Growth and nitrogen partitioning of fodder beet crops grown under varying amounts of water and nitrogen in shallow soils

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Abstract

The combined effects of water and nitrogen (N) on growth processes of fodder beet (*Beta vulgaris*) are not well known on shallow soils in New Zealand. Therefore an experiment was carried out on a shallow stony silt loam soil to investigate dry matter (DM) yield, N uptake and apparent N use efficiency (*a*NUE) under different irrigation (rain-fed and full irrigation) and N inputs (0, 50, 100 and 200 kg N/ha). Final harvest DM yield increased from 13 t DM/ha for the control N (0 kg N/ha) to 18 t DM/ha for the 200 kg N/ha in rain-fed treatments. Similarly, for the irrigated treatments DM yield increased from 23 to 28 t DM/ha for the same N treatments. Mean total N tissue concentration at the final harvest was higher for the rain-fed (2.6%) than the irrigated (2.1%) treatments. Thus, total N uptake was similar for the irrigation treatments but increased with N supply, from 185 kg/ha to 386 kg/ha for the control N and 200 kg N/ha treatments, respectively. Apparent NUE was higher for the irrigated (37 kg DM/kg N) than the rain-fed (22 kg DM/kg N) treatments. For the irrigated treatments, *a*NUE decreased from 49 to 22 kg DM/kg N applied for the 50 and 200 kg N/ha treatments, respectively, and was unaffected by N supply under rain-fed conditions. Under irrigated conditions optimum *a*NUE and DM yield were attained at 50 kg N/ha rate. Based on this single year results we recommend application of 50 kg N/ha for irrigated crops grown on shallow soils.

Additional keywords: *Beta vulgaris* L. subsp. *vulgaris var. alba*, apparent N use efficiency, nitrogen uptake

Introduction

Historically the main winter forage crops used for dairy cow feeding in the South Island of New Zealand are kale (*Brassica oleracea* var. *acephala* L.) and swedes (*Brassica napus* L. ssp. *napobrassica* (L.) Rchb.) (White *et al*., 1999). However in recent years there has been a major expansion of fodder beet (*Beta vulgaris* L. subsp. *vulgaris var. alba*) area (Gibbs, 2014; Milne *et al*., 2014) due to its yield and feed quality advantage over forage brassica crops (Draycott and Christenson, 2003; Chakwizira *et al*., 2013). There was an estimated 16,000 ha of fodder beet grown in New Zealand in the 2014-15 season (Gibbs, 2014; Milne *et al*., 2014), an increase of 60% over the previous three seasons (Matthew *et al*., 2011; Chakwizira *et al*., 2012). Furthermore, estimates by industry professionals suggest that the area has risen sharply to approximately 60,000 ha in the 2015-16 season. Recent studies in New Zealand have reported biomass yields >20 t DM/ha per year (Matthew *et al*., 2011; Chakwizira *et al.*, 2014a; 2014b; Edwards *et al*., 2014a) which are higher than those achieved with forage kale and swedes (Gowers *et al*., 2006; Fletcher *et al*., 2007; Chakwizira *et al*., 2009; 2011).

Major limitations to maximum dry matter (DM) production on the east coast of New Zealand are the prevalence of drought and variable soil nitrogen (N) fertility. Quantitative data on effects of N supply and water use on fodder beet production in deeper soils (>1.6 m in depth, with high water holding capacity (WHC) of ~190 mm/m depth) have been reported by Chakwizira *et al*., (2014a; 2014b). However the effects of water and N limitation and their interaction on growth of fodder beet crops in shallow soils with low WHC are less well known. There is a need to establish accurate irrigation and N recommendations for optimum production while allowing for differences in soil type, and therefore avoiding yield penalties due to undersupply (Chakwizira *et al*., 2014a; 2014b) or environmental pollution e.g. nitrate leaching due to oversupply of these key resources (Edwards *et al*., 2014b).

The objectives of this experiment were to determine the combined effects of water and N supply on DM yield, N uptake and N use efficiency of fodder beet crops grown on shallow soils of the Canterbury region of New Zealand.

Materials and Methods

The experiment was conducted at the Lincoln University's Ashley Dene (43° 38' 45.5" S 172° 20' 34.4" E, 30 m a.s.l) research farm in Canterbury, New Zealand in the 2013-14 season. The experiment was on a shallow Balmoral stony silt loam soil (*Udic Haplustept* loamy skeletal) (Webb and Bennett, 1986; Hewitt, 2010), with a shallow topsoil (0.2 m in depth). The soil has a WHC of about 90 mm/m of depth (Sim *et al*., 2012). The site had been previously under lucerne (*Medicago sativa* L.) from 2008 to 2011 followed by two successive forage kale crops from 2011 to 2013. The climate at the site is temperate, with mild to cool winters and warm summers (Figure 1). Mean annual rainfall is approximately 600 mm, distributed evenly throughout the year (NIWA, 2014). Weather data was retrieved from a temporary weather station located at the experimental site and average long-term (30 year) climate derived from 1970-2010 records (NIWA, 2014).

The cumulative evapotranspiration (ET) for the growing season was 644 mm and the total rainfall was 638 mm. However, the cumulative ET for the main growth period (sowing to 20 March) was 565.4 mm, compared with total rainfall of 387 mm (see Figure 1) (i.e. ~230 mm gap as irrigation). Furthermore, the total amount of rainfall for the end of season (after 20 March 2014) was 251 mm (~40% of the season total) compared with a cumulative ET of 81 mm. This meant there were no irrigation events after 20 March 2014.

The experiment was a randomised complete block design, with eight treatments arranged in a factorial combination of two rates of irrigation (rain-fed control and full replacement of potential ET twice weekly (max = 50 mm/week if no rain)) and four nitrogen rates (0, 50, 100 and 200 kg N/ha), replicated three times. The site was prepared by deep ploughing followed by power harrowing. Fodder beet ('Rivage'; a grazing type) was drilled on 3 November 2013 with an air seeder at 100,000 seeds/ha to establish at least 80,000 plants/ha. Row spacing was 0.5 m.

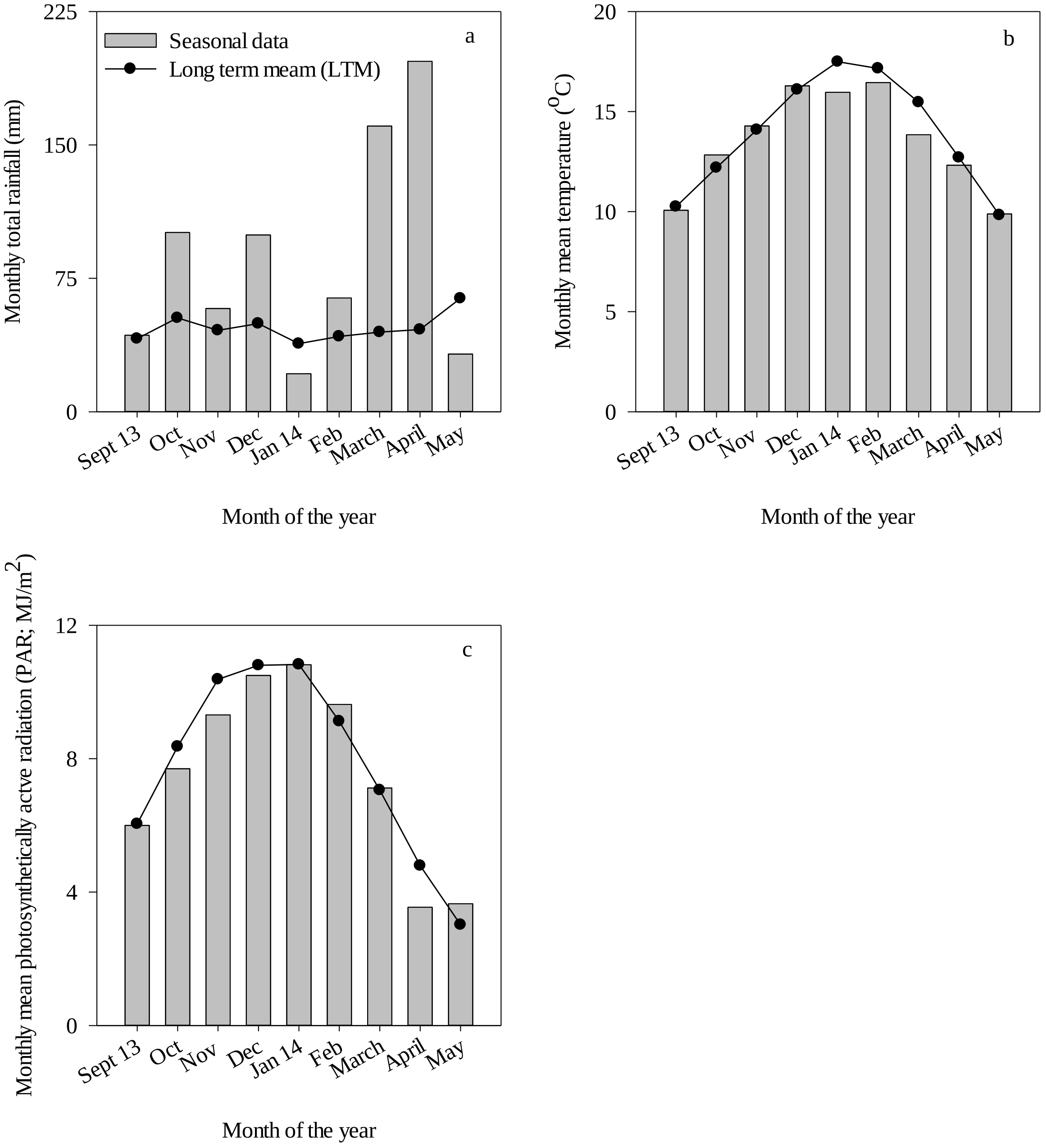

Figure 1: Monthly (a) total rainfall, (b) average temperature and (c) average photosynthetically active radiation (PAR) for Lincoln University's Ashley Dene research farm, Canterbury, New Zealand in the 2013-2014 season. Long-term (1970-2010) means obtained from a nearby Broadfield weather station (NIWA, 2014).

Table 1: Soil fertility test results (0-0.15 m) for the site. The 'optimum' values given are general recommendations for non-limited crop production (McLaren and Cameron, 1996; Nicholls *et al.*, 2012).

Experiment	pH	Olsen P	K	Ca	Mg	Na	Mineral N[a]
		mg/kg					kg/ha
Ashley Dene	5.8	16	160	1000	45	25	78 (136)
Optimum	5.8-6.0	20-30	120-200	500-1250	≥50	10-15	100-200

[a] The number in parenthesis is the total mineral N in the top 0.3 m (shallow soils).

Ten random soil samples to a depth of 0.15 m were taken on 30 July 2013 and average soil tests results are given in Table 1. The amounts of soil nutrients were determined as ‘MAF quick-test units’ (Mountier *et al*., 1966) and converted into mg/kg dry soil using the following conversion factors: P, x1.1; Ca, x125; K, x20; Mg and Na, x5 (Chapman and Bannister, 1994).

Basal fertiliser was applied as 250 kg/ha triple superphosphate (20.5% P and 1% S), 350 kg/ha sodium chloride (40% Na and 60% Cl), 200 kg/ha potassium chloride (52% K and 48% Cl), 10 kg/ha borate 46 (15% B) on 19 October 2013. Soil mineral N (nitrate and ammonium) tests were taken from individual plots, before the application of the N treatments and also at the end of the season to a depth of 0.3 m (shallow because of the limited soil depth). Nitrogen treatments were applied as urea (46% N) on three separate application dates (30, 57 and 91 days after sowing (DAS)) with 20%, 40% and 40% of the total N per treatment (0, 50, 100, and 200 kg N/ha) applied on each date, respectively.

Agrichemicals were applied to the crop when needed to control weeds, insects or disease infection at similar rates and timing to those described by Chakwizira *et al.* (2014b).

Dry matter (DM) yield

Dry matter (DM) harvests were taken at four-weekly intervals from 18 December 2013 to the final harvest on 21 May 2014. The area harvested per plot differed with the size of the crop: 1 m^2 per plot (1 m length by 2 rows of crop) for the first harvest, followed by 2 m^2 per plot (2 m length by 2 rows of crop) for all the later harvests from 17 January to the final harvest. Plant density and total fresh weight per harvest per plot were determined in the field at each harvest. A representative two-plant subsample was retained to determine total DM. Each subsample was partitioned into leaf lamina, petiole and bulb. However, DM yield partitioning was reported as shoot (combined petiole and leaf lamina) and bulb for simplicity. Dry weight was determined after drying, in a forced air oven at 60°C to constant weight. Total subsampled leaf lamina was used to `determine leaf area, using a leaf area meter (LI-COR model LI-3100; Lincoln, NE, USA). The total leaf area per quadrat was determined and used to calculate green leaf area index (GLAI; m^2/m^2). The accumulated GLAI and a critical GLAI ($GLAI_{crit}$: GLAI at which the crop was intercepting 90-95% incoming radiation) of 3-4 m^2/m^2 (Chakwizira *et al.*, 2016) were used to describe canopy development over the season.

Nitrogen uptake and use efficiency

Total N concentration (N%) for both the shoot and bulb fractions was determined by Dumas combustion using a LECO CNS-200 analyser (LECO Corporation, St Joseph, MI, USA). Total N uptake (kg N/ha) was calculated as the product of the DM yield and N% in the harvested crop.

Nitrogen-use efficiency was defined as an adjusted value (*a*NUE, Equation 1) (Baligar *et al*., 2001) and is analogous to the term 'agronomic efficiency'. In this calculation, yield response is adjusted for the additional yield above the control treatment (no N applied) (Asseng *et al*., 2001) and therefore does not account for the response due to residual soil mineral N as shown in the equation:

$$a\text{NUE} = \frac{\text{Crop biomass at } N\text{x} - \text{Crop biomass at } No}{\text{kg of N applied at } N\text{x}}$$

Where Nx = N rate > 0 and N_0 is crop yield for the control crops.

This differs from the traditional calculations of NUE as a quotient of total DM and total available N (soil N plus fertiliser N) (Moll *et al*., 1982).

Specific leaf nitrogen (SLN; g N/m^2 leaf area) was calculated as the quotient of leaf nitrogen content and specific leaf area (Massignam *et al*., 2001).

Data analysis

Data analyses were performed in GenStat version 17 (VSN International Ltd, UK) and figures were prepared in SigmaPlot v. 12.5 (Systat Software Inc. San Jose, CA, USA). Significant interactions and main effects were separated using Fisher's protected least significant difference (LSD) tests (α=0.05). Where values show $P < 0.1$, a trend is indicated in the text.

The DM yield, N uptake, N% and GLAI have been reported for the whole growing season, while the *a*NUE was reported for the final harvest.

Results

The soil mineral N tests at the end of the growing season showed that residual soil N was unaffected by both the irrigation and N treatments ($P>0.56$) averaging 24 (20-27) kg/ha to 0.3 m depth. This meant a nett of 112 kg N/ha (Table 1) was potentially available for crop uptake across the treatments. There were no interactions between treatments for any of the measured variables. Plant establishment was unaffected by treatments ($P>0.67$) with an average population of 76,600 plants/ha. Total DM yield at the final harvest increased with both irrigation and N treatments ($P\leq0.03$), from 13.7 t DM/ha for the control N (0 kg N/ha) to 18.5 t DM/ha for the treatments receiving 200 kg N/ha under the rain-fed treatments (Figure 2). Similarly, for the irrigated treatments total DM yield increased from 23.4 t DM/ha to 27.9 t DM/ha for the same N treatments. However, there were no differences among treatments receiving ≥50 kg N/ha for the irrigated treatments, with an average yield of 27.2 (26-27.9) t DM/ha and also the treatments that received 100 and 200 kg N/ha for the rain-fed treatments, with an average yield of 17.1 (15.8-18.5) t DM/ha.

The partitioning of DM to the bulbs and shoots showed a consistent pattern throughout the season (Figure 2). Shoot DM increased with both N supply and irrigation ($P<0.001$) throughout the growing season. For the rain-fed treatments shoot DM increased from 1.4 t DM/ha for the control N treatments to 2.3 t DM/ha for the treatments receiving 200 kg N/ha. Similarly, for the irrigated treatments shoot DM increased from 2.3 to 3.7 t DM/ha for the respective N treatments. For irrigated treatments shoot DM increased with increasing total biomass up to mid-February (108 DAS) and remained constant until mid-April (163 DAS). However, for the rain-fed treatments shoot DM decreased from about 2.2 t DM/ha in mid-January (Figure 2 b) to means of 1.5 and 1.7 t DM/ha for the February and March harvests, respectively. The maximum shoot DM yields of 5.3 and 3.8 t DM/ha were attained at the 200 kg N/ha rate in April (irrigated) and May (rain-fed) (Figure 2), respectively. However, for the irrigated treatments shoot DM yield decreased to 3.5 t DM/ha at the final harvest.

The bulb DM yield increased with irrigation (P<0.001) but was unaffected by N supply (P=0.28) (Figure 2). At the final harvest, bulb DM yield for the rain-fed treatments increased from 11.2 to 13.7 t DM/ha for the control N and 200 kg N/ha treatments, respectively. In parallel, the bulb yield for the irrigated treatments increased from 20 to 23 t DM/ha for the respective N treatments. The bulb DM yield for the 200 kg N/ha treatment under irrigated treatments remained unchanged from mid-April (163 DAS) until final harvest. However, bulb DM for ≤100 kg N/ha treatments continued to increase until final harvest at 199 DAS. For the irrigated treatments, the proportion of the total DM that was bulb decreased with water stress (P=0.013) and N supply (P=0.003), from 0.85 for the control N treatments to 0.82 for the plots receiving 200 kg N/ha. Similarly, for the rain-fed treatments the proportion of the bulb decreased from 0.82 to 0.74 for the same N treatments.

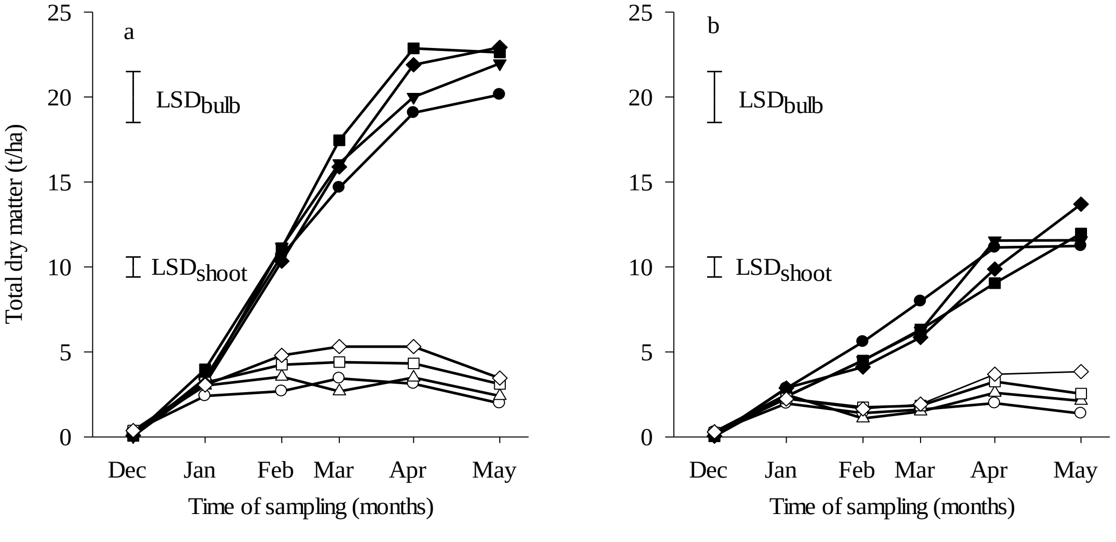

Figure 2: The accumulation of dry matter (DM) yield of bulb (closed symbols) and shoot (open symbols) for irrigated (a) and rain-fed (b) fodder beet grown under different nitrogen rates (kg N ha^{-1}): 0 (●○), 50 (▼∆), 100 (■□) and 200 (◆◇) at Lincoln University's Ashley Dene research farm, Canterbury, New Zealand in 2013-14 season. Bars represent the least significant differences (LSD$_{0.05}$; d.f. = 60).

The GLAI increased with both irrigation and N supply ($P<0.001$) (Figure 3a). However, the difference between irrigation treatments did not extend beyond April as there was sufficient late season growth with high rainfall events in March and April (Figure 1). The accumulation of GLAI for the rain-fed treatments was cyclic; increased rapidly to a mean of 1.7 m^2/m^2 by mid-January. Thereafter, the GLAI decreased to 1-1.4 m^2/m^2 between February and March (Figure 1) before increasing rapidly to maximum values in April of 2 m^2/m^2 for the control N and 3.7 m^2/m^2 for the 200 kg N/ha treatments. Furthermore, the maximum GLAI for the irrigated treatments was attained from mid-February to mid-March period and ranged between 2.6 and 4.2 m^2/m^2 across the N treatments. At the final harvest GLAI was unaffected by irrigation and increased from 1.5 m^2/m^2 for the control N to 2.9 m^2/m^2 for the 200 kg N/ha treatments. Overall, only the 100 and 200 kg N/ha treatments under both irrigation treatments attained the $GLAI_{crit}$ of 3-4 m^2/m^2 (Figure 3a), between February and April for the irrigated treatments and between April and May for the rain-fed treatments.

Total N concentration (N%) at the final harvest increased with both irrigation and N supply ($P<0.001$). For the irrigated treatments N% increased from 1.8% to 2.1% for the control N and 200 kg N/ha treatments, respectively. Comparably, for the rain-fed treatments N% increased from 2.0% to 2.6% for the respective N treatments. The N% decreased with time over the growing season, from 4.4% at the first harvest to 1.3% at the final harvest. Total N uptake increased with N application rate and irrigation ($P<0.001$) up to the April harvest (Figure 3b). In April total N uptake under the rain-fed treatments increased from 160 to 310 kg/ha for the control N and 200 kg N/ha and also increased under the irrigated treatments from 230 to 370 kg N/ha for the same N treatments. However, there were no differences in N uptake between the irrigation treatments at the final harvest in May; with N uptake increasing two-fold to 386 kg/ha for the treatments receiving 200 kg N/ha compared with the control N treatments.

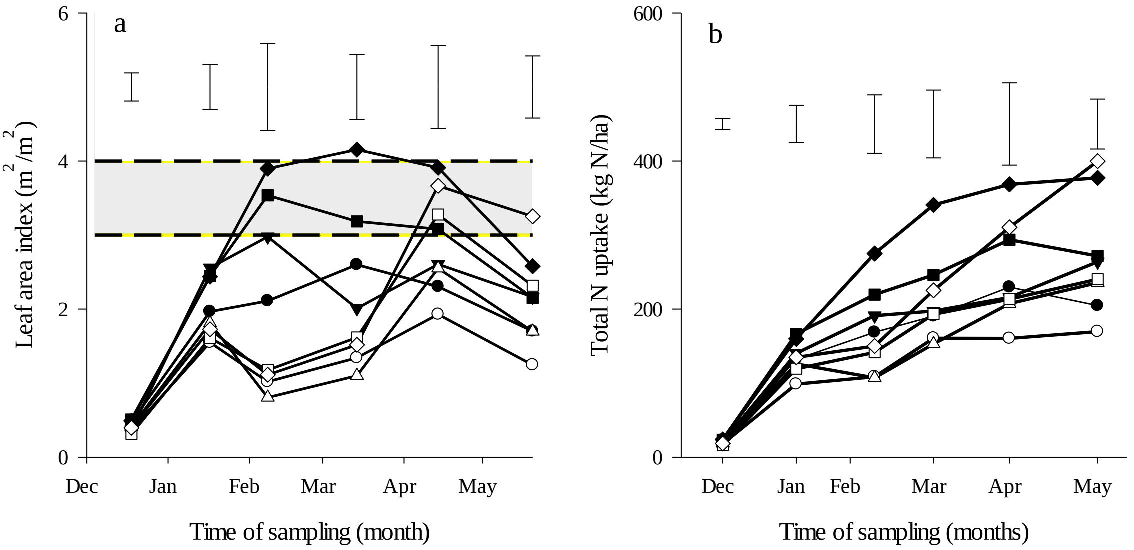

Figure 3: The accumulation of (a) leaf area index and (b) total N uptake for the irrigated (closed symbols) and rain-fed (open symbols) fodder beet grown under different nitrogen rates (kg N/ha): 0 (●○), 50 (▼Δ), 100 (■□) and 200 (◆◇) at Lincoln University's Ashley Dene research farm, Canterbury, New Zealand in 2013-14 season. Bars represent the least significant differences (LSD$_{0.05}$). The grey area (dotted lines) indicates a critical range of GLAI (GLAI$_{crit}$) when radiation interception is between 90 to 95% of total incoming radiation.

Both N and irrigation treatments resulted in increased bulb N uptake throughout the growing season. But effects were inconsistent at the final harvest when bulb N uptake was unaffected by irrigation (P=0.16) but increased with N supply (P<0.001) from 124 kg/ha for the control N treatments to 257 kg/ha for the treatments receiving 200 kg N/ha. Both N and irrigation treatments had no effect (P≥0.30) on the proportion of N in the bulb to total N uptake, with an average of 66% of the total N in the bulb. Late-season N uptake was higher in the rain-fed treatments with comparable final N accumulation in both water treatments.

At the final harvest specific leaf N (SLN) decreased with irrigation (P<0.05) but was unaffected by N supply (P=0.15) (Table 2). The mean SLN for the rain-fed treatments was 2.8 g N/m^2 compared with 2.2 g N/m^2 for the irrigated treatments and averaged 2.5 across the N treatments. During the growing season the SLN for the rain-fed treatments attained maximum values (3.2-3.6 g N/m^2) during the drier periods at the end of summer/ early autumn (Figure 1) when leaf area was at its lowest (Figure 3). However, the SLN for the irrigated treatments remained constant at 2.2 (2.0-2.6) g N/m^2 throughout the growing season.

The *a*NUE increased with water supply, from a mean of 22 kg DM/kg N applied for the rain-fed treatments to 37 kg DM/kg N applied for the irrigated treatments (Table 2). However, *a*NUE was independent of N treatments, decreasing with increasing N under irrigation and remaining constant (mean of 22 kg DM/kg N applied) under the rain-fed conditions.

Table 2: The impact of N application on specific leaf nitrogen (SLN) and apparent nitrogen use efficiency (*a*NUE) of fodder beet grown with or without irrigation at Lincoln University's Ashley Dene farm, Canterbury, New Zealand in 2013-14 season.

N rate (kg N/ha)	SLN (g N/m^2)		*a*NUE (kg DM/kg N)	
	Irrigated	Rain-fed	Irrigated	Rain-fed
0	2.2	2.6	-	-
50	2.2	2.9	49.0	23.0
100	2.2	2.8	40.0	21.0
200	2.3	3.0	22.0	24.0
$LSD_{\alpha=0.05}$				
Water (W)	0.1		18.7	
N rate (N)	0.2		16.1	
W^{x}N	0.3		28.0	

Discussion

There were no interactions of irrigation and N treatments on any of the measured variables. Similar plant population across the treatments meant that any differences in other measured variables (e.g. DM yield) were driven by the actual treatments. The increase in DM yield with both irrigation and N supply (Figure 2) was consistent with previous reports (Chakwizira *et al.* 2014a; 2014b). The mean yield of 27.2 t DM/ha for the treatments receiving ≥50 kg N/ha for the irrigated treatments (Figure 2) was within the range of 25-28 t DM/ha reported by the same authors for fodder beet treatments receiving 100-200 kg N/ha. There were no DM yield differences for the treatments receiving ≥50 kg N/ha for fully irrigated treatments (Figure 2); this coupled with the high yield averaging 23 t DM/ha for the irrigated, control N treatments could be attributed to the relatively high background soil N (136 kg N/ha) in the top 0.3 m of soil profile at the site (Table 1). These results could also be attributed to the irrigation technique employed in this experiment, of irrigating more frequently, with less water per irrigation event (twice per week, see Material and Methods). The increased frequency of irrigation was proposed to minimise drainage below the rooting zone in these shallow soils. This was the opposite of the recommendations of applying more water, less frequently in deep soils (Chakwizira *et al*., 2014b). The decrease of the proportion of bulb DM with both water stress and N supply meant that the crops grown under rain-fed treatment and higher N rates contained a greater relative proportion of shoot component and hence, by implication, higher feed quality. Chakwizira *et al*. (2013) reported higher crude proteins and fibre content and lower metabolisable energy in the shoot compared with the bulbs of fodder beet crops.

The DM yield of 13-18 t DM/ha for the rain-fed treatments was 56-66% of the total DM yield under irrigation across the N treatments. The difference in yield between irrigation treatments was attributed to the cyclic accumulation of GLAI for the rain-fed treatments (Figure 3a), characterised by pronounced GLAI decrease during the dry summer period (January-February). Leaf senescence was higher than leaf appearance during this period, hence the decreasing GLAI. Furthermore, during the same period, the GLAI for all the N treatments under the rain-fed treatments was below the critical green leaf area index ($GLAI_{crit}$), implying that these treatments were not intercepting all the radiation available for growth. This was particularly important as the canopy for the rain-fed treatments was not closed during the summer period, when both mean temperatures and radiation (Figure 1b, c) are highest in this environment. However, after the late season rainfall, the GLAI for the rain-fed, high N treatments increased rapidly from mid-March across the N treatments and attained the $GLAI_{crit}$ in mid-April. This late-season rain (Figure 1b) coincided with decreasing temperatures and radiation (Figure 1b, c) and therefore did not boost yield.

The *a*NUE was higher for the irrigated than rain-fed treatments. This is consistent with reports for other C_3 plants e.g. wheat (Asseng *et al*., 2001). The continuous availability of soil moisture under irrigated conditions allowed the irrigated treatments to take up N consistently through the growing season and accumulate more DM for the same N rates compared with rain-fed treatments and hence the higher efficiencies. Furthermore the decrease in *a*NUE with N supply for the irrigated treatments (Table 2) was also consistent with the results of Chakwizira *et al*. (2014a) who reported a decrease from 63 kg DM/kg N applied for the 50 kg N/ha treatments to 34 kg DM/kg N applied for the 200 kg N/ha treatments. This compares closely with the 49 and 22 kg DM/kg N applied for the same treatments in the current experiment (Table 2). However *a*NUE was unaffected by N supply under rain-fed conditions, averaging 22 kg DM/kg N applied. This was due to the proportional increment in additional DM between treatments with increasing rate of N applied under the rain-fed treatment, while there were no differences between the treatments receiving ≥100 kg N/ha under irrigation.

The increases in N uptake (Figure 3) with N supply were similar with the values and trends reported previously (Chakwizira *et al*., 2014a). However N uptake was unaffected by irrigation, which could be explained by the timing of N application, rainfall distribution (Figure 1a), and overall DM accumulation patterns (Figure 2). For all treatments 60% of the fertiliser was applied by 10 December 2013 and this period received about twice the long-term mean rainfall (Figure 1a). Some of the N fertiliser may have been lost through early leaching. This period was followed by a very dry period in January-February, coincidentally the period when the remaining 40% of the fertiliser was applied. In the rain-fed treatments N may have been leached at both ends of the season, remained unused during the dry summer period (January-February), thus compromising DM production. The high rainfall period at the end of the season would have likely allowed the rain-fed treatments to take up any available N that was resident in soil and hence similar amounts were taken up by the crops under both irrigation treatments. This was reflected in the higher N% for the rain-fed compared with the irrigated treatments leading to higher late-season N uptake in the rain-fed treatments, comparable with final N accumulation in both water treatments.

The higher SLN for the rain-fed crop (Table 2) may have been due to the late rapid N uptake (Figure 3) as a result of the replenished soil moisture (Figure 1) from mid-season to the final harvests. Lack of response to N supply could be a result of high initial soil N levels (Table 1) which meant proportional leaf N per unit leaf area. However, Chakwizira *et al*. (2014a) reported increase in SLN with N supply in deeper soils with moderate initial soil N.

Conclusions

Final DM yield increased with both irrigation and N supply. Furthermore N uptake increased with N supply but was unaffected by irrigation treatment. However these results were most likely influenced by the rainfall pattern during the growing season. Late-season N uptake was higher in the rain-fed treatments, resulting in similar total N uptake in both water treatments at the end of the season. The apparent NUE increased with water supply and N rate under irrigated conditions. This confirms the importance of irrigation in the management of N and associated risks of leaching in crop production. Under irrigated conditions optimum *a*NUE and DM yield were attained at 50 kg N/ha rate. These results could have been influenced by the high initial soil N levels (136 kg N/ha) at the site and the irrigation technique (twice per week) employed in this experiment which meant less water was lost through drainage. The crops showed a capacity to take up N later in the season when soil moisture conditions were suitable and there was a residual N supply in the soil available for uptake. Based on this single year results we recommend application of 50 kg N/ha for irrigated crops grown on shallow soils.

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