Wheat response to nitrogen under contrasting irrigation regimes

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Abstract

Water and nitrogen (N) supply interactions are important in understanding and improving crop production and reducing the environmental footprint of farming. Wheat responses to water and N supply interactions have been studied previously in New Zealand. However, cultivars from those studies are not currently being used in New Zealand. A field experiment was conducted in a rain-out shelter facility in Lincoln, New Zealand, using the wheat cultivar 'Discovery'. Treatments consisted of two irrigation regimes, drought (almost no irrigation) and full irrigation (frequent replacement of water use), and three N rates split applied through irrigation, of 0, 50 and 250 kg/ha. Total dry biomass and grain yield increased with water and N applied. Water use did not differ between N rates under a drought regime. However, under full irrigation, water use was higher for the high N rate (250 kg/ha) than the lower N rates (0 and 50 kg/ha). Water use efficiency was higher under drought than full irrigation, and was lowest for the low N rate (0 kg/ha) than the higher rates (50 and 250 kg/ha). 'Discovery' wheat yield, yield components and water use dynamics therefore had different interactions with water and N supply.

Additional keywords: *Triticum aestivum* 'Discovery', yield, production, nitrogen supply water use, water use efficiency

Introduction

Water and nitrogen (N) supplies, and their interaction, are amongst the main factors dictating the crop yield and environmental footprint of farming systems (Hooper and Johnson, 1999; Li *et al.*, 2004; LeBauer and Treseder, 2008). Water is often a limited (drought and/or regulatory restrictions) and costly resource for the grower but is essential for photosynthetic function and increases nutrient availability to the crop (Seiffert *et al.*, 1995). Nitrogen supply through fertilisers is expensive, and excess supply can have detrimental effects on the environment, but it also can increase the crop's water use efficiency (Qiu *et al.*, 2008; Teixeira *et al.*, 2014).

Wheat (*Triticum aestivum*) is one of the main arable crops grown in Canterbury, New Zealand, and usually under intensive practices (high irrigation and fertiliser inputs). Previous studies have investigated drought and drought timing effects on wheat yield and quality (Christen *et al.*, 1995; Jamieson *et al.*, 1995; Rajala *et al.*, 2009; Minchin *et al.*, 2011; Chakwizira *et al.*, 2014). Other work has focused on the relationship between N supply and water use efficiency, or on water supply and N uptake (Abreu *et al.*, 1993). The effects of water and nutrient supply on wheat yield and quality have been previously investigated in New Zealand by Jamieson *et al.* (2001), who showed that water and N were the main factors to influence yield, with almost no response to phosphorus (P) and potassium (K) on typical cropping soils. The study was carried out across a range of soil types and growing conditions using one cultivar, ‘Domino’. Another study by Wang *et al.* (2014) aimed to characterise the effects of different water and N supply treatments on wheat grain yield and root biomass, and showed that yield increased with water and N supply.

Many of those studies have a strong focus on soil nutrients and chemistry, and some were carried out in climatic conditions that differ strongly from those in Canterbury or New Zealand, and/or involved cultivars which are not used currently or which have been bred for different conditions from those in New Zealand.

This paper has a strong focus on the interaction between water and N supply and their effects on production and physiology. This study also made use of an automated system to measure soil water continuously to 1.8 m depth. This work should help to confirm previous work and/or fill gaps in current knowledge for wheat responses to water and N supply in conditions specific to Canterbury.

Materials and Methods

Experimental details

The experiment was conducted at The New Zealand Institute for Plant and Food Research Ltd mobile rain-out shelter facility at Lincoln, Canterbury, New Zealand (43° 38’S, 172° 30’E). The facility allows the exclusion of rainfall from the experimental site (Martin *et al.*, 1990). The site is located on a deep (>1.6 m in depth) and well drained Templeton silt loam over sand (*Udic Ustochrep*, UDA Soil Taxonomy) (McLaren and Cameron, 1996), with a plant available water-holding capacity of approximately 190 mm/m of depth (Jamieson *et al.*, 1995). Physical characteristics of the soil have been described by Martin *et al.* (1992). The site had been under a mown perennial ryegrass (*Lolium perenne* L.) crop for the previous three years and then oats for the six months immediately prior to the experiment, to remove excess nitrogen from previous experimentation and to deplete soil N concentrations over the experimental site. The oats were removed by mowing before the experiment so that only stubble was left. Soil mineral N available to the crop at the start of the experiment, down to 1500 mm depth, was measured at 64 kg N/ha.

The experiment was set up as a randomised block design with four replicates and six factorial treatments, giving a total of 24 plots. Plot size was 5.0 m long by 3.6 m wide, with a minimum of 0.4 m fallow buffer area between plots. The treatments consisted of two irrigation regimes and three N rates applied during the season. Irrigation was applied using a dripper irrigation system, with emitters spaced 300 mm x 225 mm apart. The irrigation regimes were: i) drought, where irrigation was only applied during N applications and on one occasion during late vegetative development to ensure the crop did not die; ii) full irrigation, where measured water use (based on methods described later) from the crop was replaced weekly. The N rates were: i) 0 kg N/ha; ii) 50 kg N/ha applied as two applications of 25 kg N/ha, once at GS23 (Zadoks *et al.*, 1974) (49 days after sowing (DAS)) and once at GS32 (70 DAS); iii) 250 kg N/ha applied as three applications, one of 50 kg N/ha at GS11 (29 DAS), one of 100 kg N/ha at GS23 (49 DAS), and one of 100 kg N/ha at GS32 (70 DAS). All N was applied as dissolved urea through the irrigation system (fertigation).

The site was prepared by deep ploughing (200 mm), followed by one pass of a harrow and Cambridge roller, power harrowing, and a final harrow and roll. Soil samples to 150 mm depth were randomly taken from the experimental area and used to determine amounts of base fertiliser to be applied. Average soil test results in MAF quick-test units (Mountier *et al.*, 1966), except for sulphate sulphur, were: pH 5.8, Olsen P 20, K 6, Ca 10, Mg 13, Na 9. Sulphate sulphur in the soil was 25 mg/kg soil. Lime was applied at the rate of 5 t/ha. Base fertiliser was applied by broadcasting before sowing and consisted of 100 kg/ha of KCl and 150 kg/ha Triple Super (31 kg P/ha, 50 kg K/ha, 1.5 kg S/ha, and 24 kg Ca/ha). Herbicide, fungicide and pesticide management was carried out throughout the season to prevent any yield limitation by pests and diseases.

Milling wheat (‘Discovery’) was sown on 10 September 2015 at 0.15-m row spacing and using 164 kg seed/ha, giving a total of 24 rows per plot and a plant population of 275 plants/m^2. ‘Discovery’ is a high yielding milling wheat cultivar, also suitable for feed, with a moderate to good resistance to most leaf diseases (PGGWrightson, 2018). Irrigation was managed in common across the experiment while the crop was establishing. Following 13 October (33 DAS), irrigation was applied as per the treatments. The site was irrigated twice with overhead irrigation (10 mm each time) during emergence to reduce soil surface capping. Plots under drought treatment received a total of 116 mm of irrigation regardless of the N rate treatment. Plots under full irrigation treatment received a total of 330, 400, and 460 mm of irrigation for the 0, 50, and 250 kg/ha N rate treatments respectively.

Measurements

Reflectometers (Model CS650 Water Content Reflectometers, Campbell Scientific Inc., Utah, USA) were installed in each plot after emergence (33 DAS) and used to measure soil volumetric water content (VWC) at the following depths: 0-150 mm (two reflectometers installed at this depth, within and between drilled rows); 150-300 mm; and then in 300 mm increments from 300 mm to 1800 mm depth (total of eight reflectometers per plot). Reflectometers were connected to a data logger (Model CR1000, Campbell Scientific Inc., Utah, USA) which recorded VWC at 15-min intervals.

Crop water use (WU) for the season was calculated as the sum of daily changes in VWC from 0 to 1800 mm depth during the measurement period (ΔVWC), starting when the automated reflectometers were installed (33 DAS), plus any input from irrigation during the period (I):

$$WU = \sum(\Delta VWC + I).$$

Water use efficiency (WUE) was calculated as the relationship between final grain yield and WU:

$$WUE = \text{final grain yield} / WU.$$

A total of six dry matter (DM) harvests were completed by hand at key growth stages (Tottman and Makepeace, 1979): mid-tillering (GS23), stem elongation (GS30), flag leaf appearance (GS39), flowering (GS60), mid-grain fill (GS85) and a final harvest at grain maturity. Quadrat samples of 0.4 m length of 7 rows (0.42 m^2) per plot were taken for the sequential DM harvests, except for the final harvest, which was 1.34 m length of 7 rows (1.41 m^2). A buffer zone was left between each sequential harvest. For each harvest, total fresh biomass from the quadrat was measured. Twenty stems were then randomly selected to measure biomass partitioning into leaf, stem, dead material and ear. Dry biomass partitioning was measured after drying at 60°C to constant weight. The total leaf laminae from the 20 stems subsample was also used to determine leaf area using a leaf area meter (model LI-3100, LI-COR Inc., Nebraska, USA). The total leaf area per quadrat was determined and used to calculate leaf area index (LAI; m^2/m^2). A 300-g subsample from the quadrat sample was used to measure dry matter biomass after drying at 60°C to constant weight.

From the start of grain fill (late December) to maturity, the final harvest area of each plot was covered with bird netting to eliminate damage by birds. The final harvest was carried out on different dates for each treatment to fit in with the different timing of grain maturity (GS92) created by the experimental setup: 137 DAS for the drought 0 kg N/ha treatment; 144 DAS for the drought 50 and 250 kg N/ha treatments; and 156 DAS for all the full irrigation treatments. The final harvest ear samples were threshed using a Saatmeister Kurt Pelz mill to separate the grain from the chaff. The proportion of screenings (%) was determined for each plot on a 200-g grain sub-sample passed through a 2.1 mm screen. Other yield components measured included: 1000 seed weight (TSW), and grain moisture content using a calibrated moisture meter (model GAC®500XT, DICKEY-john Corp., Illinois, USA). Harvest index (HI) was calculated as the proportion of grain dry yield in the total biomass dry yield.

Data analyses

Analyses were carried out in Genstat version 17 (VSN International Ltd, UK). Total biomass, grain yield at 14% moisture, HI and TSW data from final harvest were analysed using a mixed model approach, fitted with restricted maximum likelihood (REML) as implemented in Genstat. Assumptions were checked via standard residual plots. Tiller count (TC) data from final harvest were modelled using a Poisson generalized linear mixed model. Fixed effects in the model were nitrogen, irrigation, and their interactions. Random effects accounted for the position in the field (block). An estimate of the variation associated with predicted means is provided by a 5% least significant difference ($LSD_{0.05}$). Where values show $P<0.1$, a trend is indicated in the text.

LAI data from the intermediate harvests, WU and WUE were analysed using a mixed model approach, fitted with REML as implemented in Genstat. Assumptions were checked via standard residual plots and log transformation applied. Fixed effects in the model were nitrogen, irrigation, time of sampling (LAI data only) and all interactions. Random effects accounted for the position in the field (block).

For ease of interpretation, LAI, WU, and WUE data presented in figures and tables was back-transformed from log. As such, those figures and tables do not have any LSD associated with the means displayed. Trends indicated in the text are based on the log transformed data when $p<0.1$ and an estimate of the variation associated with predicted means provided by a 5% least significant difference ($LSD_{0.05}$).

Results

There was an interaction between irrigation and N rate treatments on total dry biomass and grain yield ($p<0.001$). As expected, both variables increased with irrigation and with N applied to the crop. However, the increase of total dry biomass and grain yield with N applied was greater under full irrigation. Total dry biomass increased from 4.1 t/ha for the drought with 0 kg N/ha treatment to 15.6 t/ha for the full irrigation with 250 kg N/ha treatment (Table 1). Grain yield increased from 2.8 t/ha for the drought with 0 kg N/ha treatment to 9.9 t/ha for the full irrigation with 250 kg N/ha treatment (Table 1).

HI was significantly affected by N rate ($p=0.008$), being lower at 0.54 for 250 kg N/ha than at 0.58 for both 0 and 50 kg N/ha (Table 1). However, there was no evidence that HI was affected by the interaction of irrigation regime and N rate treatments ($p=0.231$).

Table 1: Total dry biomass, grain yield at 14% moisture, yield components [tiller count (TC), harvest index (HI), and thousand seed weight (TSW)], and water parameters [water use (WU), water use efficiency (WUE)] for ‘Discovery’ wheat grown under different nitrogen and irrigation regimes at Lincoln, Canterbury, New Zealand (2015-16 season). Note that WU and WUE back-transformed data (from log transformation) are presented here so no LSD is associated with those means. TC means are provided with 95% confidence intervals in brackets.

Treatment[1]	Total biomass (t/ha)	Grain (t/ha)	HI (g/g)	TSW (g)	TC (tillers per m^2)	WU (mm)	WUE (kg grain/ha/mm)
Dr 0	4.1	2.8	0.58	45.1	263 [225-309]	164	16.7
Dr 50	6.5	4.5	0.59	44.3	329 [285-379]	198	22.5
Dr 250	9.5	6.0	0.54	46.0	459 [406-519]	185	32.2
Irr 0	6.1	4.1	0.58	47.6	277 [237-323]	341	11.8
Irr 50	9.6	6.3	0.56	47.8	405 [355-461]	293	21.4
Irr 250	15.6	9.9	0.55	50.9	559 [500-626]	433	22.8
LSD	1.3	0.8	0.03	3.0	n/a	n/a	n/a

[1] Dr 0 = drought 0 kg N/ha, Dr 50 = drought 50 kg N/ha, Dr 250 = drought 250 kg N/ha, Irr 0 = irrigated 0 kg N/ha, Irr 50 = irrigated 50 kg N/ha, and Irr 250 = irrigated 250 kg N/ha

Irrigation regime had a strong effect (p<0.001), and N rate a weak effect (p=0.056) on TSW but there was no interaction between the effects of those treatments (p=0.458). TSW was higher under full irrigation than under drought conditions, averaging 48.8 and 45.1 g respectively (Table 1). TSW was also higher for 250 kg N/ha, averaging 48.5 g, but was not different between 0 and 50 kg N/ha, averaging 46.2 g.

There were strong effects of N rate (p<0.001) and irrigation regime (p=0.004) on TC, but again, no interaction between treatment effects (p=0.438). TC increased with N applied to the crop under full irrigation (95% confidence intervals do not overlap), from 277 to 559 tillers/m^2 (Table 1). Under drought, TC was highest with 250 kg N/ha at 459 tillers/m^2, but the difference were less prominent between 0 and 50 kg N/ha (95% confidence intervals overlap), at 263 and 329 tillers/m^2 respectively.

Screenings did not differ enough between treatments to warrant deeper analysis (measured between 0.01 and 0.03% for individual plots).

Irrigation regime had a strong effect (p<0.001) on WU, which, as expected, was higher under full irrigation (Table 1). Under drought conditions, there was no significant difference in WU between the different N rates. Under full irrigation, there was a significant difference in WU between the high N rate of 250 kg N/ha, which used 433 mm of water, and the two lower rates of 0 and 50 kg N/ha, which used 341 and 293 mm of water respectively. Thus there was a weak interaction between treatment effects for WU (p=0.055).

N rate strongly affected WUE (p<0.001). Irrigation regime also had an effect on WUE (p=0.018). WUE was higher under drought conditions than under full irrigation, with an average WUE of 23.0 and 17.9 kg grain/ha/mm respectively (Table 1). WUE was lowest for the lower N rate of 0 kg N/ha, at 14.0 kg grain/ha/mm, compared with the other N rates of 50 and 250 kg N/ha, at 21.9 and 27.1 kg grain/ha/mm. There was no evidence of an interaction between these factors for WUE (p=0.362).

The full irrigation with 250 kg N/ha treatment resulted in the highest LAI (p<0.001) throughout the duration of the experiment, with reduction in N rate and/or water supply causing substantial reductions from the second time of sampling data onwards (Figure 1). There were no interactions between the effects of irrigation regime, N rate and time of sampling on LAI (p=0.358).

Discussion

The increase in total dry biomass and grain yield with increasing water and N supply was consistent with results presented in previous work (Abreu *et al.*, 1993; Jamieson *et al.*, 2001; Wang *et al.*, 2014). These results are also consistent with previous work that illustrated the importance of considering interactions between water and N supply: water supply improves nutrient availability, and in turn an adequate N supply can improve WUE (Seiffert *et al.*, 1995; Qiu *et al.*, 2008; Teixeira *et al.*, 2014). Indeed, in the current study the increase in total dry biomass and grain yield with N supply was greater under the full irrigation regime: the crop had better access to N to produce biomass with a regular supply of water than under drought conditions. Furthermore, WUE also increased with N supply for both irrigation regimes. WUE was higher for the drought regime than the full irrigation, which is consistent with results from other studies (Chakwizira *et al.*, 2014; Teixeira *et al.*, 2014). Most WUE reported in this study were consistent with those in previous reports (Kirkegaard *et al.*, 2007; Sadras and Lawson, 2013; Chakwizira *et al.*, 2014), except for the drought with 250 kg N/ha treatment which was higher than previously reported. This treatment did, however, produce a total dry biomass and grain yield of, respectively, 9.5 and 6.0 t/ha (Table 1); which were similar to those achieved by the crop under full irrigation and 50 kg N/ha. The experiment was located on a deep soil with a high water-holding capacity. With such a high N input, the crop root system could have grown better than at the lower rates of N and deeper-extracted water, thus having the potential to reach such a high yield with a low WU.

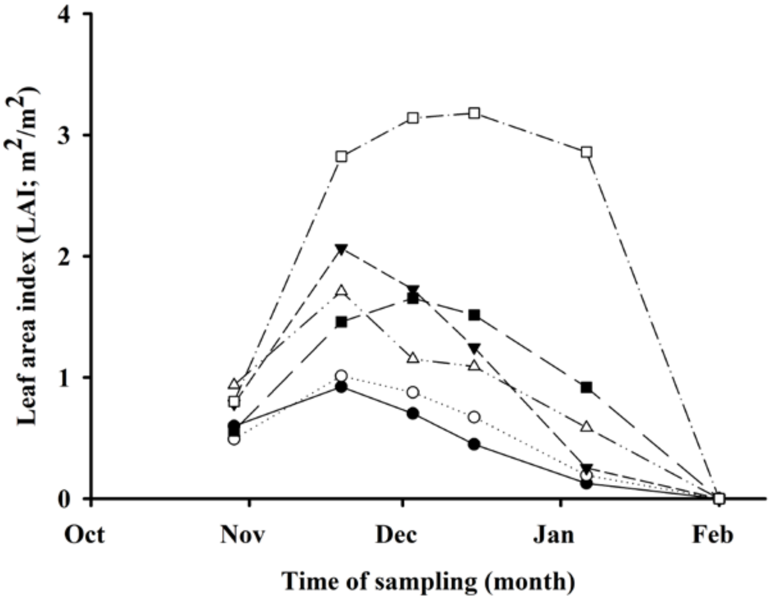

Figure 1: Cumulative leaf area index (LAI, m^2/m^2) for 'Discovery' wheat grown under different nitrogen and irrigation regimes at Lincoln, Canterbury, New Zealand in the 2015-16 season: ● Drought 0 kg N/ha; ○ Drought 50 kg N/ha; ▼ Drought 250 kg N/ha; ∆ Full irrigation 0 kg N/ha; ■ Full irrigation 50 kg N/ha; □ Full irrigation 250 kg N/ha. These data are based on back-transformed (from log) means and do not have associated LSDs.

LAI was affected separately by the irrigation regime and by the rate of N: it was higher under full irrigation than under drought conditions, and for the highest N rate. Under drought stress, the plant will develop faster, illustrated by the earlier harvest of the drought plots than the full irrigation plots. Drought and low N supply also meant that the plants were only able to maintain a more limited green canopy and for a shorter time frame compared with when they had sufficient water and N inputs. All of this can in turn help to explain the total dry biomass and grain yield differences between the treatments. Even though there were indications that HI was affected by the N rate, and was significantly lower at the higher N rate of 250 kg/ha, it did not vary by much between treatments, with means between 0.54 and 0.59. Those HI values are consistent with those reported in the literature for other grain wheat cultivars (Foulkes *et al.*, 2011; Rose *et al.*, 2017), are still below the maximum potential described by Austin (1980), and they tend towards the high end of previously reported values. Protein contents under the different treatments were not measured in the current study, so HI results should be treated cautiously. N partitioning to yield and protein depends on the rate of N applied, the amount of N present in the soil, and the cultivar used (Craighead and Burgess, 2000), and will affect HI. TSW was affected mostly by the irrigation regime, being higher under full irrigation than under drought conditions. TSW was affected by the N rate to a lesser extent: it increased only under the high rate (250 kg/ha). TC increased with the N rate under full irrigation, but under drought the differences were not significant between the two low N rates (0 and 50 kg/ha), and TC increased significantly only with a high N rate (250 kg/ha). Under full irrigation, the adequate water supply allowed the crop to use all the N applied, and this resulted in a higher TC, which contributed to the higher dry biomass production and grain yield. Under drought conditions, this experiment did not reveal any differences in TC between the two lower N rate treatments.

Summary

Overall, dry biomass and grain yield increases with water and N input were explained by the different yield components measured in this study. HI did not change much between treatments, even though differences were picked up by the analysis, and the range was within expectation for a spring grain wheat crop. Some yield components were more affected by the irrigation regime, such as TSW, which was higher under full irrigation and would help to explain the higher yields for that treatment. Other yield components were affected by both irrigation regime and N rate treatments. TC also followed the same trends as yield, with the exception that no significant differences were detected for the two lower N rates under drought.

LAI trends showed that, with higher water and N inputs, the crop was able to maintain more green leaf area, which also explains some of the yield differences between the treatments.

As expected, WU was higher under full irrigation. N rate only affected WU under full irrigation, with higher N application resulting in an increase in WUE. WUE did increase with N input under both irrigation regimes and was also higher under drought conditions. WUE for 250 kg N/ha under drought was higher than previously reported values but that could be explained by the soil properties at the site where the experiment was conducted.

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Potassium fertiliser requirements of fodder beet

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Abstract

In the last five years there has been a four-fold increase in area under fodder beet (*Beta vulgaris* L.) production in New Zealand. This has been attributed to demand for high yielding and high energy feeds for wintering of livestock. However, fodder beet yields are frequently lower than their potential, often because of sub-optimal soil fertility management and general crop health issues. Recommendations for potassium (K) fertiliser applications have been derived from limited and dated local or international research. Four experiments on timing [all at sowing, or split at sowing, canopy closure and mid-season (February)] and five rates [0–450 kg/ha] of K were carried out at four locations in the South Island of New Zealand in 2016–2017. Background exchangeable K at the sites varied from 2.8 to 4.0 Quick test units, and the reserve K (tetraphenylboron K; TBK) from 0.3–2.8 me/100 g. At the final harvest, neither the rate nor the timing of K application had any strong effect on biomass yield of fodder beet at each of the four sites. However, K uptake (91–700 kg K/ha) increased with the rate of K applied, but was unaffected by timing of application. The apparent recovery of K fertiliser was moderate, at 28–45%. The rest of the total uptake was attributed to the soil K reserves. Therefore K fertiliser rates should be adjusted according to the potential of soil to supply K and feeding strategy (i.e. grazed *in situ* or lifted). If crops are lifted and fed off the source paddock, more fertiliser K may be required to replace the K offtake; and if grazed *in situ,* a maintenance rate should be applied, as most of the K will be returned in urine.

Additional keywords: *Beta vulgaris* L., feed quality, grazing utilisation, *in situ*, yield potential.

Introduction

Fodder beet production is increasing rapidly in New Zealand as farmers look to benefit from its high yield potential and desirable feed quality characteristics (Chakwizira *et al*., 2013; 2014a) for enhancing animal body condition during wintering and finishing animals. This has seen the area under fodder beet increase four–fold in the last 5 years, to about 60,000 ha in the 2016–17 growing season (Gibbs, 2014; Milne *et al*., 2014; Chakwizira *et al*., 2016a). Favourable crop attributes include a high potential dry matter (DM) yield (>20 t/ha), high feed quality (Matthew *et al*., 2011; Chakwizira *et al*., 2014a; 2014b), high (>90%) grazing utilisation (Edwards *et al*., 2014a; 2014b) and perceived lower risks of nitrogen (N) leaching losses in comparison with alternative winter-fed forages (Edwards *et al*., 2014a; Malcolm *et al*., 2016; Dalley *et al*., 2017; de Ruiter *et al*., 2018).

Although there is increasing farmer interest in fodder beet as a late-autumn or winter fed crop in New Zealand, the yields at farm level are frequently below the genetic potential, which reduces the profitability of the crop. The yield potential in most regions is between 25 and 28 t DM/ha (Chakwizira *et al*., 2018), but reported yields are often much lower (13–20 t DM/ha) (Milne *et al*., 2014; Judson *et al*., 2016). Factors contributing to yield reductions include sub-optimal crop management and related soil fertility and crop health issues. There is a significant opportunity to improve productivity and profitability of fodder beet through improved crop management and consistent advice to farmers on fertiliser management.

Current information on K fertiliser requirements for fodder beet has been derived from limited (Chakwizira *et al*., 2013) and dated local (Stephen *et al*., 1980; Magat and Goh, 1988; Goh and Magat, 1989) and international research (Draycott and Christenson, 2003a). Further information has also been derived from related crop species such sugar beet (*Beta vulgaris* L.) (Draycott *et al*., 1974; Draycott and Christenson, 2003b; Khan *et al*., 2013). Therefore, updated information is needed to refine recommendations to better match plant nutrient requirements for optimum growth, as well as optimising the feed value for livestock and recommendations for sustainable management of nutrients. It is unclear if the results and recommendations from recent work on K in Central Canterbury (Chakwizira *et al*., 2013) can be applied to other regions in New Zealand, given the soil and climatic differences.

Most crops, including fodder beet are capable of extracting large amounts of K from soils even if the readily available K concentrations are low as reported previously (Craighead and Martin, 2003; Wilson *et al*. 2006; Trolove, 2010). High-yielding (20–30 t DM/ha) crops of fodder beet have been shown to take up more than 500 kg K/ha (Chakwizira *et al*., 2013), similar to the amounts reported for both fodder beet and sugar beet (Draycott and Christenson, 2003a, b). International literature suggests that both fodder and sugar beet require moderate amounts of K fertiliser (Draycott and Christenson, 2003a, b), but K can be taken up in excess of plant requirements, i.e. ‘luxury consumption’. Overseas K fertiliser recommendations (Draycott and Christenson, 2003a) suggest application rates of between 80 and 250 kg K/ha are required for fodder beet production, on soil K status equivalent to <3 to >12 quick test K (QTK) units (Chapman and Bannister, 1994). The optimum rates and timing of K application for fodder beet, are not known for the different agroecological zones in southern New Zealand. The aim of these experiments were to validate the growth and yield responses of fodder beet in regional experiments, to confirm general recommendations for differing soil and climatic conditions.

Materials and Methods

Experimental details

A total of four on-farm sites were selected for the experiments where fodder beet is commonly grown in the South Island of New Zealand (Table 1): Southland (Gore; 45°56'32.46"S 168°59'27.84"E and Riverton; 46°20'38.40"S 167°52'58.37"E); representing Eastern and Western Southland, respectively and Canterbury (Southbridge; 43°50'4.10"S 172°14'5.10"E and Orari; 44° 4'58.89"S 171°16'48.82"E), representing Central - and South Canterbury, respectively. All crops were for winter grazing and had similar seasonal growth duration (Table 1), except for the Western Southland (Riverton) site (Table 1). Both Canterbury sites were irrigated, and the Southland sites were rain-fed. Four cultivars (Table 1) were grown, which are classified as low (≤15% e.g. 'Brigadier'), moderate (15-18%, e.g. 'Blaze' and 'Geronimo') and high (>18% e.g. 'Rivage') DM percent (DM%) cultivars (Milne *et al*., 2014). These authors have also reported that three of the four cultivars used in the current experiments ['Rivage', 'Brigadier' and 'Blaze'] produce similar biomass yields, in work carried out in different South Island regions: Canterbury, Otago and Southland.

Table 1: Crop details (cultivar, sowing details, final harvest date and season duration) at each of the four fodder beet experimental sites.

Site	Cultivar	Sowing date	Sowing rate (plants/ha)	Final harvest	Season duration (days)
Southbridge	'Rivage'	26 Oct. 2016	83,000	29 May 2017	224
Orari	'Geronimo'	11 Oct. 2016	90,000	22 May 2017	224
Gore	'Brigadier'	17 Oct. 2016	90,000	10 May 2017	206
Riverton	'Blaze'	3 Dec. 2016	85,000	9 May 2017	158

Both Canterbury sites were on Recent soils but of different properties; shallow (0.2–0.45 m deep) and low to moderate water holding capacity (WHC; 60–89 mm/ m depth) at Orari, and moderately deep (0.45–1 m), with moderate WHC of 90–119 mm/ m depth at Southbridge. At the Southland sites, soils at Riverton are Podzols, which are deep [>1m], moderately drained, with high WHC of >250 mm/ m depth. At the Gore site, predominant soils are Anthropic, derived mainly from gold mining, very shallow (<0.2 m), low WHC of < 30 mm/ m depth and moderately drained. Key soil characteristics are fully described in McLaren and Cameroon, (1966).

Base soil fertility at each site was determined to 15 cm depth (Table 2), before cultivation of the paddocks. The base paddock fertiliser at each site was applied based on that particular site's background fertility in relation to the established optimum fertility for general crop production (Table 2). The soil pH, Ca, Mg, Na and B concentrations were adequate for general crop production on all the sites. However, only one of the sites had adequate Olsen P, while both anaerobically mineralisable nitrogen (AMN) and quick test K (QTK) values were low for all sites. Furthermore, the tetraphenylboron K (TBK) values were lower at the Riverton site, but high at the other three sites.

Basal fertiliser was applied at 200 kg N/ha, as urea (46%N), split equally and broadcasted at sowing and canopy cover. Other base fertilisers were broadcast evenly at sowing, at rates of 50 kg P/ha as triple superphosphate (0–20.5–0–1), 150 kg/ha sodium chloride (40% Na and 60% Cl) and 25 kg/ha borate 46 (15% B) at sowing for each of the site. Potassium was not applied as a base fertiliser but to the relevant plots as designated treatments (Table 3).

Agrichemicals were applied to the crop when needed so that crop yield was not compromised by weeds, insects or disease infection; similar rates to those described by Chakwizira *et al.* (2014b) were used.

Table 2: Soil properties[1] measured before establishment of the experiments at each site. The optimum values are for general crop production (Nicholls *et al*., 2012).

Site	pH	Olsen P	Ca	Mg	K[2]	Na	B	TBK	AMN
		(µg/mL)	---------	QT Units	-------		ppm	me/100 g	(kg/ha)
Southbridge	6.3	17.0	9.8	18.0	2.8 (1, 2)	11.0	1.0	2.3	39
Orari	6.1	17.8	11.5	16.5	4.0 (3, 4)	8.5	1.2	2.3	62
Gore	6.2	32.0	11.5	25.5	3.0 (2, 3)	8.5	1.8	2.8	88
Riverton	5.7	11.3	10.0	18.8	3.3 (2, 4)	12.0	1.2	0.3	80
Opt. amount	5.8-6.2	20–30	4–10	8–10	5–10	5–8	1.0	1.0	100-200

[1] Phosphorus (P), Calcium (Ca), Magnesium (Mg), Potassium (K), Sodium (Na), Boron (B), Tetraphenylboron K (TBK) and available mineralisable N (AMN).

[2] Numbers in parenthesis represent QTK at the final harvests for the 0 and 450 kg K/ha treatments, respectively.

Experimental design

The experimental treatments comprised four different K rates and two timings (all at sowing; or split of K application at sowing, full canopy cover and mid-season (mid-February) (Table 3), arranged in a randomised complete block design with four replications at each site. Plots were 3 m (6 rows) wide by 15 m long, at all the sites. Total K applications were 0, 150, 300 and 450 kg K/ha, applied as potassium chloride (KCL; 50%K). The range of treatments were set to represent the current industry recommendations, and applied at all the four sites irrespective of the actual soil tests results, although every effort was made to select for low soil K status (Table 2). Treatments with split applications (K4 and K5) supplied 100 or 150 kg K/ha at each application (Table 3). The K fertiliser was broadcast by a Solo Hand Spreader (SOLO Kleinmotoren GmbH. Stuttgart Straße 41. 71069 Sindelfingen, Germany) in each of the relevant plot.

Measurements

The DM yield harvests were taken three times during the growing season: at canopy cover, mid-season (February) and end-of-season (May), the first two coinciding with the timing of in-season K application (Table 3). Only the central two rows were harvested during the season, and the two outside rows were used as guard rows, to cater for overlaps in fertiliser application between treatments. The area harvested per plot differed with the size of the crop and purpose for harvesting. At the first harvest, a 0.5 m^2 quadrat was taken from each plot at canopy cover to measure nutrient (K) uptake. At the second (mid-season) and third (end of season) harvests, a 6 m^2 quadrat was harvested for both biomass and nutrient uptake. Plant density and total fresh weight per plot were determined in the field at each harvest. A representative two-plant subsample was retained to determine whole-plant DM percentage, K concentration and K uptake. Dry weight was determined by drying in a forced-air oven at 60°C to constant weight.

Table 3: Potassium (K) treatments showing initial rates of K applied at sowing (KI–K3); and additional treatments with split application of K (K4–K5) at the seven sites.

Treatment	K application (kg/ha)[1]			Total K applied (kg/ha)
	Sowing	Canopy closure	Mid-season (end of February)	
K1	0			0
K2	150			150
K3	300			300
K4	100	100	100	300
K5	150	150	150	450

[1]Actual dates varied with site, but for the first application at sowing, see Table 1.

Calculations

Potassium use efficiency (KUE) and its components

Potassium use efficiency was reported for one site (Southbridge), and defined as the ratio of additional DM yield to fertiliser K input (Equation 1); often termed 'agronomic efficiency' (Fageria *et al*., 2001). We used the Southbridge site for these calculations as it was the only site with positive differences (although very small) between the control and the rest of the treatments. In this calculation, yield response is adjusted for the yield achieved without added fertiliser K (i.e. control plots) and therefore does not account for the response due to residual soil K.

$$\mathrm{KUE} = \frac{\text{Crop biomass at } K\text{x} - \text{Crop biomass at } K\text{o}}{\text{kg of K applied at } K\text{x}} \qquad \text{-----------------}\ (1)$$

where Kx = K rate > 0 and K_0 is crop yield for the control crops.

The KUE was also expressed as the product of K uptake efficiency (KupE; the ability of plants to remove nutrients from the soil) and the K utilisation efficiency (KutE; the ability of plants to use nutrients to produce biomass yield) as (Zhu *et al*., 2017):

$$\mathrm{KUE} = \mathrm{KupE} \times \mathrm{KutE} \qquad \text{----------------}\ (2)$$

And:

$$\mathrm{KupE}\ (\%) = (\mathrm{Ykf} - \mathrm{Yk}_0) \times \frac{100}{\mathrm{kf}}\ \text{, and}$$

$$\mathrm{KutE}\ (\text{g/ g per m}^{-2}) = \frac{\text{Crop biomass at } K\text{x} - \text{Crop biomass at } K\text{o}}{\mathrm{Ykf} - \mathrm{Yko}}$$

where Ykf is the crop K yield with application of fertiliser K, and Yk_0 is the corresponding crop K yield without fertiliser application for the same treatment and replication.

Statistical analysis

Data analyses for each site were analysed using analysis of variance (ANOVA) fitted with least squares in GenStat version 17 (VSN International, Hemel Hampstead, UK). This was followed by a meta-analysis of data from all four experimental sites; by using a mixed model fitted with the restricted maximum likelihood (REML) programme in GenStat version 17. This was made possible as three of the four cultivars have been reported to produce similar biomass yield in different agroecological regions of the South Island of New Zealand (Milne et al., 2014). An estimate of the variation associated with treatment means was given by least significant difference ($LSD_{5\%.}$) with associated degrees of freedom (df). Data were graphed in Microsoft® Excel. Where values show $P < 0.1$, a trend is indicated in the text.

Results

Biomass yield

At the final harvest, neither the rate nor the timing of K application had any strong effect (P=0.29) on biomass yield of fodder beet (Figure 1). The mean overall biomass yield per site were 31 t DM/ha at Orari, 25 t DM/ha at Southbridge, 12.6 t DM/ha at Riverton and 23 t DM/ha at Gore. For the Orari site, DM yield increased (P<0.001) with each successive harvest, at an average rate of 268 (240-330) kg DM/ha/day for period between canopy cover and mid-season (February) harvests, compared with 110 and 122 kg DM/ha/day for the period before canopy cover and the period from mid-season (February) to final harvests, respectively.

Potassium concentration

At the final harvest, the K concentration in the tissues increased (P<0.012) with increasing rate of K application across the four sites (Figure 2). The effect of timing of K application (single vs triple applications for a total of 300 kg/ha K applied) on plant K concentration was significant (P<0.001) for all sites except Orari. This effect was due primarily to the uptake difference at the first and second harvests but not at maturity (Figure 2). The overall K concentration within each application rate and timing treatment decreased with time after sowing.

Potassium uptake

The overall K uptake (product of total biomass yield and K concentration), increased with K application at all the four sites (Figure 3) with a significant ($P<0.03$) linear trend with rate of K applied. At the final harvest, K uptake increased from 91 kg/ha for the control crops to 330 kg/ha when 450 kg K/ha was applied at Riverton.

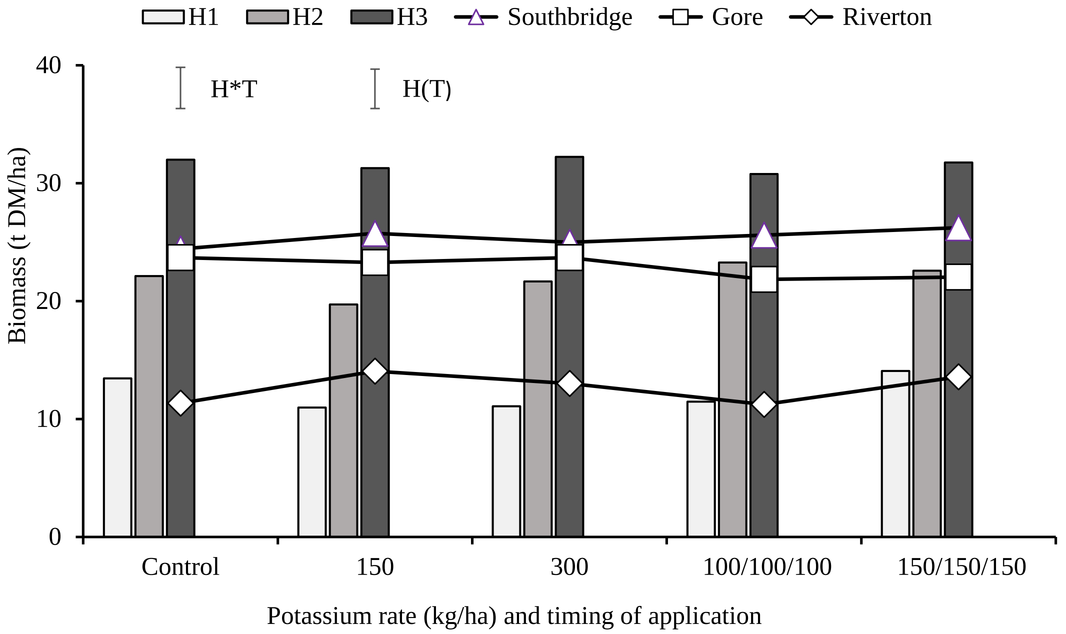

Figure 1: Biomass yield (t DM/ha) for fodder beet crops grown under different rates of potassium (K; 0–450 kg K/ha) and different timings of K application (sowing only, or sowing, canopy cover and mid-season). Crops were harvested three times during the season at canopy closure (Harvest 1, H1), mid-season (H2), and at the end of the season in May (H3). Bars are the yield for Orari (Canterbury) site. Error bars are least significant difference ($LSD_{5\%.}$) to compare treatment means across harvests events (H*T) and for treatments within same harvest (H (T)) for the Orari site only. The line graphs represent the final biomass yield for the other three sites.

Similarly, K uptake increased from 550 kg/ha to 690 kg/ha for the same respective treatments at Orari (Figure 3). Similar trends were observed at Gore and Southbridge; with intermediate uptake values. At Riverton, K uptake was lower than for the other sites, across the treatments (Figure 3). The difference between K uptake in the control treatments compared with those with K applied (contrast with single applications only) was significant ($P<0.003$) at all sites. At the Orari site, timing of application (contrast between single and multiple applications totalling 300 kg/ha K applied) did not affect ($P=0.76$) total K uptake. This effect of timing was, however, significant at the Southbridge ($P=0.03$), Gore ($P<0.02$) and Riverton ($P<0.001$) sites.

Potassium uptake and utilisation efficiency

The calculated K uptake efficiency (KupE) for the Southbridge (Table 4) site increased from 28% for the 300 kg K treatment, applied as a split throughout the season (Table 3), to 45% for the 150 kg K/ha treatments applied at sowing. When the same rate was applied at different times (e.g. 300 kg/ha), crops tended to take up more K from the single early application, than when K was split three times during the season. There was no difference in KUE, averaging 5 (2-9) g DM/ g K_{uptake} /m^2.

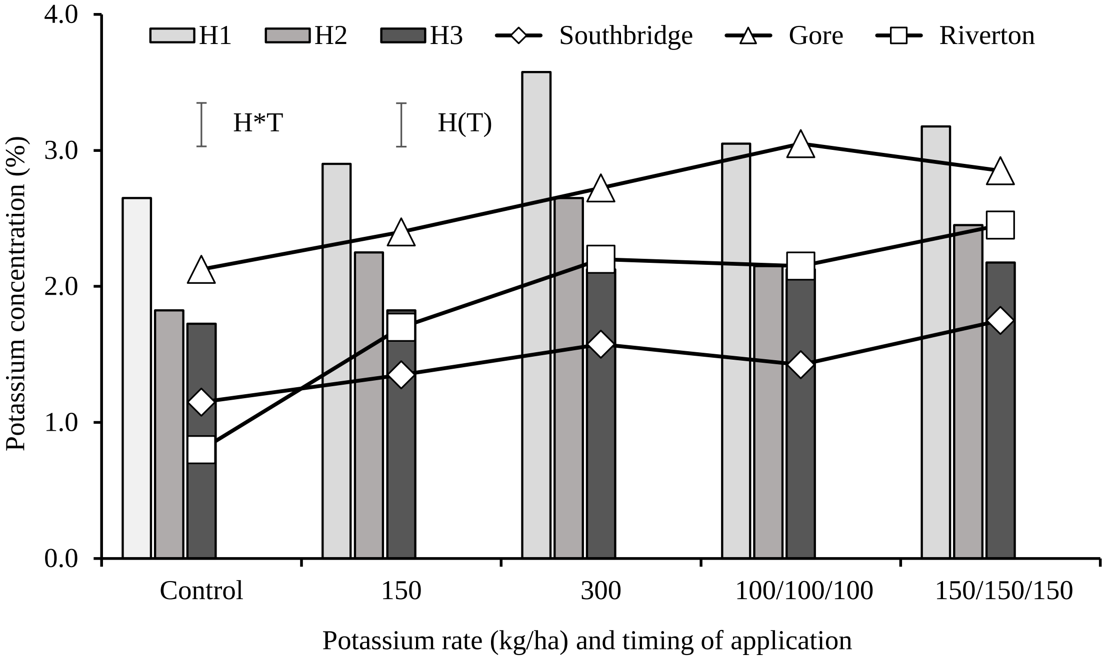

Figure 2: Potassium (K) concentration (%) for fodder beet crops grown under different rates of potassium (K; 0–450 kg K/ha) and different timings of K application (sowing only, or sowing, canopy cover and mid-season). Crops were harvested three times during the season at canopy closure (Harvest 1, H1), mid-season (H2), and at the end of the season in May (H3). Bars are the yield for Orari (South Canterbury) site. Error bars are least significant difference ($LSD_{5\%}$) to compare treatment means across harvests events (H*T) and for treatments within same harvest (H (T)) for the Orari site only. The line graphs represent the K concentration at the final harvest for the other three sites.

Table 4: Potassium fertiliser applied, final harvests biomass yield, additional biomass yield (difference between final biomass and control crops) and potassium use efficiency components: uptake efficiency (KupE; %) and utilisation efficiency (KutE; g DM/ g K_{uptake} /m^2) for fodder beet grown at Southbridge, Central Canterbury in the 2016-17 season.

Fertiliser applied[1] kg K/ha	Biomass yield (kg DM/ha) Total	Biomass yield (kg DM/ha) Additional	KUE components KupE	KUE components KutE
0	24,400	-	-	-
150	25,800	1,400	45.3	20.6
300	25,000	600	36.7	5.5
300 (100/100/100)	25,600	1,200	28.7	14.0
450 (150/150/150)	26,200	1,800	39.1	10.2

[1] Timing of application is described in Table 3.

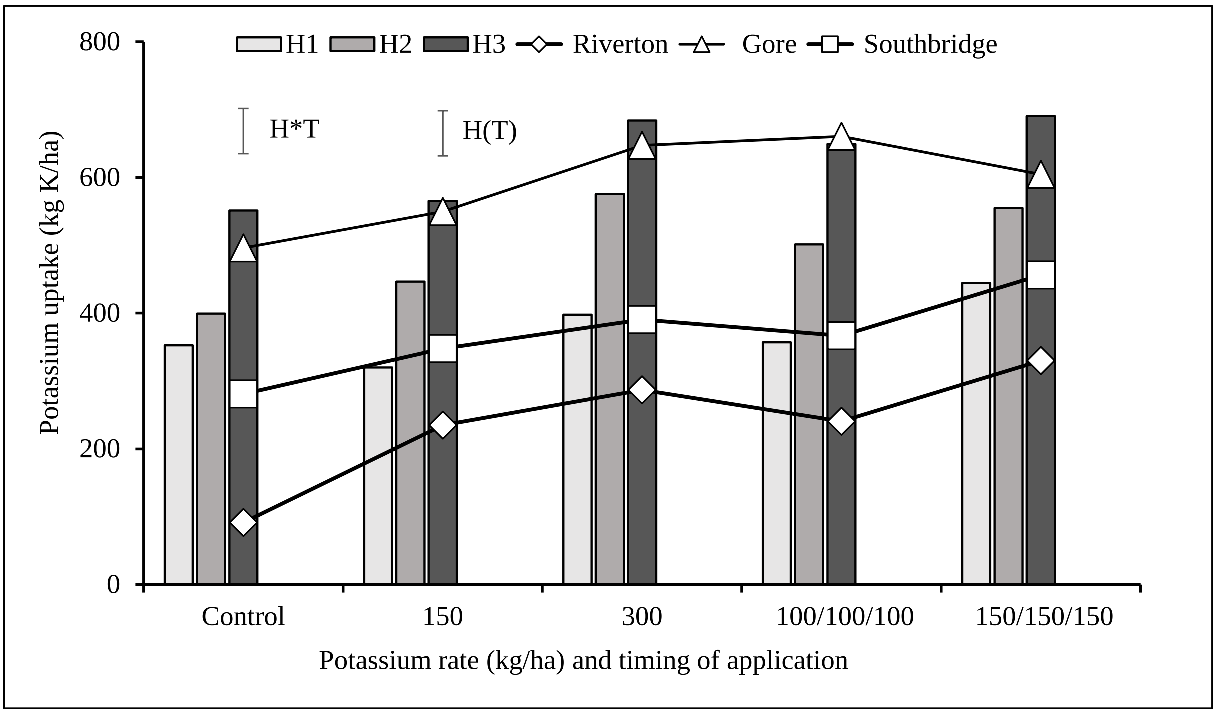

Figure 3: Potassium (K) uptake (kg/ha) for fodder beet crops grown under different rates of potassium (K; 0–450 kg K/ha) and different timings of K application (sowing only, or sowing, canopy cover and mid-season). Crops were harvested three times during the season at canopy closure (Harvest 1, H1), mid-season (H2), and at the end of the season in May (H3). Bars are the yield for Orari (South Canterbury) site. Error bars are least significant difference ($LSD_{5\%.}$) to compare treatment means across harvests events (H*T) and for treatments within same harvest (H (T)) for the Orari site only. The line graphs represent the K uptake at the final harvest for the other three sites.

Discussion

Biomass yield, K concentration (%K) and K uptake response data from the four experimental sites indicated that K was not a nutrient limiting crop performance. Even though the residual soil K content (QTK) were relatively low (≤4.0, Table 2), there was no effect of K rate or timing on DM yield. Despite there being no effect of K application on yield, the capacity of plants to utilise either residual K or applied K was evident, with effects on the %K in whole plants and the amounts of K uptake in response to rate of K applied. Fodder beet showed a capacity for efficient uptake of K from the soil (Table 4). Similar high K uptake efficiency has been reported for sugar beet (Samal *et al.*, 2010), when compared with maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.) and was attributed to higher K influx (K uptake per cm of root per second) for sugar beet, thus more efficient acquisition in low available soil K. Because of a strong root system, fodder beet may be able to derive significant amounts of K from below the soil depth tested (Jackson, 1985; Carey and Metherell, 2003). Furthermore, fodder beet has been shown to extract water from depth of up to 1.4 m (Chakwizira *et al.*, 2014b) and as K uptake is mainly driven through the transpiration stream (Mengel and Kirkby, 2001), this could explain the high K uptake. Another possible explanation is that most New Zealand sedimentary soils have high K reserves (Craighead and Martin, 2003) and K that was released by mineralisation during the growing season (Carey *et al*., 2011; Moir *et al*., 2013) was sufficient for unrestricted growth.

The lack of yield response to K fertiliser was consistent with reports in recent published work in Canterbury for fodder beet (Chakwizira et al. 2013) and seed potatoes (*Solanum tuberosum* L.) (Craighead and Martin, 2003). Similar results have also been reported overseas for a range of crops, including a related species, sugar beet (Draycott *et al*., 1974; Khan *et al*., 2013). The sites chosen for the current study had lower than the recommended optimum QTK values (≥5.0, Table 2). However, the TBK ranges of 2.3 – 2.8 at three of these sites (Table 2), indicated high K reserves, as both Edmeades *et al*. (2010) and Carey *et al*. (2011) have shown that near-maximum pasture production corresponds to TBK > 1.0. At these amounts, crops usually do not require high rates of K fertiliser to support high yield. Previous K research on other crops in New Zealand, such as forage brassicas (Wilson *et al*., 2006) and seed potatoes (Craighead and Martin, 2003), showed that K fertiliser did not significantly increase the DM yield, even when initial soil K amounts (QTK, TBK) were lower than recommended optima. These results also suggested that K fertiliser is necessary only as a replacement for the K taken up by the crop and removed from the paddocks (Trolove, 2010), to ensure K deficiencies do not occur in future from over-mining the soil reserves. Furthermore, as the fodder beet crops grow at high rates during the bulb expansion phase (Figure 1), with K uptake reaching over 10 kg K/ha/day (Buzas and Johnston, 1999), moderate K fertiliser may be beneficial to ensure crop demand for K does not exceed the supply of K from soil reserves (Trolove, 2010). In cereal crops, simulations of K requirement (Curtin *et al*., 2004) showed that K fertiliser should be applied to avoid deficiency during the rapid growth phase, when demand for K can reach 4–5 kg K/ha/day. The rate of release of K on differing soil types may be important in formulating K fertiliser recommendations.

Increasing the supply of K did result in higher tissue concentration and consequently total K uptake (Figures 2, 3). The increase in K concentration in the plant tissues across the sites was consistent with earlier findings on fodder beet (Chakwizira *et al*., 2013). The decrease of K concentration through the season (Figure 2), termed the nutrient dilution, has been reported for other nutrients in fodder beet (e.g. nitrogen; Chakwizira *et al*., 2016b) and was consistent with reports for other crops from similar photosynthetic group (C_3), such wheat (Justes *et al*., 1994; Ziadi *et al*., 2010), and forage kale (*Brassica oleracea var. acephala* L.) (Fletcher and Chakwizira, 2012; 2015). This was attributed to the increased DM as the season progressed. The K uptake values at crop maturity, excluding the late sown Riverton site (330 kg/ha) of 450 to 690 kg/ha were similar to the 500 kg/ha reported in an earlier study in Central Canterbury (Chakwizira *et al*., 2013) and overseas reports of 450-480 kg/ha for both fodder and sugar beet (Draycott and Christenson, 2003a, b). The lower K uptake at Riverton (Figure 3) was attributed to the late sowing of the crops (Table 1) because the paddock was wet and inaccessible in spring. These crops were still immature when harvested in May 2017, and had accumulated less K because of the shorter crop duration (Table 1). The high K uptake at the Orari and Gore sites (Figure 3) was associated with high K concentrations in the herbage (Figure 2) at Gore and high DM yield at Orari, and also the longer crop-growing duration at both sites. Whole-plant K uptake was comparatively low at the Southbridge and Riverton sites. At Southbridge this could also be related to the relative differences in biomass and a low K tissue concentration (Figure 3), and at Riverton, due to the low biomass yield (Figure 1) as a results of the shorter crop-growing duration (Table 1).

There was no significant treatment effect on potassium use efficiency (KUE) at the Southbridge site (Table 4), a reflection of the similar DM yields observed across the treatments and across the site. At all the sites, the soils were able to provide enough K for maximum production. There is a paradox here, as all the sites had QTK values below the reported optima for maximum production of crops (Nicholls *et al*., 2012), and yet similar yields were observed between the control crops and those receiving higher K fertilisers (e.g. 450 kg K/ha). These results could be attributed to the fact that up to one-third of New Zealand agricultural soils (soils derived from sedimentary parent materials) are typically high in reserve K (TBK) (Carey *et al*., 2011; Moir *et al*., 2013; 2017a), and can supply large amounts of K for plant uptake; therefore they are not likely to require high rates of K fertiliser (Chakwizira *et al*., 2013).

The QTK values measured at the final harvests for the 0 kg K/ha plots were consistently lower than the initial amounts determined before the crops were sown (Table 2). The differences between initial and the final QTK for the control crops meant that the fodder beet crops were mining soil K, which may have an effect on the following crops in the rotation, particularly if the fodder beet crops are lifted and fed off the paddock.

The amount of K taken up by crops was related to the rate of K fertiliser applied. The apparent recovery of K (KupE) was moderate, and ranged between 28% and 45% of the applied K fertiliser, with better recovery where less K was applied. The implication is that the crops took up K from both the applied fertilisers and residual K in the soil, either as available or reserve K. As the K fertiliser recovery rate was ≤45% (Table 4), the rest of the total uptake was attributed to the soil reserves. This is important, as it implies that K fertiliser requirements of fodder beet crops should be managed within the background of residual soil nutrient availability, and adjusted according to the K requirement of crops. The demand for nutrients by the crop following fodder beet, as well as the economics of production should also be considered in determining actual amounts of K applied. If fodder beet is lifted and fed off the source paddock, more fertiliser K may be required to restore the K offtake (Trolove, 2010). If animals are grazed *in situ,* then a maintenance rate of K should be applied, as most of the K will be returned in urine. Where farmers use a pasture block between daily grazing of fodder beet, the paddock should be treated as for lifted crops, as most of the K returns are deposited off the fodder beet paddock.

Results reported here show that even at low QTK, fodder rarely respond to K application, but take up large amounts of K, a sign that soils are able to provide K to the plant and this is mostly from the soil reserves. It is therefore suggested that soil tests methods should take more into account the K reserves of the soil. To this, the TBK test of Jackson (1985) can be used, particularly on sedimentary soils.

Conclusions

Potassium (K) treatments (rate and timing) did not affect DM yield, but the fodder beet crops took up large amounts of K. Potassium uptake increased linearly with increasing K applied across the sites. The K fertiliser recovery efficiency ranged between 28 and 45%, and utilisation efficiency was negligible, as there were no biomass differences among the treatments. These moderate K recovery rates mean background soil K amounts should be used to derive K recommendations.

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