Water use efficiency of fodder beet crops

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Abstract

In New Zealand, summer rainfall is unpredictable and usually insufficient to meet crop water requirements. The impact of water availability on yield potential of fodder beet (*Beta vulgaris* L.) is unknown. A single year, single site replicated field experiment investigating biomass production, water use (WU) and water use efficiency (WUE) was carried out on a deep Templeton silt loam soil at Lincoln in 2013. The experiment had four water treatments: 1: Rain fed control, 2: Full potential evapotranspiration (ET_o) replaced weekly, 3: 50% of ET_o replaced every 3 weeks and 4: 50% of ET_o replaced weekly. Final dry matter (DM) yield differed with treatments, increasing from an average of 24 t/ha for the rain fed crops and those receiving 50% of ET_o weekly to 28 t/ha for the full ET_o replacement crops and those receiving 50% of ET_o once every 3 weeks. Water use more than doubled with full irrigation compared with the rain fed crops (774 vs 316 mm). The WU for the intermediate crops was 483 mm. However, DM yield was higher for the treatment with 50% of ET_o replaced every 3 weeks rather than weekly. Water use was related to DM yield and accounted for the observed variation ($R^2=0.75$) in final yield. The WUE decreased with water supply, from 80 kg DM/ha/mm for the rain fed crops to 46 kg DM/ha/mm for the full ET_o replacement treatments, and 64 and 57 kg DM/ha/mm for the 50% of ET_o replaced weekly and every 3 weeks, respectively. Similar DM yield and marginal WUE for the full ET_o treatments and those receiving 50% of ET_o replaced every 3 weeks, meant that the most economic WUE was 57 kg DM/ha/mm. Although these results are from a single and site, they suggest that full ET_o replacement was uneconomic in this type of soil and therefore partial irrigation to 50% of ET_o replaced every 3 weeks may be the optimum for this type of soil. It is recommended to investigate similar treatments on shallow and stony soils.

Keywords: *Beta vulgaris* L., evapotranspiration, water use, water use efficiency, water extraction pattern, water extraction depth.

Introduction

Droughts are a major limitation to crop productivity in the east coast and central North Island regions of New Zealand (Burrows & Greenland 1979). Summer rainfall is unpredictable and usually insufficient to meet crop water requirements. For example, in Canterbury, potential evapotranspiration (ET_o) in summer, accounts for approximately twice the mean rainfall (Jamieson *et al.* 1995). Furthermore, most of the soils used for fodder beet (*Beta vulgaris* L.) production in these areas are shallow and stony with low water holding capacity. In these situations, yield may be compromised when the crop is exposed to extended periods of restricted water availability. There is lack of information on the effects of water supply on fodder beet production in New Zealand, with most of the current recommendation based on data from overseas or other species, e.g. sugar beet (DairyNZ 2013; Brown *et al.* 1987).

Both fodder beet and sugar beet are sensitive to drought, especially during establishment (Brown *et al.* 1987; DairyNZ 2013; Martin *et al.* 1983), but tolerant once the root system has been established. Current recommendations for irrigated fodder beet are to apply irrigation little and often prior to canopy closure and increase both return interval and rate as the season progresses. This encourages deeper and more efficient rooting. However, overwatering in late autumn encourages high humidity under the canopy which can exacerbate leaf diseases and reduce green leaf area. Brown *et al.* (1987) reported that early drought affected fibrous roots of sugar beet more severely than late drought. Early drought reduced leaf canopy expansion, and consequently, reduced total accumulated radiation intercepted (RI) by the crops, while late drought led to premature senescence of the leaves. Drought reduced radiation use efficiency (RUE; g DM/MJ), from 1.64 g DM/MJ for the fully irrigated crops to 1.37 and 1.51 g DM/MJ for the early and late drought crops, respectively. Consequently, DM yield decreased from 21 t/ha for the fully irrigated crops to 16.1 t/ha and 17.9 t/ha for the early and late drought treatments, respectively. Both RI and RUE decreased with water stress. The RI decreased by 8% for both early and late drought treatments, while RUE decreased by 27% and 13% for the early and late drought treatments, respectively, compared with the fully irrigated crops. These results suggests that RUE was the more dominant factors in limiting DM production, a similar conclusion reached for other forage crops, e.g. forage rape *(Brassica napus spp.*

Biennis) and bulb turnips *(Brassica rapa spp. rapifera; syn. B. campestris)* (Chakwizira & Fletcher 2012).

For other forage crop species, Jacobs *et al*. (2004a) reported a higher WUE for the rain fed crops: ryegrass (*Lolium perenne* **L**.), two brassica species (Hunter, *Brassica campestris x Brassica napus* and PG545) and millet (*Echinochloa utilis*) compared with those under full ET_o replacement and deficit irrigation. Martin *et al*. (2006) identified 20 kg DM/ha/mm as an appropriate benchmark for irrigated dairy pastures for Canterbury region of New Zealand. Furthermore, Moot *et al*. (2008) reported WUE of 7 to 40 kg DM/ha/mm, for a range of pastures in New Zealand, with the high WUE attributed to the application of sufficient N. For forage brassicas species, Jacobs *et al*. (2004b) reported WUEs of 6–45 kg DM/ha/mm for forage turnips, while Nielsen *et al*. (2000) reported WUE of 15–38 kg DM/ha/mm for four forage brassicas with clear differences between species. The conclusion drawn from these results (Jacobs *et al.* 2004a, b; Martin *et al.* 2006; Moot *et al.* 2008) was that WUE varied with crop species.

Matthew *et al*. (2011) reported that more precise fodder beet management is required to achieve desired populations (8–10 plants per m^2) and yields than with the traditional winter feeds, e.g. forage brassica crops. However, high yields (19–35 t/ha) and quality of fodder beet make it an attractive and cost effective winter feed option. Previous research in New Zealand has focussed on soil fertility and fertilisers and their effect on DM production and feed quality (Chakwizira *et al.* 2012, 2013b, 2014; Goh & Magat 1989; Magat & Goh 1988). However, the influence of water availability on fodder beet production in New Zealand is still unknown, particularly for the summer dry east coast regions of Canterbury and Otago where most of the crops are grown. The objectives of this experiment were to describe DM response of fodder beet to water deficit, and determine the relative crop water use and water use efficiency under differing irrigation regimes. It is envisioned this knowledge will be used to derive recommendations for optimum soil water management to maximise yield and feed quality for fodder beet crops.

Material and Methods

The experiment was conducted at The New Zealand Institute for Plant & Food Research Limited, Lincoln (43.83°S, 171.72°E), Canterbury, in New Zealand. The site was situated on a deep (>1.6 m), well drained Templeton silt loam (Immature Pallic soil (Hewitt 2010); Udic Ustochrept (Soil Survey Staff 1998)) with an available water-holding capacity of about 190 mm/m of depth (Jamieson *et al*. 1995). Physical characteristics of the soil were reported by Martin *et al*. (1992).

The experiment was a randomised block design, with four water treatments, replicated four times. Fodder beet seed (cv. 'Rivage') was direct drilled with an air seeder at 100 000 seeds/ha on 29 October 2012, to establish at least 80 000 plants/ha. Seeds were sown at a row spacing of 500 mm, which is the standard with sowing contractor machinery. The four water treatments were: **1:** Rain fed control, **2:** Full potential evapotranspiration (ET_o) replaced weekly (max 50 mm per week if no rain), **3**: 50% of ET_o replaced every 3 weeks (max = 25 × 3 = 75 mm (if no rain)) and **4:** 50% of ET_o replaced weekly (max = 25 mm (if no rain)). Irrigation was based on cumulative ET_o at the Broadfield weather station (NIWA 2014) located about 50 m from the experimental site. The actual amount of water calculated to replace ET_o was reduced by the amount of rainfall in the period between irrigation events. For treatments 3 and 4, 50% of ET_o adjusted for rainfall was applied at each irrigation event. The cumulative ET_o for the growing season was 774 mm and the site received 316 mm of rainfall during the same period (Figure 1). Irrigation totals for treatments 2, 3 and 4 were 458, 163 and 170 mm, respectively, for the period between sowing and the final harvest. Irrigation treatments were imposed on 6 December 2012 (39 days after sowing; DAS) applying sufficient water to replace full ET_o (treatment 2) and 50% of ET_o (treatments 3 and 4). Plot sizes were 4 m wide × 10 m long.

The site was prepared by deep ploughing followed by power harrowing. Ten soil samples to 0.15 m depth were randomly taken on 21 August 2012. Soil test results were: pH 6.3, P 16 mg/kg, Ca 10 mg/kg, K 7 mg/kg, Na 7 mg/kg, S 5 mg/kg and mineralisable N 79 kg/ha. 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: Ca, ×125; K, ×20; Mg, Na, ×5; P, ×1.1(Chapman & Bannister 1994). Basal fertiliser was applied on 29 October 2012 at 250 kg/ha triple superphosphate (20.5% P), 350 kg/ha sodium chloride (40% Na and 60% Cl), 200 kg/ha potassium chloride (52% K and 48% Cl), 15 kg/ha boronate (10% B) and 108 kg/ha urea (46% N). Additional N as urea was applied twice, at 50 kg N/ha on 29 November 2012 and 100 kg N/ha on 21 December 2012, giving a total of 200 kg N/ha for the growing season. Weeds, pest and disease were controlled as shown in Table 1.

Environmental data (Figure 1) were collected on-site. Long-term data were obtained from the Broadfields Meteorological Station (NIWA 2014).

Measurements

Neutron probe (NP) access tubes and Time Domain Reflectometer (TDR) wave guides were installed for the duration of the experiment in each plot following seedling emergence. Volumetric soil water content was measured at 2-weekly intervals from 6 December 2012.
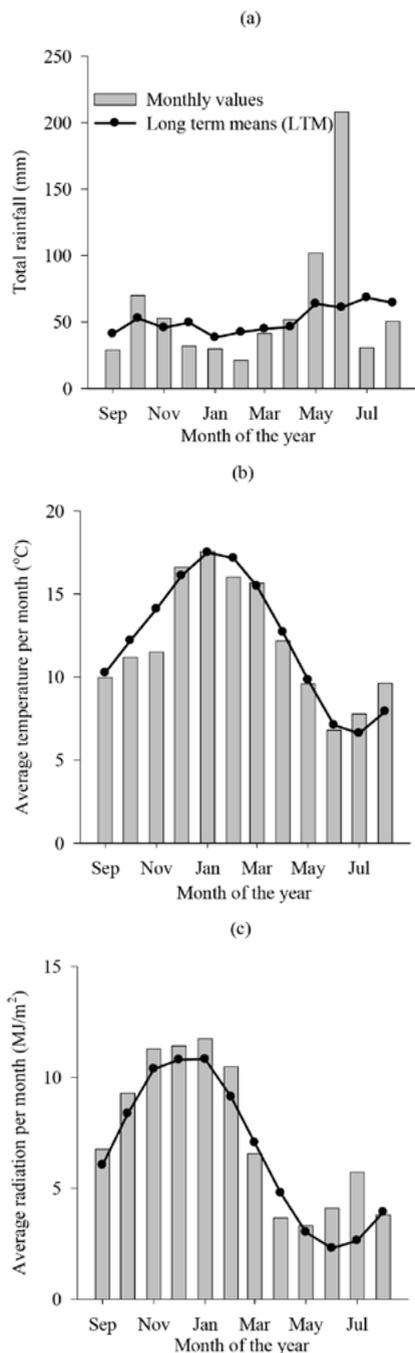
Figure 1   Monthly (a) rainfall (mm), (b) average temperature (°C) and (c) average photosynthetically active radiation (PAR; MJ/m^2) for the growing season (September 2012 to August 2013) and long-term mean (LTM) data at Lincoln, Canterbury, New Zealand. Long-term data are from 1970 to 2010 (NIWA 2014).

Measurements were made in 0.2 m increments to a depth of 1.6 m. The 0–0.2 m depth was measured using TDR, while all other measurements were made using NP.

Seasonal crop water use (WU) was calculated from volumetric soil water content between the current day and the start of the experiment (29 October 2012), plus any inputs from irrigation and/or rainfall. The WU values reported here included water lost due to transpiration and evaporation. It was assumed that drainage losses were negligible for the soil type of this experiment. The water extraction pattern and cumulative water deficit were determined to 1.6 m depth for all the treatments. Water extraction pattern was determined for the rain fed treatment alone as irrigation confounded the interpretation of the water extraction in the other treatments (Fletcher *et al.* 2010). Water use efficiency (WUE; kg DM/ha/mm) was calculated as the linear regression of the sequential crop dry matter (DM) measurements plotted against WU for the duration of the experiment. Dry matter data were not available from when soil water measurements were initiated and therefore the linear fits were not forced through the origin. The economic WUE, defined as the ratio of the marketable unit of yield per unit of water used (the cost of the water used) (Dalton 2000; Martin *et al.* 2006), was based on total amount (irrigation + rainfall) of water recieved. Marginal water use efficiency (MWUE; kg DM/ha/mm irrigation water) was calculated as the additional DM produced (DM yield minus control (rain fed) DM yield) from applied water (Jacobs *et al.* 2004a).

Dry matter harvests were taken at 4-weekly intervals from 20 January until 15 May 2013. At the first harvest 1 m^2 was harvested per plot and 2 m^2 per plot for all subsequent harvests. Plant population and total fresh mass were determined at each harvest. A representative 2-plant subsample was retained to determine %DM. Subsamples were partitioned into leaf lamina, petiole and bulb. However, DM yield partitioning is reported as shoot (combined petiole and leaf lamina)

Table 1   Herbicides and insecticides applied during establishment of the fodder beet crops grown at Lincoln, Canterbury in 2012–13.

Herbicide	Active ingredient[1]	Application rate (/ha)	Date applied (2012)
Nortron®	500 g/litre ethofumesate (WSC)	2 litres	30 October
		200 ml	29 November
		200 ml	10 December
		500 ml	22 December
Betanal® Forte	160 g/ litre phenmediphan and 160 g/ litre desmediphan (EC)	500 ml	29 November
			10 December
		1 litre	22 December
Goltix® DF	700 g/kg metamotron (WD)	1 kg	29 November
			10 December
			22 December
Lorsban™	50% chlorpyrifos (EC)	1 litre	30 October
Gallant™ Ultra	520 g/ litre haloxyfop (EC)	500 ml	31 December

[1] EC=emulsifiable concentrate, WSC= water soluble/ suspension concentrate, WD=water dispersible
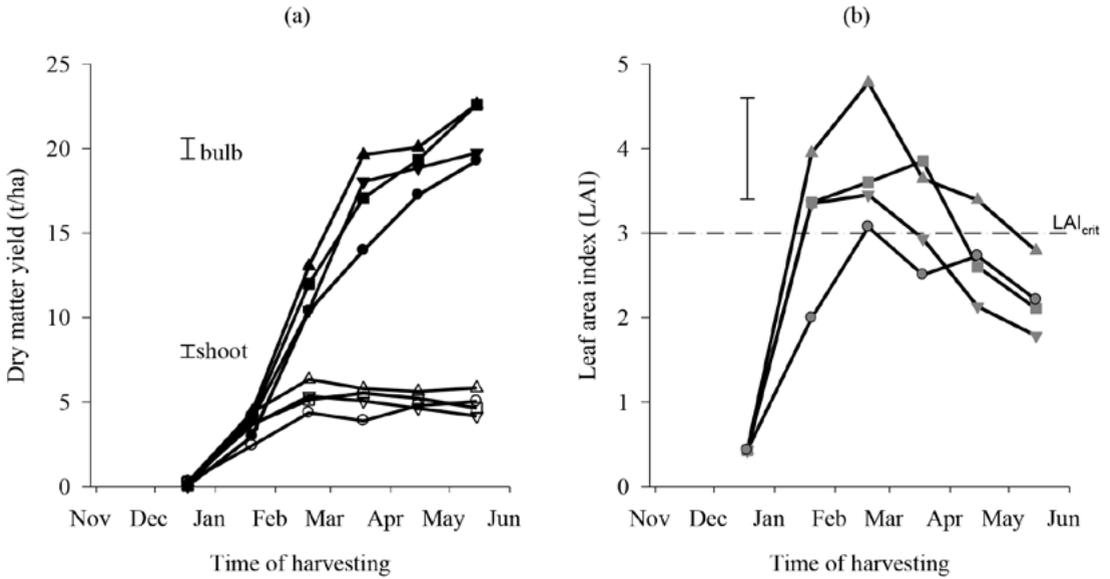
Figure 2   The accumulation of: (**a**) bulb dry matter yield (black symbols) and shoot dry matter yield (open symbols) and (**b**) leaf area index (grey symbols) for fodder beet crops grown under different irrigation regimes (mm water/ha): Rain fed (O), full ET_o replacement ($\triangle$), 50% ET_o replacement every 3 weeks ($\square$), 50% ET_o replacement every week ($\triangledown$) at Lincoln, Canterbury in 2012–13. Vertical bars represent the least significant differences ($LSD_{0.05}$; d.f. = 35) determined by MANOVA. LAI_{crit} = critical leaf area index (Martin 1986; Milford *et al.* 1980).

and bulb for simplicity. Total subsampled leaf lamina was used to determine leaf area, using a leaf area meter (LI-COR model LI-3100; Lincoln, Nebraska, USA) and used to calculate leaf area index (LAI). Dry mass was determined after drying at 60°C to constant weight. The accumulated LAI and a critical LAI of 3 (LAI_{crit}: LAI at which the canopy is intercepting $\geq$ 95% of the incident radiation; Martin 1986; Milford *et al.* 1980) was used to describe canopy development over the season. The specific leaf area (SLA) was calculated as the ratio of leaf area (cm^2) per plant to leaf dry weight (Albayrak & Çamas 2007; Evans & Poorter 2001)

Total N concentration for both the shoot and bulb fractions were determined by the Dumas combustion using a LECO CNS-200 analyser (LECO Corporation, St Joseph, MI). Total N uptake was then calculated by multiplying plant component DM yield by the concentration of N in the harvested component. Specific leaf nitrogen (SLN; g N/m^2 leaf area) was calculated as the quotient of leaf nitrogen content and specific leaf area.

Data analyses

Data were analysed using multivariate analysis of variance (MANOVA) for repeated measures and analysis of variance (ANOVA) for single measurements. 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. All analyses were performed in GenStat v.14 (VSN International, Hemel Hampstead, UK) . The regression lines were fitted for the treatment means at each harvest. Water use efficiency parameters (slopes, and intercept) were also calculated per plot and analysed through ANOVA, to confirm comparisons among the treatments. The R^2 was used to describe the pooled variation of the dataset from the fitted model.

Results

At the final harvest, the number of plants was unaffected (P=0.27) by the irrigation treatments, averaging 86 000 plants/ ha. However, dry matter (DM) yield differed (P<0.001) with treatments, increasing from an average of 24 t/ha for the rainfed crops and those receiving 50% of weekly potential evapotranspiration (ET_o) to 28 t/ha for the full ET_o replacement crops and those receiving 50% replacement of ET_o once every 3 weeks.

The bulbs represented 79–83% of total DM yield at the final harvest (Figure 2) and accounted for 99% of the variation in total DM yield (Figure 3). Between the first harvest (84 DAS) and the final harvest (199 DAS), for every 1 t/ha increase in total DM, the bulb DM increased by 0.91(±0.04) t/ha. Bulb DM yield increased (P<0.001) from 19.5 t/ha for the rainfed crops and those receiving 50% of weekly ET_o to 22.6 t/ha for the full ET_o replacement crops and those receiving 50% replacement of ET_o once every 3 weeks. Between 64 and 78% of the total bulb DM was accumulated between January and March; the period
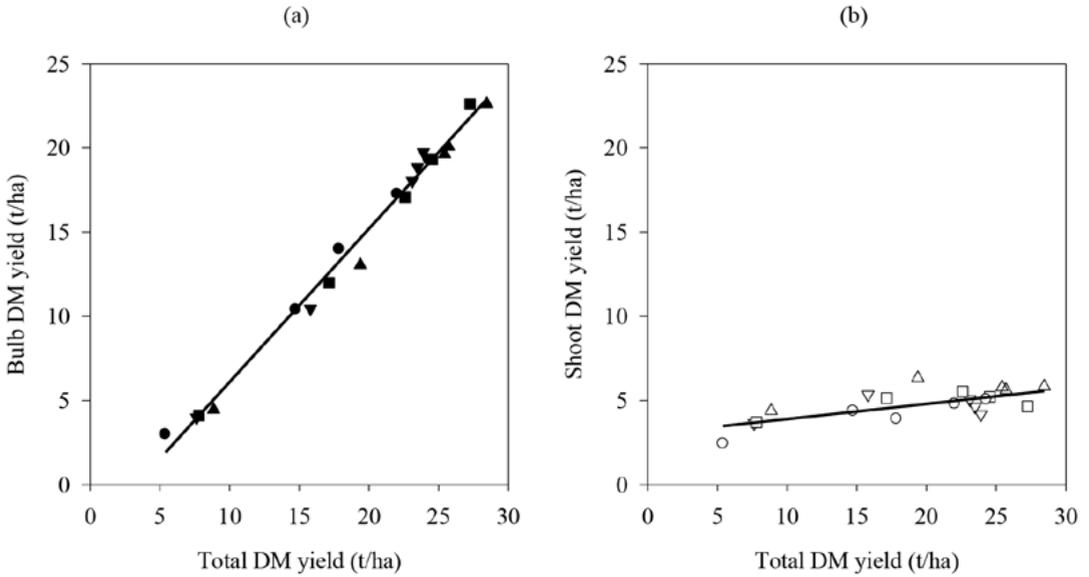
(a)

(b)

Figure 3   Relationship between **(a)** bulb DM and total DM yields (Y=0.91(±0.04)x - 3(±1.1); R² = 0.99), **(b)** shoot DM and total DM yield (Y=0.09(±0.04)x+ 3(±1.4); R² = 0.49) for fodder beet crops grown under different water treatments: Rain fed (○), full ET$_o$ replacement (△), 50% ET$_o$ replacement every 3 weeks (□), 50% ET$_o$ replacement every week (▽) at Lincoln, Canterbury in 2012–13. Bracketed values represent SE for coefficients.
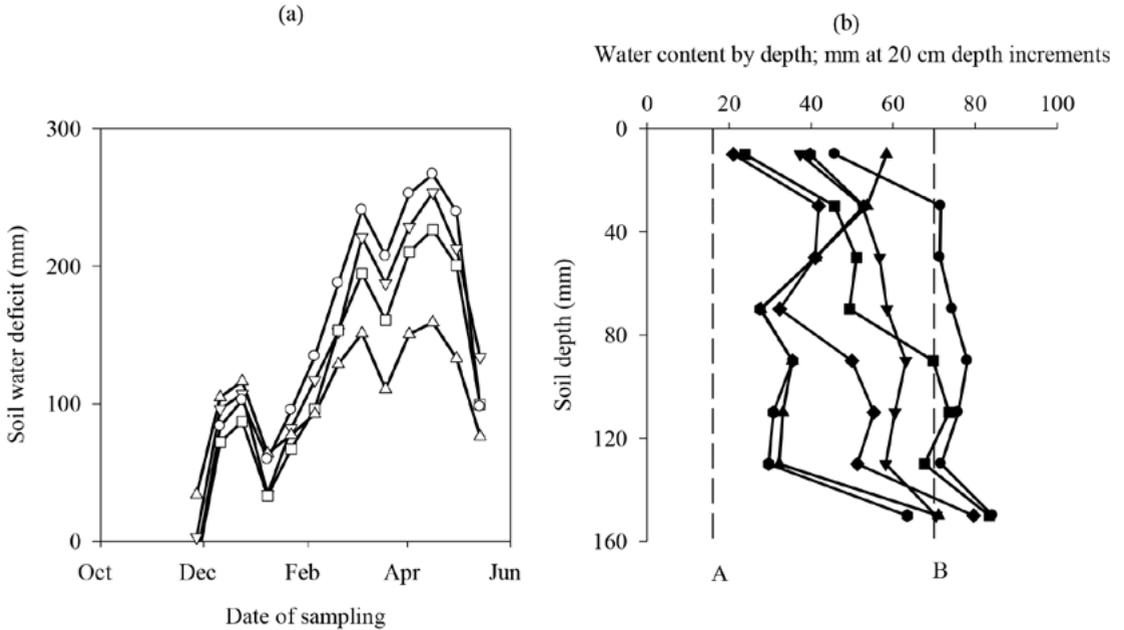
(a)

(b)

Water content by depth; mm at 20 cm depth increments

Figure 4   Soil water deficit under a fodder beet crop grown under (a) Rain fed (○), full ET$_o$ replacement (△), 50% ET$_o$ replacement every 3 weeks (□) or 50% ET$_o$ replacement every week (▽) irrigation treatments and (b) water extraction pattern for the rain fed crop ((●, 27 November 2012, ▼ 24 December, ■ 22 January 2013, ◆19 February, ▲ 19 March and ● 30 April (dotted lines represent: A = stress point and B = field capacity for this soil)) at Lincoln, New Zealand.

when all irrigated plots were at or above the LAI$_{crit}$.

Shoot DM yield increased (P<0.001) with time until mid-February (118 DAS; Figure 2a), and then declined. During the same period, shoot DM was consistently lower (P=0.004) for the rain fed crops, compared with the average of the irrigated treatments (which were similar). The LAI for the rain fed crops was consistently below the LAI$_{crit}$ throughout the season (Figure 2b). At the final harvest, shoot dry matter represented 17 to 21% of total DM yield.
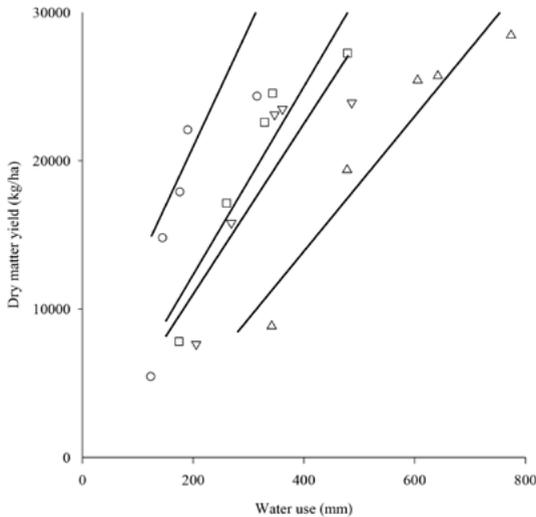
Figure 5   The relationship between dry matter yield (kg/ha) and water use (mm) for fodder beet crops grown under Rain fed (○; Y=80(±24)x + 1694(±5587) (R²=0.64)), full evapotranspiration (ET₀) replacement (△; Y=46(±8)x - 4307(±4392) (R²=0.92)), 50% ET₀ replacement every 3 weeks (□; Y=57(±13)x - 505(±4894) (R²=0.75)), 50% ET₀ replacement every week (▽; Y=64(±14)x - 371(±5306) (R²=0.86)) conditions at Lincoln, Canterbury in 2012–13. Bracketed values represent SE for coefficients.

The water deficit increased over time (Figure 4a) following the pattern of increasing water demand (Figure 4b). Water deficit was consistently highest in rain fed crops and lowest in those under full ET$_o$ replacement, e.g. 252 mm vs 150 mm, respectively, at the end of March. As expected, soil water deficit decreased when it rained. For example, in March the site received 30 mm of rain on 17 March 2013 and 41 mm for the month. Total rainfall for December–March was lower than the long term mean (Figure 1) and hence the rapid increases in water deficit under the crops with nil or partial irrigation (Figure 4), e.g. from 60 mm on 8 January to 253 mm on 2 April for the rain fed crops.

Water extraction by the rain fed crop is presented in Figure 4b. The crops extracted most of their plant available water to a depth of about 1.4 m by mid-March. During January to mid-March (Figure 1), water extraction was negligible in the top 0.3 m of the soil profile. However, after March rainfall, water content increased in the top 0.7 m. The total WU increased (P < 0.001) from 316 mm for the rain fed plots to 774 mm for the fully irrigated plots. The 50% ET$_o$ replacement treatments used 483 mm.

The water use efficiency (WUE) decreased (P<0.001), from 80 kg DM/ha/mm for the rain fed crops to 46 kg DM/ha/mm for the plots with full ET$_o$ replacement (Figure 5). The WUE for the intermediate water treatments were 57 kg DM/ha/mm for the plots under 50% ET$_o$ replacement every 3 weeks and 64 kg DM/ha/mm for those under 50% ET$_o$ replacement every week. These intermediate treatments also differed from the full ET$_o$ replacement and rain fed plots.

Nitrogen (N) uptake was higher (P=0.01) for the crops receiving full ET$_o$ replacement and 50% ET$_o$ replaced every 3 weeks at an average of 303 kg/ha, compared with an average of 255 kg/ha for the rain fed crops and those receiving 50% of ET$_o$ every week (Table 2). The SLA also differed (P<0.001) with treatments, lowest for the rain-fed crops and highest for the full ET$_o$ crops. The intermediate treatments had similar SLA values but differed from both the rainfed and full ET$_o$ crops. The SLN was higher (P=0.02) for the rain fed crops than for all the water treatments.

The MWUE of 18 kg DM/ha/mm irrigation water for the 50% replacement of ET$_o$ once every 3 weeks was higher (P=0.07) than the 50% of weekly ET$_o$ replacement crops, but was similar to the full ET$_o$ replacement crops.

Discussion

These results show the importance of water supply on fodder beet production (Figure 2). The increase in DM yield (Figure 2a) from about 24 t/ha for the rainfed crops and those receiving 50% of weekly ET$_o$ to 28 t/ha for the full ET$_o$ replacement crops and those receiving 50% ET$_o$ replacement once every 3 weeks was explained by doubling in WU with irrigation from 316 mm for the

Table 2   Total nitrogen uptake, specific leaf nitrogen (SLN) and specific leaf area (SLA) and marginal water use efficiency (MWUE) for fodder beet crops grown under different water treatments.

Treatments	N uptake (kg/ha)	SLN (g N/m² leaf)	SLA (cm²/g)	MWUE (kg DM/ha/mm)
Rain fed control	248	2.4	148	-[a]
50% ET$_o$ replaced weekly	260	2.2	162	-2.4
50% ET$_o$ replaced every 3 weeks	297	2.1	167	18.0
Full weekly ET$_o$ replaced	310	2.1	175	9.0
LSD	36	0.2	7.5	17

[a]MWUE is calculated as the difference between irrigated treatments and the rainfed control.

rain fed plots to 774 mm for the fully irrigated plots. This was consistent with findings in other forage crops, e.g. kale (Chakwizira *et al.* 2013a) where WU increased from 263 mm for the unirrigated crops to 537 mm for the fully irrigated crops. The differences in DM yield can also be explained by the differences in N uptake, SLA and SLN (Table 2) among the respective water treatments.

Water use efficiency (WUE) for fodder beet decreased with irrigation (Figure 5), from 80 kg DM/ha/mm for the rainfed crops to 46 kg DM/ha/mm for the full ET_o replacement crops. This was consistent with findings in other forage crops, e.g. brassica species, ryegrass, and millets (Jacobs *et al.* 2004a, b), where WUE was highest for the rain fed crops and lowest for the fully irrigated crops. Jacobs *et al.* (2004a) reported a WUE of 87.8 kg DM/ha/mm for the rain fed millet compared with 28.1 kg DM/ha/mm for the fully irrigated millet crops. The WUE for the 50% of ET_o replaced at weekly and fortnightly intervals, were intermediate at 44.0 and 54.3 kg DM/ha/mm, respectively. The high WUE for rain fed millets was attributed to its ability to utilise water stored in the soil profile. A similar pattern to the results of Jacobs *et al.* (2004a) was established for the fodder beet in the current experiment. However, previous experiments carried out under a rain-out shelter (which automatically covers the experimental site during rainfall events) under the same environment by Fletcher *et al.* (2010) and Chakwizira *et al*. (2013a) reported WUE of 34.1 and 40 kg DM/ha/mm for kale, respectively. In both experiments, water treatments (variable rates and frequency of irrigation) had no effect on WUE. Furthermore, the WUE values reported in our trial are higher than the 20 kg DM/ha/mm reported by Martin *et al*. (2006) for irrigated dairy pastures and 7 to 40 kg DM/ha/mm (Moot *et al*. 2008) for a range of pasture species. It is unclear why there are large differences with previously reported results, from the same environment. Neilsen *et al*. (2000) reported that WUE differed with crop species, double for turnips compared with forage rape and kale. The differences between our results and those previously reported could be attributed to species differences. Fodder beet may have the abiltiy to utilise most of the water stored in the soils or is more efficient user of available water over the summer period, similar to millets (Jacobs *et al.* 2004a). The ability to utilise stored water is supported by the extraction of water from deeper into the soil profile (Figure 4b).

The MWUE was similar (Table 2) for the high yielding treatment (Figure 2): 50% ET_o replaced once every 3 weeks and full ET_o replaced treatments and therefore the economic WUE was 57 kg DM/ha/mm for the former. This meant that it was not economic to fully irrigate this crop in this type of soil. Even though

not statistically different, the MWUE of 9 kg DM/ha/mm irrigation water for the full ET_o replacement crops compared with 18 kg DM/ha/mm irrigation water for the 50% ET_o replaced once every 3 weeks, meant that it made sense to partially irrigate these crops in these deep soils.

Total water use by crops differed in the respective treatments. Intermediate water treatments had similar WU (483 mm), but the 50% ET_o replaced once every 3 weeks treatments produced more DM yield (ca. 4 t/ha; Figure 2a) than when ET_o was replaced weekly. The implication was that the frequency, as well as amount of water applied per irrigation event were important for fodder beet. The WUE was 7 kg DM/ha/mm higher when a longer return interval was used. The deep, well-drained (Templeton silt loam) soils have a high water holding capacity of 190 mm/m depth (Jamieson *et al.* 1995) and this influenced the way soil water is used. Deficits may occur at the surface while sufficient water is stored at depth. Applying more water per irrigation event raised the root zone soil water to near field capacity (B; Figure 4b). These deep soils were able to hold onto the water for longer periods, due a larger storage capacity and reduced soil evaporation under a closed crop canopy. This also meant that the whole root volume was exposed to adequate moisture and able to take up more nutrients, particularly nitrogen (Brown *et al.* 1987). This was supported by the differences in nitrogen uptake (Table 2) for the rain fed plots (248 kg N/ha), compared with the full ET_o replacement plots (310 kg N/ha). Chakwizira *et al*. (2013a) reported that the WUE for kale crops increased with N supply, from 35.3 kg DM/ha/mm for treatments receiving ≤30 kg N/ha to 40.6 kg DM/ha/mm for those receiving ≥120 kg N/ha. Furthermore, under the longer return intervals, farmers are able to irrigate more paddocks per cycle. However, when less irrigation is applied more frequently (e.g. 50% ET_o replaced weekly) the entire root zone may not be entirely refilled in these deep soils, thus crops are continuously under moderate stress and potentially functioning at suboptimal nutrient uptake.

The SLA increased with water supply (Table 2) from a low of 148 cm^2/g for the rain fed crops to 175 cm^2/g for the full ET_o replacement crops. Wilson *et al.* (1999) reported that low-SLA leaves function more efficiently in resource-poor environments where retention of captured resources is a higher priority, and this may have improved the photosynthetic capacity of the rain fed crops, hence the high DM yield. Moreover, the SLN was highest for the water stressed crops (Table 2). The SLN of 2.1–2.4 g N/m^2 leaf was consistent with the 2.50–3.15 g N/m^2 reported by Chakwizira *et al.* (2014). The net photosynthesis of crop leaves and/or canopies is closely linked to the SLN (Sinclair & Horie 1989). Furthermore, the net photosynthesis of a crop can be

represented by radiation use efficiency (RUE; Monteith, 1977); which decreases when SLN falls below a critical threshold (Sinclair & Horie 1989). Both the SLA and SLN in this experiment may have contributed to the high DM yield for the rain fed crops.

The water deficit reported for the full ET_o replacement crops (Figure 4a) could be attributed to the fact that the generic ET_o calculation are based on a well watered grass reference crop (Allen *et al.* 1998). However, other crops species differ in key factors that affect water loss, such as rooting depth (and water extraction depth), greater for fodder beet at 1.4 m (Figure 4b) than ryegrass (0.8–1.1 m; Parry *et al.* 1992), and also crop height and canopy cover. This, coupled with the fact that water defit in our experiment was determined to a depth of 1.6 m, meant that we were underestimating the water demand for the fodder beet crops. Usually the taller crops with larger canopies are exposed to more wind and hence increased transpiration. The water extraction depth of about 1.4 m (Figure 4b) was similar to those reported for other forage crops, e.g. forage brassicas (Chakwizira *et al.* 2013a; Fletcher *et al.* 2010) grown at the same site.The rapid increase in accumulated water deficit across the treatments (Figure 4a) until March was due to the dry spell experienced during that time (Figure 1) compared to the long term means. However, as the crops were already established, the dry spell had minimum effects on the rain fed crops in these deep soils, as shown by the DM yield of 24 t/ha.

The DM yields (Figure 2) are consistent with those reported for the Canterbury region of 21–32 t DM/ha for irrigated fodder beet (Chakwizira *et al.* 2012, 2013b, 2014). The proportion of the bulb to total DM yield (79–83%) was similar to the range reported by Matthew *et al*. (2011) and Chakwizira *et al.* (2013b, 2014). The LAI for the rain fed crops was consistently below the LAI_{crit} throughout the season. The decline in LAI (Figure 2a) towards the end of the summer period, particularly for rain fed plots and also in those receiving less water but more frequently, may be associated with premature senescence (Brown *et al.* 1987) of larger, older leaves under water stress. This finding is consistent with previous reports involving fodder beet (Chakwizira *et al*. 2014) and other forage crop species (Wilson & Maley 2006).

Conclusions
The DM yield increased from 24 t/ha for the rainfed crops and those receiving 50% of weekly ET_o to 28 t/ha for the full ET_o replacement crops and those receiving 50% replacement of ET_o once every 3 weeks. For the intermediate (50% of ET_o) treatments, DM yield was higher when more water was applied less frequently. The WUE of fodder beet decreased as the quantity of applied irrigation increased, but a higher marginal

WUE for the 50% ET_o replaced once every 3 weeks and full ET_o treatments meant that the economic WUE was 57 kg DM/ha/mm. This was significantly higher than other forage species grown under similar environments. The overall conclusion drawn from this experiment was that, when grown under deep soils with high water holding capacities, it was not be economic to irrigate fodder beet. However, most of the fodder beet crops are grown on shallow soils in Canterbury and Otago regions and therefore irrigation may still be required. It is therefore recommended to investigate similar treatments on shallow and stony soils in Canterbury and/or Otago regions.

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