Arrowleaf clover		18	86
	Balansa clover		29	95
	Persian clover	Mihi	20	89
		Nitro	31	64
	Subterranean clover		50	98
Perennial legumes	Alsike clover		35	98
	Red clover		48	87
	Strawberry clover		47	93
	White clover		40	91
Annual weed grasses	Barley grass		77	68
	Goosegrass		63	89
	Ripgut brome		29[1]	80
	Vulpia hair grass		39	87
Perennial grasses	Cocksfoot		167	95
	Perennial ryegrass		66	82
	Tall fescue		60	69

Note: [1]Ripgut brome had no statistical justification (95% CI) for re-analysis using T_b = 0 °C. R^2 = coefficient of variation for linear regression (sub-optimum temperatures).

Discussion

The germination rate increased linearly as temperature rose from T_b until reaching a maximum at T_o (Figure 4). The thermal time concept summarised the time from sowing to germination at different temperatures between T_b and T_o to be expressed as a single coefficient. Base temperatures for all cultivars were ≤ 4.7 °C and, except for ripgut brome, none were different from 0 °C. This, and previous work (Moot *et al.*, 2000; Lonati *et al.*, 2009) suggests that, without evidence to the contrary, future work with temperate pasture species could assume a Tb of 0 °C for germination.

As temperatures rose above T_o, germination rate decreased linearly to zero at T_m. The strong linear relationships confirm the appropriateness of using the linear response models when estimating thermal time at sub- and supra-optimal temperatures (Lonati *et al.*, 2009). Of note, 'Commando' perennial ryegrass and 'Advance' and 'Flecha' tall fescue had an 'optimum temperature range' for germination which had a plateau across several temperatures. These responses were in line with the expected physiological response to temperature (Angus *et al.*,

1981). The linear portions on either side of the range were used to calculate the thermal time requirements for germination and therefore may not conform to results seen in the field.

The thermal time requirements calculated here for germination of the control grass species perennial ryegrass and cocksfoot were 20% shorter than those previously published (Moot *et al.*, 2000). This reflects the time for shoot initiation as defined by the different methodologies. Moot *et al*. (2000) followed the International Seed Testing Association (ISTA) descriptions of germination with normal seedling development requiring a shoot and root compared with radicle-only observations used here.

The observed differences in germination rate among cultivars of Persian clover were unexpected. In most cases germination rate is genetically determined and, without specific selection pressure, uniform within a species (Moot *et al.*, 2000). However, it is possible that these cultivars may be different sub-species. 'Nitro' Persian clover (*Trifolium resupinatum* var. *resupinatum*) had a maximum germination rate of 0.47 and is derived from the prostrate, hard seeded sub-species *resupinatum* (Wurst *et al.*, 2004). Other cultivars from this sub-species include 'Prolific' and 'Kyambro'. 'Mihi' had a maximum germination rate of 1.2 and is believed to have been selected from the erect, later flowering subspecies *majus*. These cultivars could act as adventives and be over-sown in hill and high country environments or areas with brief germination windows to colonise a site that may not be accessible to slower germinating species.

The maximum germination percentage of the annual legumes began to decline at lower temperatures than for the perennial legumes. The typical lifecycle of these annual legumes starts with germination in autumn as moisture increases. Vegetative growth continues through winter and spring before reproductive structures are formed and seed is set in spring/summer. Annual legumes avoid the drought conditions of their native environment as seed (Sulas *et al.*, 2000). The decline in germination percent at higher temperatures (> 20 °C) was consistent with previous reports (Lonati *et al*. 2009), and may be an ecological adaptation to limit seedling losses due to out of season germination (false break) when moisture is insufficient to sustain growth. This adaptation is referred to as high temperature dormancy (Knight, 1965) and, along with other strategies such as hard seed coats, may be a more important mechanism in hot dry environments such as Australia or the Mediterranean, than in New Zealand. At Lincoln University, in the dry (660 mm average annual rainfall) coastal region of Canterbury, maximum daily soil surface temperatures peak in February at approximately 38 °C, with average daily soil temperatures of 22 °C (Wilson *et al.*, 1995). Current estimates show mean air temperatures rising 3 to 4°C in the next 50 years (Salinger, 2003). This will potentially compromise germination of these annual species. Cultivars such as 'Dalkeith', with relatively low temperature onset for high temperature dormancy, reach their maximum germination potential later in the autumn, when temperature had decreased to 25 °C and below. The implications for future cultivar

suitability, requires analysis of temperature and rainfall responses under different climate change scenarios.

The perennial legumes did not show the same decline in final germination percent as the annual legumes until temperature were > 30 °C. Perennial legumes, by definition, persist throughout the summer and use other drought avoidance mechanisms such as tap roots (Thomas, 2003). As such, selection pressure within a population for summer germination avoidance may have been reduced or dealt with via other mechanisms such as hard seed.

The annual grasses germinate in the autumn and vegetative growth occurs through winter and spring before seed is set in spring/summer to avoid drought. Barley grass showed a steady decline in germination percent from 95% at 5 °C to no germination at 35 °C. Ultimate germination and seedling populations of barley grass would therefore be limited by warmer summer temperatures. Of the perennial grass species, only 'Flecha' tall fescue showed a drop in germination below 30 °C.

Among the legumes, tetraploid 'Pawera' red clover and subterranean clover had higher thermal time requirements for germination than the other legumes with lighter seeds. Larger seeds, within a species seed lot have a competitive advantage as seedlings because they are able to utilise a greater supply of stored carbohydrate in the endosperm to promote initial leaf development (Black, 1957). However, among species, smaller seeds tend to germinate more rapidly (Murali, 1997; Norden *et al.*, 2009) and at lower temperatures compared with heavier seeds (Easton and Kliendorfer, 2008). Lighter seeded species may be adapted to environments where there is only a brief period when conditions are suitable for germination (Norden *et al.*, 2009). Arrowleaf, balansa and Persian clovers are native to the Mediterranean region, including Iran, Turkey and Israel, where autumn rainfall can be brief and sporadic (del Pozo and Aronson, 2000; Dear, 2003). Rapid germination in this environment may allow these species to establish before the perennial species and confer a competitive advantage. However, germination prior to consistent autumn moisture can lead to a 'false strike', where seedlings do not receive sufficient rain to survive (Taylor *et al.*, 1984), and crop failure in winter annuals such as balansa clover (Monks *et al.*, 2008).

Of the annual weed grasses, ripgut brome required the least thermal time for germination. For example, with a mean daily temperature of 10 °C, ripgut brome would fulfil the 13 °Cd (T_b = 4 °C) requirement for germination in a little over two days. The germination rate of ripgut brome at 10 °C was 0.45. That is, 45% of agronomic germination (75% of seed germinated) occurred per day at 10 °C. The germination rate of ripgut brome, and vulpia hair grass (39 °Cd), was double that of 'Commando' perennial ryegrass, 'Flecha' tall fescue and 'Vision' cocksfoot, which required between 58 and 167 °Cd. These annual weed species would therefore germinate more rapidly than perennial grasses and are on a par with the small seeded annual legumes.

The potential to germinate rapidly in a pasture system gives weed species a competitive advantage at establishment, populating the bare space and capturing

incoming radiation. This would, in turn, compromise the establishment of other autumn sown or re-establishing species. It may also explain how they can quickly invade pastures after summer drought. Cultural and chemical management that reduce these grass weed seed populations at establishment may be required to enable control particularly for slow establishing dryland pasture species like cocksfoot and tall fescue.

Conclusion

A base temperature of 0 °C was found for all species except ripgut brome (T_b = 4.0 °C). Thermal time requirements were generally lower in annual than perennial clovers which may reflect adaptation to avoid out of season germination. Of the weed grasses, ripgut brome and vulpia hair grass both germinated as quickly as perennial ryegrass which means they are likely to compete at establishment for limited resources so pre-emergence control is recommended.

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Preliminary study of the spatial distribution of sweet potato storage roots

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Abstract

Sweet potato (*Ipomoea batatas*) plants produce adventitious roots that may swell to form localised carbohydrate storage structures as the growing season advances. These sections of the root are known as storage roots and are the part commonly harvested for human consumption. A storage root is a morphologically defined segment of an adventitious root, characterised by its distinctive lateral growth, which represents a region of marked meristematic activity and carbohydrate deposition. The storage root is attached to the sweet potato plant at the proximal end by a variable length of relatively unthickened root, known as the root stalk. At the distal end of the storage root, the unthickened root continues to extend, performing typical root functions such as absorption of water and minerals, and plant anchorage. The length of the root stalk is generally considered cultivar-specific and is used as a formal morphological feature in cultivar descriptors. This study demonstrates that the root stalk length of a cultivar may be modified by manipulating the sweet potato propagule and its interaction with the environment. The region in which the storage function occurs can be moved down the length of an adventitious root, increasing the root stalk length at its proximal end. This may be useful in developing plug-based propagation systems that eliminate the coiling of storage roots initiated within the physical constraints of a plug tray.

Additional keywords: *Ipomoea batatas*, lignification, plug propagation, root stalk

Introduction

The sweet potato (*Ipomoea batatas* (L.) Lam.), also known as kumara, is a herbaceous dicotyledonous perennial plant grown in New Zealand as an annual root crop. Factors influencing the *in situ* growth and spatial distribution of its roots are an important area of study. The plant is propagated on a commercial scale through the use of unrooted cuttings (Coleman, 1972), so all initial roots are adventitious in derivation (Esau, 1977). Sweet potato stem cuttings readily develop adventitious roots, possibly due to the presence of pericycle and endodermal tissue in the stem

(Onwueme, 1978; Caveness *et al*., 1983). Lateral roots arise directly from the adventitious roots, significantly increasing the overall root volume with primary, secondary and occasionally tertiary laterals (Weaver and Bruner, 1927).

The initial adventitious roots originate from pre-formed root primordia that are commonly visible on the aerial stem at the time of cutting (Hahn and Hozyo, 1983; Belehu *et al*., 2004). These root primordia typically form in pairs either side of the stem just below the point of petiole insertion (Togari, 1950). Sweet potato plants have a 2/5 phyllotaxis, meaning that leaves in the same vertical plane are separated by two revolutions of the stem comprising five leaves inserted in a spiral (Onwueme, 1978; Huamán, 1992). As the leaves are arranged in this spiral pattern, the adventitious roots derived at the nodes are effectively arrayed in three dimensional space without mutual interference. Further adventitious roots may develop within the callus tissue that forms on the buried end of the transplanted stem cutting (Sirju-charran and Wickham, 1988).

Swollen edible storage roots develop from the initial adventitious roots, primarily those pre-formed at nodes prior to transplanting rather than those initiated later in the stem-end callus. A storage root is a length of adventitious root that forms a localised carbohydrate storage structure. It is morphologically defined by its distinctive lateral growth, which represents a region of marked meristematic activity and carbohydrate deposition. Storage roots are the principal carbohydrate storage organ in sweet potato. Storage root growth begins with the deposition of carbohydrates at the distal end of the developing storage root and then proceeds upward to the proximal end (Kays *et al*., 1982). A relatively unthickened root stalk attaches the proximal end of the storage root to the plant's stem, while at the distal end the unthickened fibrous root continues down into the soil, performing typical root functions such as absorption of water and minerals, and plant anchorage. Both the root stalk and fibrous root delimit the storage root, and may become lignified as the storage section develops (Wilson, 1982).

The width of a storage root is due to the contribution of cells from two distinct types of cambia. In a cross sectional view, the normal vascular cambium within a developing storage root eventually forms a circle, with xylem forming on the inner face gradually displacing the cambium outward, while phloem forms to the outside (Esau, 1977). The secondary xylem also contains a large proportion of parenchyma storage cells. However, anomalous cambia are a common characteristic in sweet potato storage roots and occur within various tissue types. The anomalous cambia may form around protoxylem groups, the central metaxylem cell, within secondary xylem derived from the vascular cambium, within xylem derived from previous anomalous cambia, around protophloem groups, or even independently of vascular groups (Artschwager, 1924; Wilson and Lowe, 1973). The anomalous cambia mainly develop in the parenchyma cells around individual secondary xylem vessels or vessel groups, producing a few tracheary elements (xylem) towards the vessels, a few sieve tubes (phloem) and laticifers

(latex ducts) away from the vessels, and considerable storage parenchyma in both directions. So phloem elements may form within tissue that originally differentiated as xylem tissue (Esau, 1977). The relative importance of the different cambia is cultivar-specific. Storage roots thickened primarily by the activity of the normal vascular cambium tend to be uniformly narrow along their length while the involvement of anomalous cambia leads to more globular storage roots (Wilson, 1982).

A root developmental series based on root diameter can be broadly predicted. The first formed adventitious roots tend to have a pentarch or higher polyarch stele anatomy (McCormick, 1916; Wilson and Lowe, 1973) and may develop into 'fibrous roots' (< 5 mm diameter), then 'pencil roots' (< 15 mm diameter) and finally into 'storage roots' (> 15 mm diameter). It should be noted that roots may change anatomically from a pentarch or hexarch structure to tetrarch along their length (Wilson, 1982). The vascular structure of later-formed adventitious roots tends to be tetrarch, and they are developmentally limited to the early categories such as fibrous roots or possibly pencil roots.

Any event that limits carbohydrate deposition, or the cambial activity associated with development of a fully formed storage root, will temporarily or permanently obstruct the progress of a root along the developmental series (Togari, 1950; Kays, 1985). Some environmental switches are reversible, for example exposure of a root system to light inhibits storage root formation until the root is returned to the dark (Tsuno and Fujise, 1965; Hozyo and Kato, 1976). While the capacity of a plant to form storage roots is not permanently impaired by limited anoxic soil conditions (Chua and Kays, 1981; King, 1985), exposure to prolonged oxygen deficiency in the root zone, through waterlogged or high bulk density soils, can permanently disrupt cambial activity through lignification of the vascular stele (Togari, 1950; Watanabe *et al*., 1968; Ravi and Indira, 1996). Permanent fibrous roots, rather than those going through a transitory stage, are incapable of further lateral growth as lignification of the vascular stele permanently impairs the ability of the cambium to provide secondary thickening (Wilson and Lowe, 1973). Permanent pencil roots have a limited carbohydrate storage function as the stele may be only partially lignified, allowing some secondary lateral thickening (Wilson, 1970).

The effect of propagation system on carbohydrate distribution to plant components has been discussed previously (Lewthwaite, 1999). This study examines the location of root carbohydrate storage, with reference to storage root stalk length. It represents a preliminary contribution to a more comprehensive investigation into the location and development of sweet potato carbohydrate storage structures.

Materials and Methods

Sweet potato sprouts were produced by bedding storage roots of the cultivar 'Owairaka Red' in trays of commercial potting mix in an unheated glasshouse. The sprouts produced were passed through various pre-planting treatments to determine their effect on crop establishment and growth (Table 1). The treated sprouts were transplanted into a commercial sweet potato field at

Dargaville, New Zealand, on 28 November 1997 and thoroughly watered in by a tractor-drawn tanker.

The soil at the field site consisted of Kaipara clay, to which superphosphate (NPK 0-10-0) had been broadcast (1 t ha^{-1}) 6 months prior to transplanting. One month before planting muriate of potash (NPK 0-0-50) at 0.5 t ha^{-1} and urea (NPK 46-0-0) at 0.1 t ha^{-1} were broadcast and incorporated. The soil was sampled on the day of transplanting with the following analysis: phosphorus 74 g ml^{-1}, potassium 1.83 me 100 g^{-1}, calcium 18.9 me 100 g^{-1}, magnesium 3.08 me 100 g^{-1}, sodium 0.20 me 100 g^{-1}, cation exchange capacity 31.3 me 100 g^{-1}, available nitrogen 86 kg ha^{-1}, pH 5.9, and a volume:weight ratio of 0.95 for dried ground soil.

Weed control was by hand weeding and application of Gramoxone® at 0.5 l ha^{-1} (paraquat dichloride, 25% active ingredient), 30 days after transplanting (Lewthwaite and Triggs, 2000).

The field experiment was laid out in a modified-alpha row and column design (Williams and John, 1989), comprising 48 plots arranged in a rectangular array of 12 rows and 4 columns. There were 16 treatments each with 3 replicates, and each plot consisted of 4 rows of plants with only the 2 middle rows being harvested. The harvested portion of each plot was 3.5 m long by 1.5 m wide and contained 20 plants arranged in 2 rows of 10 plants, at a 30 cm within-row plant spacing. Plants at either end of the plot were discarded so plots were fully buffered, leaving 16 datum plants in each plot.

Storage roots (above 15 mm in diameter) were hand harvested on 20 January 1998 (53 days after transplanting). Storage root stalk length was measured at full extension, from the point of stalk attachment on the underground stem to the shoulders of the storage root. Stalks of any storage roots broken during harvest or with poorly defined storage root shoulders were not measured. Of all the storage roots produced, 84% had their stalk length measured. The root stalk length data was analysed using the GenStat®: ANOVA procedure (with and without storage root number as a covariate).

Storage root stalk samples were fixed in formalin-acetic acid-alcohol (FAA). The FAA solution consisted of formalin (13 ml), glacial acetic acid (5 ml) and 50% ethanol (200 ml). Sections for lignin staining were immersed overnight in 50% ethanol prior to sectioning at approximately 90 μm, using a vibratome. Lignin was stained using acidified phloroglucin (Sass, 1951).

Table 1: Sweet potato cv. 'Owairaka Red', plant propagule treatments.

Treatment	Description
Control	Sprouts of commercial size (30 cm long, with 6 nodes), transplanted with 4 nodes inserted into the soil the day following cutting
Held-1	As for the control, but held for 3 days under moist conditions at ambient temperature prior to transplanting
Held-2	As for the control, but held for 6 days under moist conditions at ambient temperature prior to transplanting
Held-3	As for the control, but held for 9 days under moist conditions at ambient temperature prior to transplanting
Sand-1	As for the control, but held for 3 days with 4 nodes inserted into river sand prior to transplanting
Sand-2	As for the control, but held for 6 days with 4 nodes inserted into river sand prior to transplanting
Sand-3	As for the control, but held for 9 days with 4 nodes inserted into river sand prior to transplanting
Anti-1	As for the control, but with leaves dipped in an anti-transpirant solution (Vaporgard® at 2% v/v) just prior to transplanting
Anti-2	As for the control, but with leaves dipped in an anti-transpirant solution (commercial fish oil (NPK 5-1-1) at 1% v/v) just prior to transplanting
Start-1	As for the control, but watered in with 200 ml sprout^{-1} of monopotassium phosphate (NPK 0-52-34) in a 1% w/v solution
Start-2	As for the control, but watered in with 200 ml sprout^{-1} of monoammonium phosphate (NPK 12-61-0) in a 1% w/v solution
Mould	As for the control, but transplanted into a protective groove formed along the top of the soil ridge, to reduce exposure
Size-1	Small sprouts (4 nodes) with 1 node inserted into the soil the day following cutting
Size-2	Small sprouts (4 nodes) with 2 nodes inserted into the soil the day following cutting
Size-3	Small sprouts (4 nodes) with 3 nodes inserted into the soil the day following cutting
Plug	Small sprouts (3 nodes) with 1 node inserted into 45 ml plugs, 23 days before transplanting

Results and Discussion

The number of storage roots produced under the various treatments at 53 days after transplanting differed significantly ($P<0.01$), so a covariate analysis of stalk length on storage root number was conducted. However, any apparent covariate effect was due solely to the high numbers of storage roots and long stalk lengths within the plug treatment alone. As there was no significant relationship between storage root number and stalk length across the other 15 treatments, a standard ANOVA was used. The treatments Start-1 and Size-2 produced storage root stalk lengths just significantly longer than the control ($P<0.05$). However, the plug treatment produced much longer storage root stalks ($P<0.001$), on average over twice the length of the control treatment (Figure 1). By selectively staining transverse sections of storage root stalk and storage root tissue for lignin, it was demonstrated that there was greater lignification in the stalks relative to tissue at active storage sites.

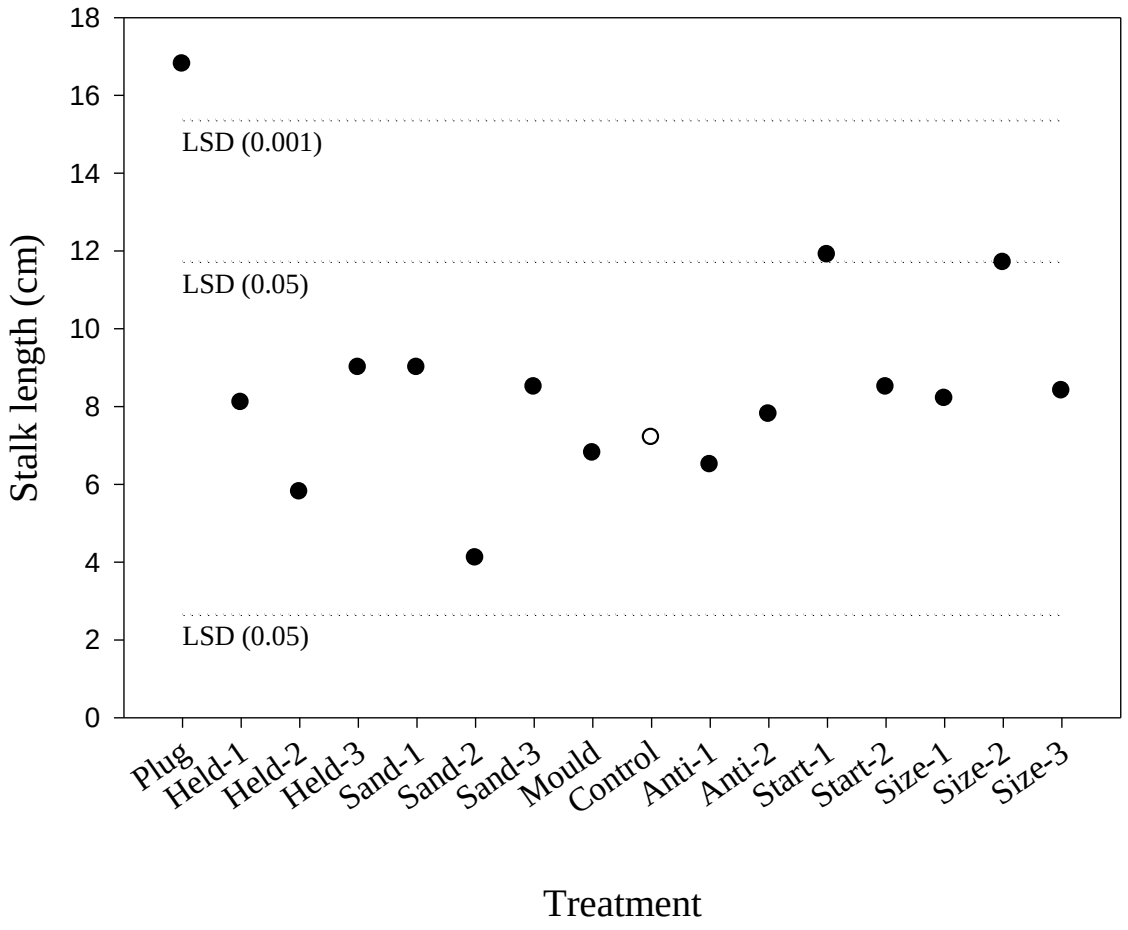

Figure 1: The average length of sweet potato cv. 'Owairaka Red' storage root stalks under various transplant treatments, following 53 days of field growth. The open circle represents the control treatment. Least significant differences (LSD) relative to the control are shown at 0.1 and 5% levels.

Interest in the conservation and utilization of international plant resources has led to the development of systematic descriptor lists for a wide range of plant species (Gotor *et al*., 2008). For sweet potato germplasm various characterisics are considered useful, allowing identification of specific cultivars and the classification of cultivars by individual morphological traits (CIP *et al*., 1991). A cultivar's storage roots may be classified *in situ* by their arrangement on the underground stem, depending on the relative proximity of their point of attachment, with states ranging from a closed to extremely dispersed storage root cluster. A further characteristic is storage root stalk length, where a 10-point scale is used, ranging from the complete absence of a stalk where storage root attachment to the underground stem is sessile, to very long root stalks (> 12 cm) (CIP *et al*., 1991). The predominant New Zealand cultivar 'Owairaka Red' typically has root stalks which are considered short (2-5 cm) on the sweet potato descriptor scale (CIP *et al*., 1991). However, in this experiment longer root stalks developed. Although the length of the root stalk is generally considered cultivar specific and is used as a formal morphological characterisation feature, this study demonstrates that root stalk length may be profoundly influenced by the interaction of the sweet potato propagule with its environment.

Sweet potato plug transplants have become an area of research interest in the last decade, both as a potential means to propagate the crop (Lewthwaite, 1999; Lewthwaite and Triggs, 1999; Tateishi and Murase, 2000; Islam *et al*., 2002; Islam *et al*., 2006) and as a research tool (Afreen-Zobayed *et al*., 1999; Zobayed *et al*., 2004). There have been reports that sweet potato storage roots initiated during plug transplant production may grow on in a coiled state to become abnormally shaped in the field (Islam *et al*., 2002; Islam *et al*., 2006). However, this is not consistent with local experience (Lewthwaite and Triggs, 1999). In this trial, the plug treatment did not produce abnormal storage roots due to lignification (Wilson and Lowe, 1973) of the roots coiled within the plug. Only the unlignified extensions from these roots, developing outside the plug volume, had the capacity for a storage function. This process effectively moved the storage function down the root's length, leaving an extended root stalk (Figure 1). Storage root formation occurred at the same soil depth for all the treatments, as the stalks in the plug treatment were coiled. Root lignification in this trial was a natural consequence of particularly warm, and dry, seasonal conditions (Figure 2), especially in the ridged soil profile. However, artificially contrived root lignification may provide a method for relocating storage root initiation sites.

Sweet potato roots are categorised as feeder, pencil, or storage roots, depending primarily on root thickness but also on their anatomy (Kays, 1985). These categories define roots by their most developed state, but under-represent the complexity within an individual adventitious root, which may exhibit all three states simultaneously. As demonstrated by this study, lignification is a mechanism that may delimit the specific location and degree of carbohydrate storage along the length of an individual root. That lignification

may act in a highly localised way is borne out by examination of comprehensively conjoined roots, one component classified as pencil and the other storage, both roots confined to simultaneous growth and adjacent positions within the soil (S.L. Lewthwaite, unpubl.). When the tissues of these conjoined roots are stained with acidified phloroglucin, the pencil component consistently shows a high degree of lignification relative to the storage component.

The spatial distribution of storage roots *in situ* is an important issue for sweet potato production. Storage roots that are widely dispersed within the soil ridge may be exposed to light, pathogens, pests, or be damaged by harvesting. Sweet potato phyllotaxis is significant to the production of well-shaped storage roots, as demonstrated by the mutual interference of roots when fasciated stem transplants are used for propagation. Finally, an understanding of the effect of anoxic soil conditions on root lignification is critical to optimising sweet potato propagation, yield and quality.

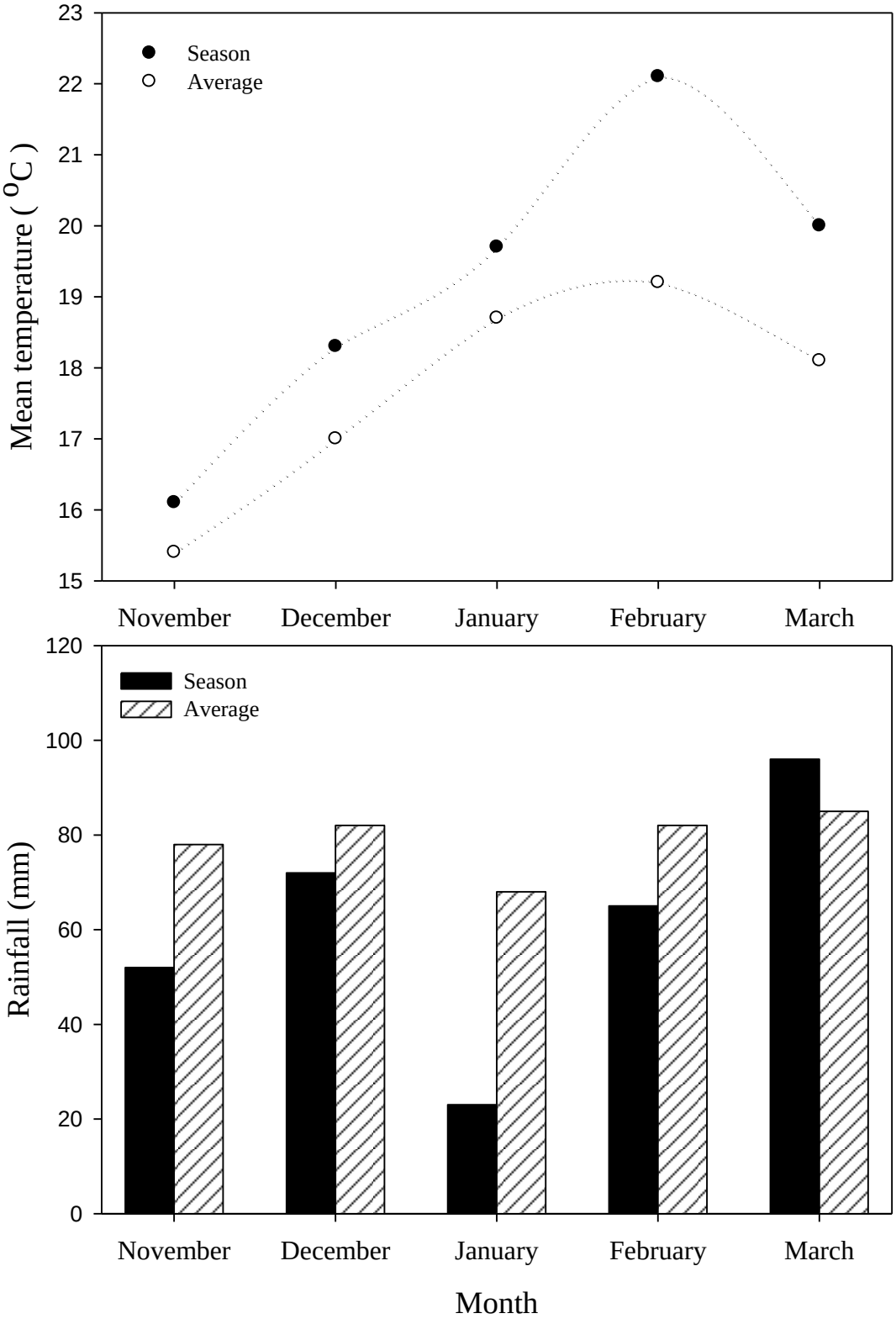

Figure 2: Mean monthly temperature (°C) and monthly rainfall (mm) at Dargaville in the 1997-1998 growing season, contrasted with long term averages (50-55 years). Data courtesy of the National Institute of Water and Atmospheric Research Ltd.

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Thermal control of disease in carrot seed crops

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Abstract

Alternaria radicina is a soil- and seed-borne fungal pathogen of carrot, which initially causes an infection on the lower leaves/petioles and eventually black rot of the carrot root. The effects of thermal treatments (flaming and steaming) were first investigated in commercial carrot seed fields in Canterbury, New Zealand in September 2006. A tractor mounted burner and a steamer were driven at 1.7, 2.3 and 2.7 km h^{-1} over carrot plants, destroying the infected carrot foliage. Plants regrew to normal size within 60 days, with no effect on their overall dry matter accumulation. Foliage infection was initially reduced by the treatments, but by three months after treatment, disease incidence was similar to that of the control. Steaming significantly reduced ($P \leq 0.05$) black rot disease ratings on carrot roots but flaming did not. Steaming was investigated again in the following season, using the same speeds but with two different application dates (5 June and 20 July 2007). Treated plants took 80 days to recover their growth, and again there were no adverse effects on overall dry matter accumulated after this period. As before, foliage disease ratings were initially reduced but were similar to the untreated control by 3-4 months after treatment. Steaming at 2.3 km h^{-1} and 2.9 km h^{-1} in the first week of June gave better control of black rot ($P \leq 0.05$) than all other treatments but did not reduce carrot seed infection by *A. radicina*, which probably resulted from wind borne inoculum from surrounding external sources.

Additional keywords: *Alternaria radicina*, flaming, steaming, carrot seed, black rot, *Daucus carota*

Introduction

About 50% of the world's carrot (*Daucus carota* L.) seed is grown in Canterbury, New Zealand (Keast, 2006). Carrot is a biennial crop and requires 14 months to complete its life cycle in a 'seed-to-seed' production system. *Alternaria radicina* is a seed- and soil-borne fungal pathogen of carrot seed crops (CABI/EPPO, 1998) which is most prevalent on older plants and senescing leaf tissues which touch the soil surface (Meier *et al*., 1922; Soteros, 1979; Pryor, 2002). In winter, young carrot plants become susceptible to *A. radicina* infection, as senescing leaves touch

surrounding contaminated soil. The pathogen produces conidia on necrotic and senescent leaf tissue, which are then spread by wind, overhead irrigation, and splashing rain water (Neergaard, 1977; Pryor, 2002), causing petiole infection and leaf blight as well as seed infection (Grogan and Snyder, 1951; 1952; Tylkowsa, 1992).

In summer the black necrotic lesions produced on petioles provide avenues for the infection of root crowns and tap roots which then develop black rot symptoms on the shoulder regions (Grogan and Snyder, 1952; Farrar *et al*., 2004). Wind-borne conidia then move through the crop and infect umbels. After harvest of the carrot seed crop, *A. radicina* can survive in dead plant debris and its conidia can remain viable for more than 8 years in the soil in the absence of a host plant (Maude and Shuring, 1972; Maude and Bambridge, 1991 (cited in Farrar *et al*., 2004).

Heat has long been used as a method to control weeds (Atkinson, 1995) and pests and diseases (Hardison, 1976; Skoglund *et al*., 1999).

Thermosanitation can control some soil-borne diseases by killing the resting structures of the pathogens, although the effectiveness depends on the heat that can be applied and depth to which it can penetrate the soil (Newhall, 1955; Bollen, 1985). The use of heat to control pathogens in seeds and harvested crops (e.g. carrot roots) has been effectively applied for many years (Farrar *et al*., 2004), but its ability to control foliar pathogens has been little investigated.

This paper reports the effect of flaming and steaming treatments, applied in winter, with the aim of destroying foliar borne inoculum of *A. radicina*, thereby potentially reducing black rot development in commercial carrot seed crops.

Materials and Methods

First Year Experiment (2006)

Four commercial hybrid carrot seed fields in mid-Canterbury were chosen for thermal trials. Flaming treatments were applied at all sites, while steaming treatments were applied at two sites. As flaming was originally the major method being investigated, the flaming treatments were replicated four times, and for observation, the steaming treatments twice. Each experimental plot was 15 x 3 m. The tractor driven flame burner and steamer were described by Merfield (2006) and Merfield *et al*. (2009). Treatments, which were applied on 6 September 2006, were tractor speeds of 1.7, 2.3 and 2.9 km h^{-1}. The plants not heat treated in each farm were used as controls.

The effects of flaming and steaming on carrot plant regrowth were assessed by visual observation of treated plants and untreated plants at regular intervals. Carrot plant dry matter accumulation was determined in December 2006. Whole plant samples were collected from a randomly selected 1 m row section. The plants were washed under tap water to remove soil and other debris, cut at the base of the shoot with a sharp knife, and the roots and shoots weighed separately. Both roots and shoots were dried at 70 °C to constant dry weight; this was determined by removing the samples from the oven every day and weighing. From the final dry weights, total dry matter weight (kg ha^{-1}) was calculated.

Assessment of black rot disease on roots

In January 2007, 10 carrot plants were uprooted from each plot and washed under tap water. Air dried tap roots were visually assessed for black rot infection, using a 0 to 4 rating scale where: 0 = healthy; 1 = 1-25% of the shoulder region blackened due to black rot; 2 = 26-50% of the shoulder region blackened due to black rot; 3 = 51-75% of the shoulder region blackened due to black rot; 4 = > 75% of the shoulder region blackened due to black rot.

Assessment of foliage disease

Ten carrot plants per plot were tagged and inspected for foliage infection every month after application of thermal treatments (until the difference between treated and untreated plants became non-significant) using a 1 to 10 rating scale where: 1 = no infection; 2 = infection on lower leaves; 3 = infection on lower stem and lower leaves; 4 = infection on lower stem and lower leaves senesced; 5 = infection on middle stem and leaves; 6 = infection on middle stem and all leaves; 7 = infection on upper stems and all leaves; 8 = leaves senesced and infection on upper stems; 9 = leaves senesced and most of the stem diseased and 10 = leaves senesced and all of the stem diseased (Merfield, 2006).

Second Year Experiment (2007)

The steaming trial was repeated in 2007 at one mid-Canterbury site, using the same tractor speeds as in 2006, but two different dates (5 June and 20 July, 2007). Disease and dry matter weight assessment were made as before.

Seed infection was assessed at maturity, in April 2008, using 10 primary umbels hand harvested from each plot. Seeds were dried at 30 °C to 8% seed moisture. Seed was then hand removed from dried umbels and cleaned by hand-rubbing to remove spines. Seeds were then thoroughly mixed. Hands were washed in 70 % ethanol between the cleaning of each sample to reduce the chance of contamination. Seed infection was assessed by plating 100 carrot seed $plot^{-1}$ onto a semi-selective agar (ARSA) (Pryor *et al*., 1994), and incubating in the dark at 27 °C for 14 days. After incubation, seeds which had produced distinguishable black hyphae of *A. radicina* were counted as infected seeds and those that did not as non-infected (Pryor *et al*., 1994).

Statistical Analysis

Data were checked for normal distribution, by the Shapiro-Wilk Test using Genstat Edition 12, and were square root transformed where required. Statistical analysis was performed on raw data when normally distributed and on transformed data when not normally distributed. For the latter, back transformed results are presented.

In 2006, as each experimental site had a different growing environment and carrot hybrids black rot infection data at each site or foliage infection at each assessment month at each site were analysed separately.

In 2007, foliage infection data at each assessment date, for each treatment application, were separately analysed using one-way ANOVA because the assessment dates for each treatment time differed. However, black rot infection data were analysed using two-way ANOVA to determine individual as well as interactions between treatments. The effect of the two treatment timings on

black rot infection was analysed through a paired t-test. Treatment means were separated by using Fisher's LSD at a 5% significance level. All statistical computations used Genstat Edition 9.

Results

First Year Experiment (2006)

The flaming treatment burnt carrot foliage immediately while steaming darkened it initially, but after 24 hours the foliage developed a similar burnt appearance. Carrot plants regrew foliage such that, by 60 d after the thermal treatment, growth was similar for both flame and steam treated and control plants. By December there was no significant difference (P>0.05) in total carrot dry matter between treated and untreated plots (data not presented) which suggested that flaming and steaming had no adverse effects on plant productivity. Although not measured, there were no visual differences in time of flowering or umbel density.

Infection of new foliage was initially reduced by the treatments (P≤0.05), but by three months mature leaves had a similar disease incidence to the untreated controls (Figure 1, 2). At all three speeds, steaming reduced (P≤0.05) black rot disease ratings on carrot roots but flaming did not (Figure 3).

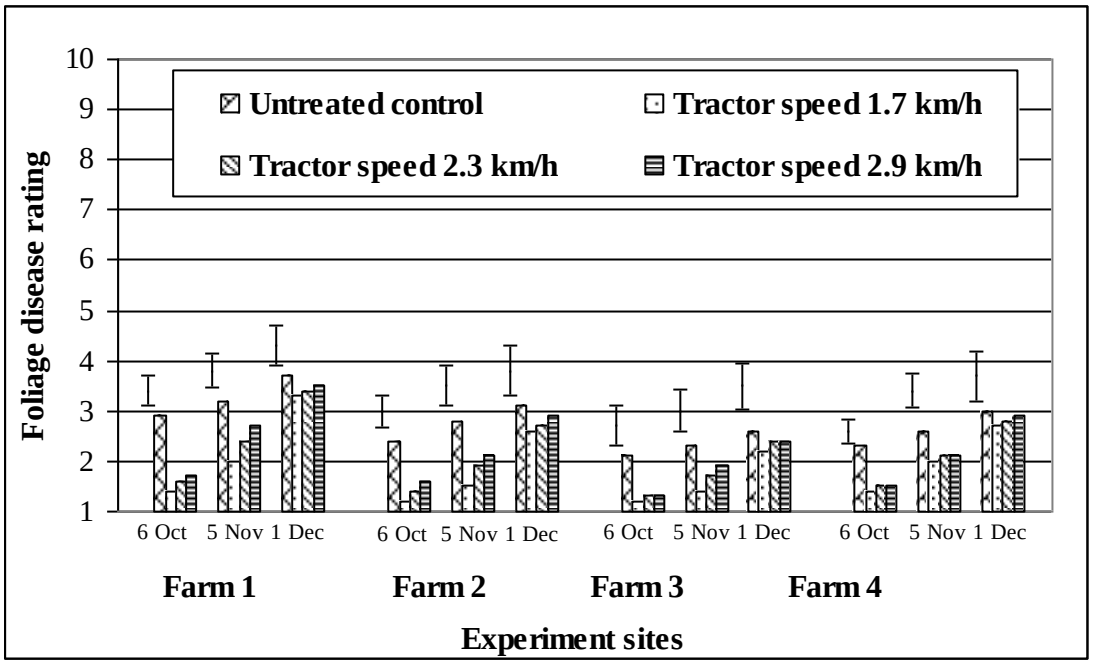

Figure 1: Effect of flaming on carrot foliage infection caused by *A. radicina* in 2006. Statistical analysis at each farm at each assessment date was done separately. Bars indicate LSD values (P≤0.05).

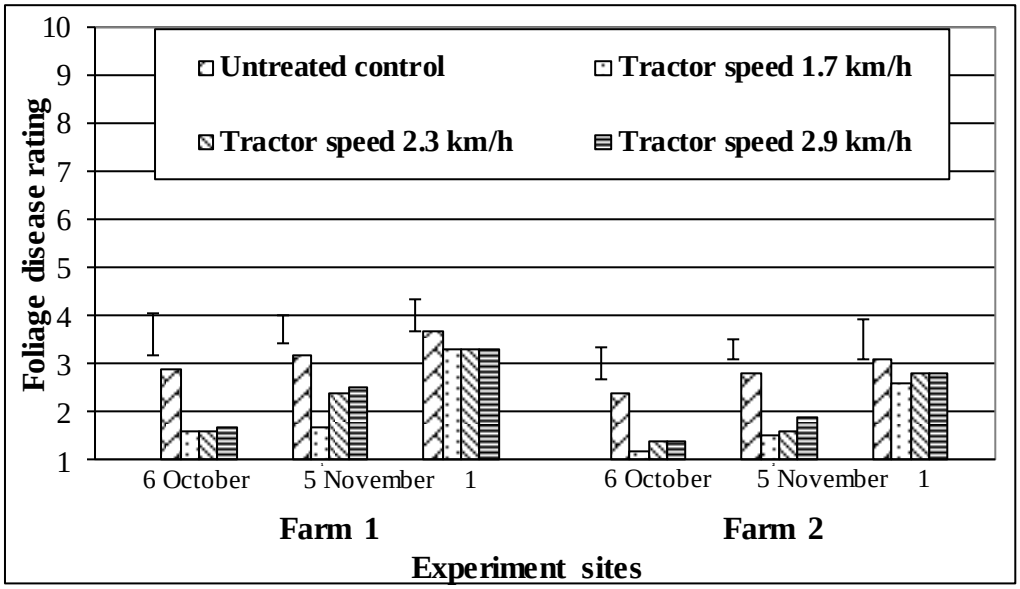

Figure 2: Effect of steaming on carrot foliage infection caused by *A. radicina* in 2006. Statistical analysis at each farm at each assessment date was done separately. Bars indicate LSD values (P≤0.05).

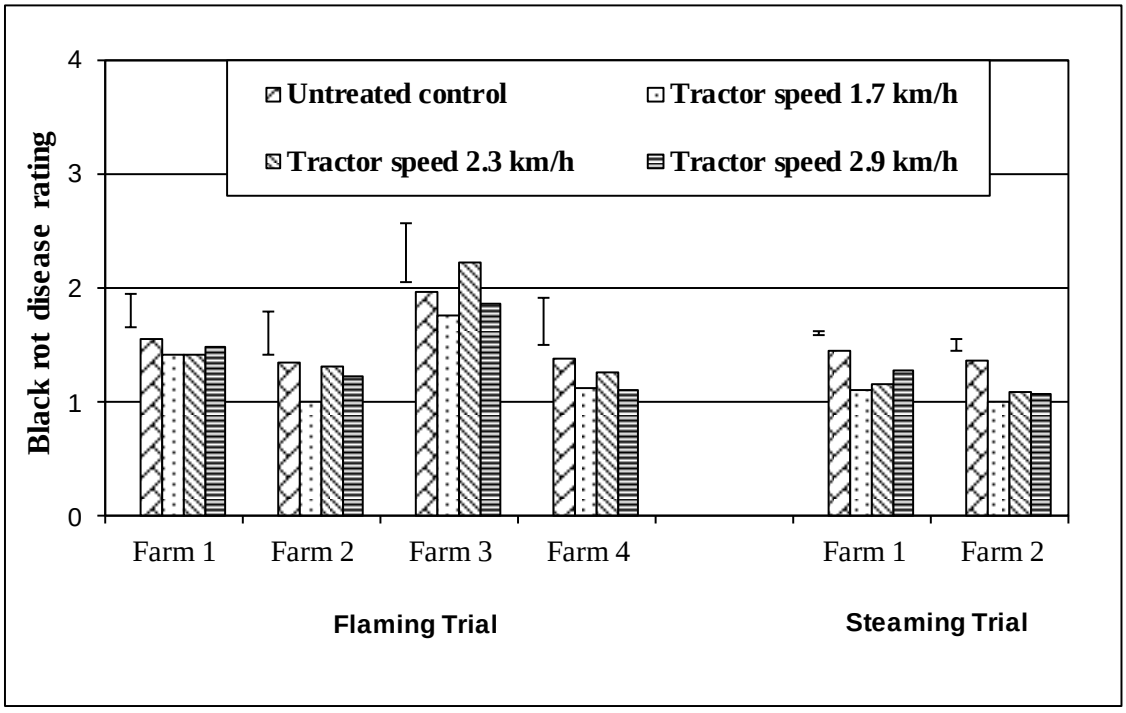

Figure 3: Effect of flaming or steaming on subsequent black rot disease expression in carrot roots in January 2007. Statistical analysis at each farm was done separately. Bars indicate LSD values (P≤0.05)**.**

Second Year Experiment (2007)

Treated carrot plants took 80 days to recover their growth, and again there was no adverse effect on dry matter production when assessed in December (data not presented), which confirmed that steaming has no adverse effect on normal carrot crop growth.

Foliage disease ratings were again initially reduced by steaming ($P \leq 0.05$; Figure 4). Carrot plants treated in the first week of June had a significantly lower disease rating for three months compared with only two months for the third week of July application (Figure 4).

Steaming at 2.3 km h^{-1} and 2.9 km h^{-1} in June 2007 gave significantly ($P \leq 0.05$) better control of black rot disease compared with steaming at 1.7 km h^{-1} and the control (Table 1). Steaming in June gave a significantly ($P \leq 0.05$) better disease control than steaming in July. Steaming had no significant effect ($P \leq 0.05$) on the percentage of seeds (mean = 14%) infected by *A. radicina* (data not presented).

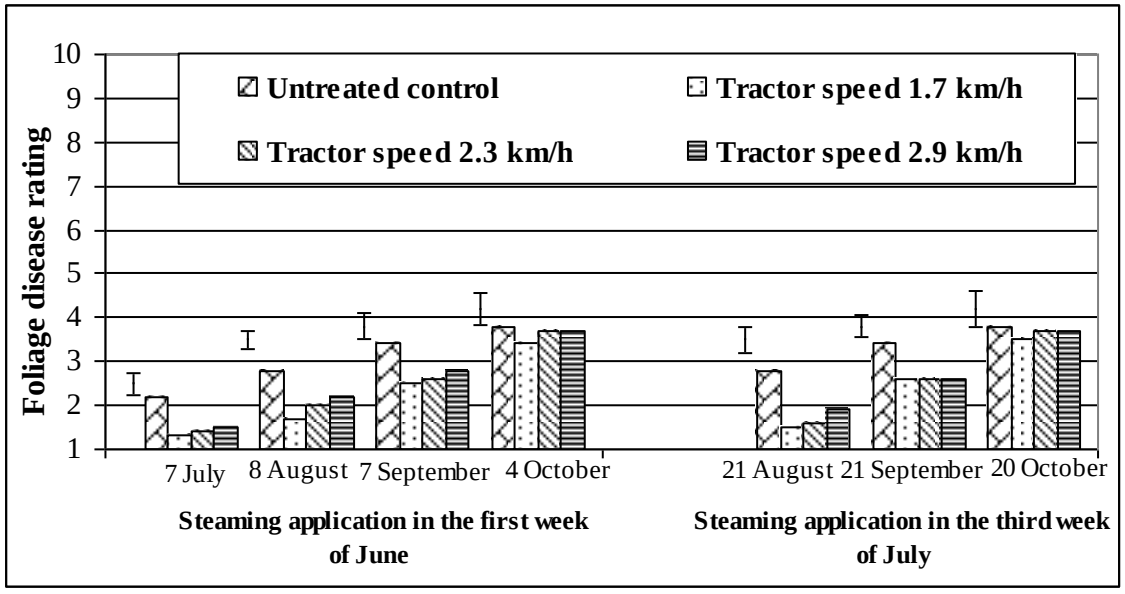

Figure 4: Effect of date of steaming on carrot foliage infection caused by *A. radicina* in 2007. Statistical analysis at each assessment date at either treatment application date was done separately. Bars indicate LSD values ($P \leq 0.05$).

Table 1: Effect of steaming on black rot disease in carrot roots assessed in January 2008.

Speed of steamer	Time of steaming*		Mean black rot disease rating at different steamer speeds**
	First week of June 2007	Third week of July 2007	
Control	1.33 c	1.33 c	1.33 h
1.7 km h^{-1}	1.32 c	1.32 c	1.32 h
2.3 km h^{-1}	1.07 a	1.30 c	1.18 k
2.9 km h^{-1}	1.16 ab	1.26 bc	1.21 k
Mean disease rating at different times***	1.21 s	1.30 t	

*For comparison of interaction of steamer speed by time of application.
**For comparison of mean value of disease rate at different speeds of steamer.
***For comparison of mean values of disease rating at different times.
Mean values followed by a different letter are significantly different according to the LSD test ($P \leq 0.05$).

Discussion

Merfield (2006) applied thermal treatments (flaming and steaming at 2 km h^{-1}) to pot grown (from seed) two month old carrot plants artificially inoculated with *A. radicina*, *A. dauci* and *Cercospora carotae* and reported complete elimination of all of the pathogens. In the field, in both seasons, flaming and steaming both significantly reduced, but did not eliminate *A. radicina* for two to three months after treatment. However, subsequent infection levels did not differ from that of the untreated plants. This was not unexpected, as thermally treated plots were surrounded by the remainder of the commercial crops, from which inoculum would have spread.

Merfield (2006) demonstrated that once carrots had reached the 6 leaf stage (approximately 8 cm in height) they survived thermal treatment, because as rosette-forming plants, both the apical and axillary meristems are protected by petioles that are often thickened. Merfield (2006) also found that thermal treatment of carrots after the transition from vegetative to reproductive growth negatively impacted on carrots by checking plant growth, reducing height, delaying the onset of flowering, and reducing seed yield. Thermal treatment of still vegetative carrot plants in mid/late winter had no permanent effect on subsequent plant growth. Two or three months after treatment there were no obvious visual differences between treated plots and the control. By December, total plant dry matter from treated plots did not differ from the control.

Flaming had no effect on black rot, but steaming, in both years, significantly reduced occurrence of the disease. Steaming is considered more lethal than flaming (Ascard *et al*., 2007) due to the considerably larger latent heat of condensation/vaporisation of water compared with the specific heat of dry air, and less heat loss via evaporation and/or transpiration compared with open

flames (Sirvydas *et al*., 2002; Merfield, 2006).

Black rot control was not affected by tractor speed for the steaming treatment in the first year. However, in the second year control was better at the two faster application speeds. The reason for this is unknown but it is possible that at 1.7 km h^{-1}, steaming injured the carrot plants and made them more susceptible to *Alternaria radicina* infection. Timing of steaming was important, as a July application gave no disease control. However, even for a June application, while the reductions in black rot were significant, they were not large, and no treatment completely controlled the pathogen.

The failure of steaming to provide long-term control of seed borne *A. radicina* infection was not unexpected. The experimental plots were in a small area of a commercial field where surrounding plants would have provided wind-borne inoculum of the pathogen which then spread to the trial plots.

Carrot plants can be infected by *A. radicina* from at least three sources; soil, seed and wind-borne conidia. By winter or early spring, crops are already infected, and pathogen control at this time should result in a reduction in disease levels. Steaming has the potential to provide this control. However whether the potential can be turned into practise will require further investigation using much larger plots and an experimental design which seeks to minimise the opportunity for inoculum to move from control to treated plots.

In carrot seed production, the aim during vegetative growth is to reduce *A. radicina* inoculum to as low a level as possible, which subsequently will help to reduce umbel infection. Severely infected umbels may produce no seed, but more commonly produce infected seeds. This can result in the failure of a seed lot to meet contracted germination standards. In both cases the grower faces economic losses. For organic carrot seed production, if steaming is to be used as a method of weed control (Merfield, 2006), then a reduction in *A. radicina* (and other pathogens such as *A. daucii* and *Cercospora. carotae*) could be an additional benefit.

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