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Growth, Development, and Nitrogen Uptake of Fodder Beet (*Beta vulgaris L.*) Crops Grown Under Differing Rates and Timing of Nitrogen Fertiliser in New Zealand

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ABSTRACT

Fodder beet (*Beta vulgaris* L.) is an important forage crop used for cattle wintering in New Zealand. Regional nitrogen (N) fertiliser experiments over two seasons (2016–2018) consisting of different N application rates (0–300 kg N/ha) and times of N application (sowing, canopy closure, and mid-bulb development stage) were used to validate yield responses. Within site, there was a maximum of 3 t DM/ha difference in total biomass yield between control (no N) and high N treatments at maturity. Near maximum fodder beet yield was achieved in all sites with a rate of 100 kg N/ha applied as urea (split applications). Near optimum yields were achieved on higher fertility sites with preseason soil nitrate-N + ammonium-N (0–15 cm depth) of 75 kg N/ha or greater. Little additional fertiliser N was required for maximising crop yield. However, enhanced plant N concentration and crop N uptake were achieved with rates up to 300 kg N/ha. Fertiliser N management that stimulated full canopy expansion with optimum green leaf area (GLA) and GLA duration was required to maximise yield. Important management practices for maximising yield include the use of N fertiliser for earlier crop canopy closure and enhanced canopy duration during bulb development.

1 | Introduction

Nitrogen (N) fertiliser management is central to the profitability and sustainability of forage crop production (Massignam et al. 2009; Wang et al. 2003). However, in New Zealand, clear N fertiliser guidelines are lacking for the production of fodder beet (*Beta vulgaris* L.) which is used extensively for winter dairy feed production systems. The current recommendations for N management are often based on dated local data (Stephen et al. 1980) or data from overseas research (Albayrak and Yuksel 2010; Khogali et al. 2011; Turk 2010) and from sugar beet (*Beta vulgaris* L) crops bred for high sugar content (Martin 1980; Martin et al. 1982; Milford et al. 1980).

The area under fodder beet in New Zealand increased from an estimated 16,000 ha (Gibbs 2014; Milne et al. 2014) in 2013 to about 60,000 ha (Chakwizira et al. 2016a, MPI 2016) and fell to 48,000 ha in 2024 (NZ Plant Breeders' Research Association, Pers. Comm.). Approximately 80% of fodder beet is grown for feeding pregnant, nonlactating dairy cows during winter, though there is an increasing area dedicated to winter feeding in the sheep, beef, and deer sectors. This rapid increase was a result of potential high dry matter (DM) yield (>20 t/ha), appropriate feed quality (Chakwizira et al. 2014a); high grazing utilisation (>90%) (Edwards et al. 2014a; Edwards et al. 2014b) and perceived lower risks of N leaching losses in comparison with alternative winter-fed forages (Dalley et al. 2017; Edwards et al. 2014a; Malcolm et al. 2016). An emerging use of fodder beet, supplemented with higher protein content feed, is for extending milking in autumn. This may be managed by timely N fertiliser applications for early canopy development and longer leaf area duration and/or increase in the N content of tops and bulbs.

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Fodder beet yield at farm level is frequently below potential (the maximum based on genetic potential and climate), which has compromised the profitability of the crop. The yield potential in most regions is between 25 and 28 t DM/ha (Khaembah et al. 2017), but reported yields are often lower (13–20 t DM/ha) (Judson et al. 2016; Matthew et al. 2011; Milne et al. 2014). Occasionally, crops produce >30 t DM/ha (Matthew et al. 2011). These high-yielding crops are generally on highly fertile sites and invariably first crops in rotations after permanent pastures. The impact of foliar disease carry-over and nascent infection on yield potential presents a continuing barrier to sustainable high productivity (de Ruiter et al. 2017).

The bulbs of fodder beet make up to 75–85% of the total crop biomass (Chakwizira et al. 2018b, Khaembah et al. 2020), and are key to its value as a high-energy feed for a range of stock classes (Dalley et al. 2017; de Ruiter et al. 2018). A key to producing high yield is to promote early leaf growth, thus promoting light capture for longer (Chakwizira et al. 2016b), and optimising mineral uptake and water exploration by fine roots (Chakwizira et al. 2014b). Rapid production of leaves, and attainment of maximum green leaf area (GLA) assist the efficient uptake of water and nutrients.

Recent studies on fodder beet yield response to K, sodium (Na) and chloride (Cl) fertilisers (Chakwizira et al. 2012, 2013) and N and/or water (Chakwizira et al. 2014a, 2014b, 2016a) in Canterbury require validation with data from other fodder beet growing areas in New Zealand (e.g., Southland, Taranaki, and Waikato (Table 1)) to receive wider acceptance as standard practice. Traditional fertiliser recommendations often include potassium and boron applications. However, recent trials on potassium (K) and boron (B) fertiliser rates on yield formation have shown no response to these elements in sedimentary soils over a range of locations in New Zealand (Chakwizira et al. 2018a).

Evidence from studies on sugar beet in the northern hemisphere (Draycott and Christenson 2003) and from New Zealand work (Kemp et al. 1994; Stephen et al. 1980) has been used for industry recommendations for N fertiliser for fodder beet. However, there are few recent studies on the N fertiliser requirements of fodder beet in New Zealand conditions (Chakwizira et al. 2014a; 2016a; 2016c). On shallow soils, under rainfed and irrigated treatments, total biomass gains were <5 t DM/ha, comparing control (0N) with N applications up to 200 kg/ha (Chakwizira et al. 2016a). On moderate fertility free-draining soils, yield gains were <10 t DM/ha over a range of 0–200 kg N/ha applied (Chakwizira et al. 2014a). Recommendations for N applications on commercial farms are required covering a range of soil fertility. Reduction in productivity caused by suboptimal N status is difficult to predict given the high variability in N supply in differing soil types, locations, and land management combinations.

The objective of this study was to quantify the effects of N fertiliser rate and timing of application on fodder beet production, and to define optimum N fertiliser requirements across a range of locations with differing soils and climates in New Zealand.

2 | Materials and Methods

Experiments on N fertiliser responses were conducted over two growing seasons (2016–17 and 2017–18) in commercial crops established with commonly available cultivars and management practices (Table 1). The sites included dairy, arable cropping, and the sheep and beef land uses. Crops were rainfed except for two irrigated sites in Canterbury. Local contractor practices and differing sowing equipment resulted in small differences in crop establishment. Industry standard row spacing of 0.50 m was used, which allowed for lifting of crops for offsite feeding, storage or grazing in-situ. Sowing rates were set to establish 80,000–90,000 plants per ha (Table 1; Chakwizira et al. 2018a), to enable early leaf area expansion, longer leaf area duration, and optimised bulb development. Within each paddock, the trial area chosen excluded all paddock-level fertiliser inputs but allowed other paddock management.

TABLE 1 | Crop details (cultivar, sowing details, final harvest date, and season duration) at each of the seven sites in season 1 (2016–17) and four in season 2 (2017–18).

Site	Cultivar	Sowingdate	Populationsown (seeds/ha)	Finalharvest date	Growing season duration, d
Season 1					
Waikato (Cambridge)	'Ribambelle'	24 Oct 16	80,000	3 May17	192
Taranaki (Opunake)	'Rivage'	18 Nov 16	90,000	21 Apr 17	155
Whanganui (Fordell)	'Rivage'	20 Nov 16	100,000	29 Mar 17	130
Canterbury (Southbridge)	'Rivage'	26 Oct 16	83,000	29 May 17	224
South Canterbury (Ōrarī)	'Geronimo'	11 Oct 16	90,000	22 May 17	224
Southland (Gore)	SF Brigadier	17 Oct 16	90,000	10 May 17	206
Southland (Riverton)	SF Blaze	3 Dec 16	85,000	9 May 17	158
Season 2					
Waikato (Cambridge)	'Bangor'	25 Sep 17	100,000	23 May18	241
Whanganui (Fordell)	'Rivage'	1 Nov 17	100,000	14 May 18	195
South Canterbury (Ōrarī)	'Geronimo'	25 Oct 17	90,000	15 May 18	203
Southland (Mossburn)	'Bangor'	23 Oct 17	80,000	30 May 18	220

TABLE 2 | Treatments showing the sowing and mid-season N fertiliser rates (N2–N5): and additional late application of N fertiliser (N6–N8) at all sites in season 1 (2016–17) and season 2 (2016–17). Basal fertiliser was applied for nonlimiting phosphorus, potassium, boron, sodium, and sulphur.

Treatment (Season/N)	N at sowing	N at canopy closure	N at end of Feb	Total N applied
		kg N/ha		
1/N1	0	0	0	0
1/N3	50	50	0	100
1/N4	100	100	0	200
1/N5	150	150	0	300
1/N6	20	40	40	100
1/N7	40	80	80	200
1/N8	60	120	120	300
2/N1	0	0	0	0
2/N2	25	25	0	50
2/N3	50	50	0	100
2/N4	100	100	0	200
2/N5	150	150	0	300

2.1 | Experimental Design and Treatments

In season 1, experiments consisted of seven independent trials (Table 1) each with seven N fertiliser treatments (Table 2). In season 2, there were four independent trials, each with five N treatments (Tables 1 and 2). Experiments at all locations were randomised complete block designs. Season 1 and 2 had four and three replications, respectively. Plot dimensions were 10 x 3 m. In the first season, trials were located in Southland, Canterbury, Whanganui, Taranaki, and Waikato (Table 1). In the second season, trials were in Southland, South Canterbury, Whanganui, and Waikato (Table 1).

The N fertiliser treatments (0–300 kg N/ha; Table 2) were applied as urea on three dates (first season) and two dates (second season) at key growth stages, representing the current New Zealand standard of applying N fertiliser at sowing and canopy closure (second season) and adding a third application at the start of senescence (first season). The application of N fertiliser on three dates was aimed at maintaining GLA for longer and to encourage continued biomass accumulation into autumn.

2.2 | Soil Fertility

Base soil fertility (soil minerals and anaerobically mineralisable nitrogen (AMN)) at each site was determined to 0.30 m depth (Table 3) in both seasons before cultivation of the paddocks. A common base fertiliser was evenly applied to each site irrespective of the site background fertility (Table 3) to ensure no nutrients were limiting production. This was made up of 50 kg P/ha as triple superphosphate (20% P), 300 kg K/ha as potassium chloride (50% K), 59 kg Na/ha as AgSalt (39% Na), and 4.5 kg B/ha as boronate (15%B).

Soil mineral N (nitrate and ammonium) was determined to 0.9 m depth in 0.3 m increments (or to stone depth) in both seasons. Samples for mineral N were stored in transit over ice, then stored at 4°C for extraction in 2 M KCl using the method of Keeney and Bremner (1966). Calculations of the amount of mineral N per ha assumed a soil bulk density of 1.0 g/cm^3.

TABLE 3 | Soil properties[a] measured in 0–30 cm soil layer before cultivation at each of the sites in respective seasons; 2016–17 and 2017–18.

Season/Site	pH	Olsen P	Ca	Mg	K	Na	B	TBK	AMN[b]
		µg/mL	QTU	QTU	QTU	QTU	ppm	me/100g	µg/g
Season 1									
Waikato (Cambridge)	5.7	20	6	17	14	8	2.7	–	82
Taranaki (Opunake)	6.1	27	9	24	7	11	1.3	0.6	118
Whanganui (Fordell)	5.4	13	10	19	6	11	1.1	2.3	95
Canterbury (Southbridge)	6.3	17	10	18	3	11	1.0	2.3	39
South Canterbury (Ōrarī)	6.1	18	12	17	5	9	1.2	–	54
Southland (Gore)	6.2	32	12	26	5	9	1.8	2.8	88
Southland (Riverton)	5.7	11	10	19	3	12	1.2	0.3	80
Waikato (Cambridge)	5.7	44	8	34	13	3	–	1.4	53
Whanganui (Fordell)	5.9	16	9	23	4	8	–	1.6	88
South Canterbury (Ōrarī)	5.9	14	11	13	4	3	–	3.4	51
Southland (Mossburn)	6.0	20	10	13	5	3	–	1.8	134
Optimum fertility[c]	*5.8–6.2*	*20–30*	*4–10*	*5–10*	*5–8*	*5–8*	*1.5–2.0*	*0.8–1*	*100–200*

[a]Phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), boron (B), tetraphenyl boron K (TBK), and anaerobically mineralisable nitrogen (AMN).
[b]Values given for 0-15 cm depth.
[c]The optimum soil background nutrient values are given for nonlimited, general crop production (McLaren and Cameron 1996; Nicholls et al. 2012).

2.3 | Yield Components

In both seasons, a similar set of measurements were taken to monitor crop performance. DM yield harvests were taken three times (canopy closure in first season only, mid-season and maturity) during growth. The harvest at canopy closure was from a 0.5 m^2 quadrat (single 1 m row length). For mid-season and final harvests in both seasons, a 6 m length x 2 row field sample was taken from each plot. The number of plants harvested and total fresh weight per harvest per plot were determined in the field at each harvest. A representative two-plant subsample from each plot was retained, and portioned into green leaf lamina, dead leaves (lamina + petiole), petiole, and bulbs. The bulbs were finely chopped, and all yield components were dried at 60°C in a forced-air oven until constant weight was achieved. Weights of dried samples were used to calculate moisture content and total DM yield.

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

2.4 | Canopy Development

Reflectance measurements were undertaken to assess canopy development, i.e., ground cover, at each of the harvest dates using GreenSeeker (GS, Trimble Agriculture Division, CO, USA). Reflectance values on each measurement date were calculated from ≈70 measurements obtained from a 10×0.6 m area of each plot, at a height of 0.6 m above the crop canopy. The values obtained were converted into a scaled normalised difference vegetation index (Carlson and Ripley 1997; Chakwizira et al. 2015) and this was used as a surrogate for percentage of crop ground cover. In the South Island, a drone was also used to determine fractional ground cover by discriminating plant material from soil.

All green leaf lamina from the subsamples were 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 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. 2018b) were used to describe canopy development over the season.

2.5 | Data Analyses

Data were analysed in GenStat v.17 (VSN International, Hemel Hampstead, UK) using a Residual maximum likelihood (REML) analysis to adjust for a model with harvest timing factor. Significant interactions and main effects were separated using Fisher's protected least significant difference (LSD) tests ($P = 0.05$). Data were analysed initially by year, to determine significance of fertiliser rate and timing effects. A combined season analysis was also performed using a REML analysis on a reduced factor dataset including only common N treatment levels and rates.

3 | Results

3.1 | General Soil Fertility

Soil test results were variable, with soil pH, Olsen P, K, B, and Na being adequate for general crop production (Nicholls et al. 2012) in some paddocks in one or both seasons (Table 3). Only calcium (Ca) and magnesium (Mg) were adequate for production at all sites (Nicholls et al. 2012). However, the Mg levels were lower than 25–30 QT Mg required to increase crop (pasture) Mg content to >0.2% (Dawson et al. 2020), and therefore adequate for animal health (O'Connor et al. 2004).

3.2 | Soil Nitrogen

3.2.1 | Mineral Nitrogen

Mineral N concentrations in the soil at trial setup and at final harvest for the respective seasons are shown in Figure 1. Southland and Waikato sites had high mineral N fractions >150 kg N/ha in the top 0–30 cm in both seasons. The Whanganui site was intermediate in these seasons and the South Canterbury site had the lowest (<60 kg N/ha). At all sites, there was some mineral N remaining in the soil with >70 kg N/ha (0–30 cm depth) in the first season in Waikato and at the Southland (Riverton site), while at the South Canterbury and Whanganui sites, in both seasons, mineral N was reduced to low levels. In the second season, the residual mineral N at season end was still significant at ~60 kg N/ha in Waikato and Southland, but lower than in the first season.

3.2.2 | Anaerobically Mineralisable Nitrogen

In the first season, the preseason AMN levels exceeded 80 μg/g at five of the seven sites indicating a moderate basal N fertility, and the highest of these occurred in the three North Island sites (Table 3). These were also high at setup in season 2 at the Southland and Waikato sites. The Southland (Mossburn) site was on a shallow stony soil with little potential N supply from below 30 cm depth. The Waikato site was generally very fertile with high base K and N, and adequate minerals (Table 3). Based on AMN, the Canterbury and South Canterbury sites in the first season, and Waikato and South Canterbury sites in the second season, were most likely to show a response to fertiliser application.

3.3 | Yield Response to Nitrogen Fertiliser

In the first season, the average biomass yields at the final harvest, across the seven sites increased from 20.8 t DM/ha for the control (0 kg N/ha), and 23.1 (21.8–23.4) t DM/ha for treatments supplied with N fertiliser (Figure 2). However, there were no differences ($P > 0.05$) among the treatments that received N fertiliser. There was also no effect ($P > 0.05$) of timing of N fertiliser application. In the second season, the average biomass yield at the final harvest, across the four sites did not differ with N application rate nor with timing of N application, at an average of 23.0 t DM/ha (Figure 2).

At individual sites (Table 1), the biomass yield response to the rate and timing of N fertiliser application was inconsistent; yield increased with N supply in the first season at some sites, but not in the second season. Specifically, biomass yield increased with

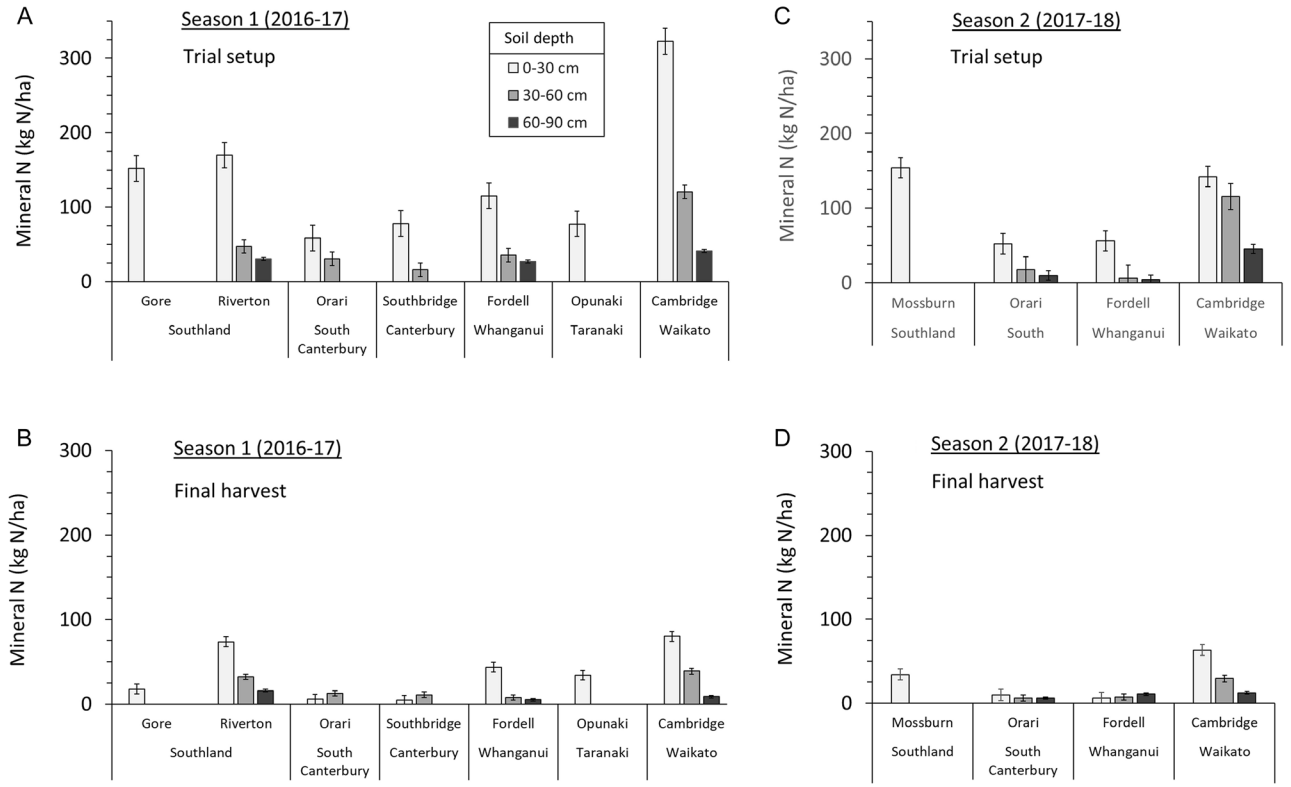


FIGURE 1 | Comparative soil mineral nitrogen (N) at trial setup (A and C) and end of season (B and D) for each site in season 1 (2016–17; A and B) and 2 (2017–18; C and D), respectively. Samples were taken from individual plots and error bars given as standard error of means (SEM). Data are reported as means over all treatments within site.

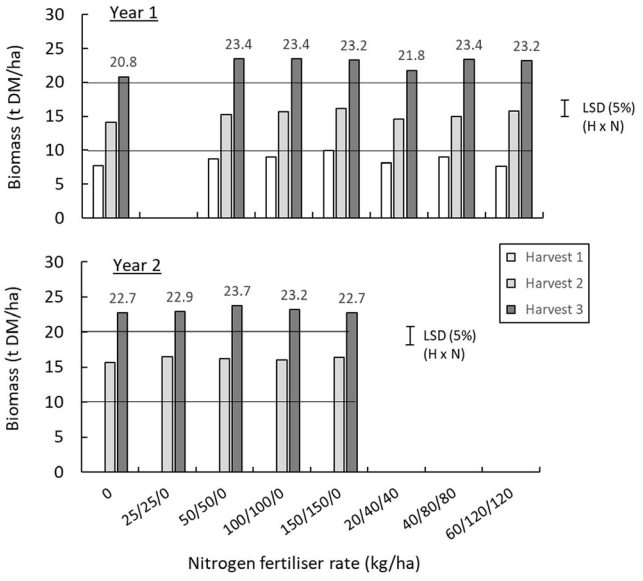


FIGURE 2 | Least squares means for yield response (over sites) to N fertiliser applied in split applications at sowing, canopy closure and mid-February. Harvest dates were at canopy closure (Harvest1), mid-February (Harvest 2), and maturity (Harvest 3). Means were for seven sites in season 1 (2016–17) and four in season 2 (2017–18).

N fertiliser application up to 100 kg N/ha at three sites (Ōrarī, Gore, and Opunake), and up to 200 kg N/ha at the Fordell site. However, there were no differences in biomass yield between 0 and 100 kg N/ha at the latter site. Biomass yield increased from 28 t DM/ha for the 0 kg N/ha crops to 33 t DM/ha for the 100 kg N/ha crops at South Canterbury (Ōrarī), while at Southland (Gore), biomass increased from 19 to 23 t DM/ha, respectively. Furthermore, at the Taranaki (Opunake) site, yield was 14 t DM/ha for the 0 kg N/ha treatments compared with the mean 18.5 t DM/ha for the N fertilised treatments. Biomass yield did not respond to N fertiliser application at Waikato (Cambridge), Canterbury (Southbridge), and Southland (Riverton) at an average of 25.8, 25.3, and 14.6 t DM/ha, respectively, across all treatments.

The timing of N application influenced crop biomass production at just two of the seven sites in the first season. For example, in Canterbury, yields were lower ($P < 0.05$) when N was split into three applications during the season (~24.6 t DM/ha) compared with 26 t DM/ha when N was applied two times, which is the industry standard in New Zealand. In contrast, at the Fordell site, the standard industry timing of N application produced lower ($P = 0.05$) yields than the three split application treatments. For example, for the 300 kg N/ha rate, the average biomass yields were 21.3 t DM/ha for the two splits compared with 24 t DM/ha for the three splits.

3.4 | Leaf Area

Across the sites, higher N application rates resulted in a greater proportion of leaf to bulb at maturity (Figure 3), but the absolute amount of leaf varied widely with differing soil and weather conditions, and disease incidence. The GLAI at "canopy closure" harvest (Table 4) across the sites and treatments ranged from 0.79 to 5.33 cm^2/cm^2 (the low GLAI occurred in a very late sown

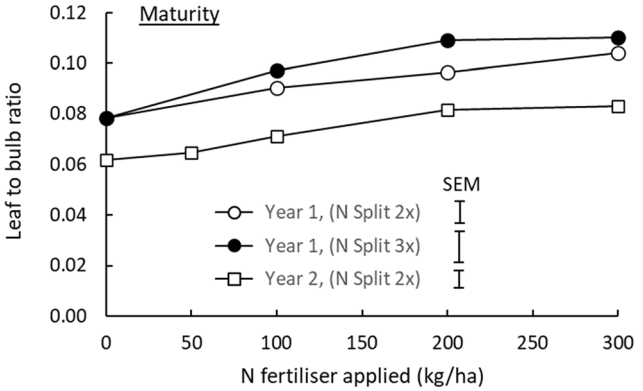


FIGURE 3 | Mean effect of fertiliser rate and timing on the leaf to bulb ratio of fodder beet crops at maturity (Harvest 3). These were grown at seven sites in season 1 (2016–17) and four sites in season 2 (2017–18). SEM is standard error of means.

crop at Riverton) in the first season. A reduction in GLAI at equivalent growth stages to crops in first season, was explained by the shift toward more disease presence in the second season, resulting in earlier and increased leaf senescence. This effect was more pronounced at early development stages. The range in GLAI at maturity over all sites and treatments was 0.36–4.24 (cm^2/cm^2). The high values were from immature, late-sown crops at the Riverton site. Splitting the N applications into three timings caused an increase in leaf: bulb ratio compared with two applications (Figure 3).

Canopy development at different sites was inconsistent in the first season, as three of the seven sites (Southbridge, Ōrarī, and Cambridge) reached the critical GLAI ($GLAI_{crit}$) of 3–4 m^2/m^2 (full canopy cover) at the mid-season harvest (Table 4). This was true for all N rates and timing treatments. However, at Riverton and Opunake, none of the treatments attained full cover. At two other sites (Gore and Fordell), some of the higher N treatments reached full cover (Table 4). In the second season, the only site where crops attained a $GLAI_{crit}$ of 3–4 m^2/m^2 at mid-season harvest was Ōrarī (Table 4). At all the other sites, canopy cover was below 3 m^2/m^2. In the second season, the GLAI at Cambridge was lowest, at both harvests, because of leaf senescence from bacterial leaf spot disease which was prevalent across all treatments. The effect of N rate on leaf area was significant ($P < 0.001$) for the mid-season harvest; and at maturity ($P < 0.013$) across all sites. The greatest response in leaf area occurred between nil and the lowest application rate, except at the higher fertility sites (Table 4).

3.5 | Crop Nitrogen Concentration and Uptake

In both seasons, N concentration of whole plants increased with N fertiliser application and decreased with time from canopy closure to the final harvest (Figure 4). The magnitude of increasing N concentration with the rate of N application varied with site. However, in the first season, under the same total N applied, the timing of N application (three splits of N) did not affect the concentration of N compared with the industry standard application (two splits of N). There was some variation in the concentration of N at the different sites for the respective N fertiliser treatments. For example, the control treatment in the first season varied from 0.86% N (Ōrarī) to 1.69% N (Riverton); while in the high-rate treatment (150 N/150 N) the whole crop N concentration ranged from 1.49% N (Fordell) to 2.26% N (Riverton) at maturity. Averaging all individual sites masked the differences, but nevertheless continued to demonstrate the effect of the rate N application on the N concentration (Figure 5A,B). The concentration of N in the component plant parts was also quite different. It was higher in the leaf than other parts, and lowest in the bulbs.

There was a general linear decline in the whole crop N concentration as the crops matured, and with increasing N fertiliser application rates, there was a higher N concentration in the whole plant (Figure 4C) and a concomitant increase in total N uptake (Figure 5D) primarily driven by the pattern of DM yield increase during maturation (Figure 4B). Invariably, crops with high yield at maturity also had high N uptake.

The N uptake response was only related to the timing of the N applied in fertiliser at the lower N rates (100 kg /ha N applied) ($P < 0.05$). Crops that received a late application in mid-February responded with higher N concentration and higher N uptake but only at total N fertiliser applications of 100 kg N/ha. At higher N rates, the differences due to timing were negligible, but differences in N concentration and N uptake were related to the total N applied.

At maturity, N uptake for control crops across sites and treatments ranged from 117–451 kg N/ha, compared with 317–530 kg N/ha, for the highest N (150N/150N) treatments. This indicated that the initial N fertility range at sowing was also a strong contributor of the variation in N uptake. Despite the low concentrations of N in the whole plant there were significant amounts of N taken up during crop growth in both seasons. Except for rare instances, the amount of N taken up was <500 kg N/ha (Figure 5C,D), and in low soil N situations was as little as 120 kg N/ha in control treatments.

4 | Discussion

The objective of this study was to define the N fertiliser requirements for optimal fodder beet production under differing soils and climates in New Zealand. Previous studies (Chakwizira et al. 2014a) have shown that fodder beet is comparatively efficient at using the N supplied in fertiliser or from soil N, and that yield is driven by the amount of N the soil-plant system and its consequent effects on plant growth parameters.

The main hypothesis was that late application of N fertiliser would promote GLA expansion (canopy growth) and its duration (development period), resulting in a yield advantage. Results showed that neither the rate nor timing of N fertiliser had any influence on GLAI development and/or GLAI duration, and therefore gave no yield advantage. Furthermore, results for biomass yield show that it did not respond to N fertiliser rates above 100 kg N/ha, across the different locations in New Zealand. These results support the use of a presowing soil test for both soil mineral N and AMN to manage starting N and in-season N fertiliser applications. Little yield response was observed when AMN was >80 ppm and mineral N was >80 kg N/ha in the top 15 cm. The recently released potentially mineralisable N soil test (Curtin et al. 2017) has been suggested as a replacement for AMN as it measures the soil's ability to release N during the growing season. This new method may accurately estimate the total amount of N required to optimise yield.

The DM yield ranges of 14–34 t DM/ha were consistent with previously reported yields in New Zealand (19–35 t DM/ha)

TABLE 4 | Mean GLA index for fodder beet crops grown under nitrogen (N) fertiliser treatments in season 1 (2016–17) and season 2 (2017–18). Data are for the mid-season harvest and final harvest (in parentheses). The split N treatments were applied at trial establishment, at canopy closure and at mid-season harvests.

N treatment (kg N/ha)	Site Green leaf area index, m^2/m^2							
Season 1 (2016–17)				Site				
	Southbridge	Ōrarī	Gore	Riverton	Fordell	Cambridge	Opunaki	Mean
0	3.1 (1.7)	3.2 (2.3)	2.3 (1.6)	1.6 (3.0)	3.0 (3.0)	3.6 (1.6)	1.3 (0.8)	2.81 (2.00)
100 (50/50)	3.6 (1.6)	4.2 (2.6)	2.6 (1.6)	2.0 (4.3)	2.9 (2.8)	3.1 (1.9)	2.0 (1.5)	3.07 (2.34)
200 (100/100)	4.0 (1.5)	4.4 (2.7)	4.3 (2.8)	1.5 (4.1)	2.7 (3.6)	3.3 (2.2)	1.3 (1.6)	3.38 (2.56)
300 (150/150)	4.5 (2.1)	4.3 (2.8)	4.2 (2.7)	1.6 (4.5)	3.1 (3.5)	3.5 (1.4)	2.9 (1.7)	3.51 (2.65)
100 (20/40/40)	3.7 (1.4)	3.9 (2.5)	2.7 (2.6)	1.6 (3.7)	2.5 (3.7)	3.3 (2.0)	2.1 (1.6)	2.95 (2.36)
200 (40/80/80)	3.5 (1.7)	4.1 (2.5)	3.2 (2.3)	1.5 (4.2)	3.1 (3.7)	3.2 (2.7)	2.1 (1.8)	3.11 (2.75)
300 (60/120/120)	4.7 (1.6)	4.8 (2.9)	4.1 (1.4)	1.6 (3.5)	3.3 (3.5)	3.4 (2.4)	1.5 (2.4)	3.64 (2.72)
N Trt Mean	3.87 (1.67)	4.13 (2.60)	3.32 (2.18)	1.64 (3.89)	2.95 (3.41)	3.34 (2.01)	2.95 (1.62)	
LSD (5%) Site				0.485 (0.556)				
LSD (5%) N Trt				0.405 (0.446)				
Prob >F: Site				0.001 (0.001)				
N Trt				0.001 (0.013)				
N Trt (Control vs Others)				0.003 (0.001)				
N Trt (Linear)				0.001 (0.038)				
Season 2 (2017–18)								
		Ōrarī	Mossburn		Fordell	Cambridge		
0	—	3.5 (1.2)	1.5 (1.9)	—	1.8 (0.8)	0.4 (1.1)	—	1.80 (1.25)
50 (25/25)	—	4.4 (1.2)	2.3 (2.1)	—	1.7 (1.1)	0.9 (1.3)	—	2.31 (1.39)
100 (50/50)	—	3.6 (1.8)	2.2 (2.9)	—	2.1 (1.1)	0.8 (0.7)	—	2.19 (1.60)
200 (100/100)	—	4.5 (2.3)	2.3 (2.8)	—	2.4 (1.6)	0.4 (0.8)	—	2.39 (1.87)
300 (150/150)	—	4.5 (2.3)	2.2 (2.5)	—	2.0 (1.2)	0.6 (0.9)	—	2.32 (1.71)
N Trt Mean	—	4.09 (1.74)	2.09 (2.44)	—	2.01 (1.15)	0.62 (0.93)	—	
LSD (5%) Site				0.341 (0.352)				
LSD (5%) N Trt				0.352 (0.380)				
Prob >F: Site				0.012 (0.001)				
N Trt				0.001 (0.014)				
N Trt (Control versus Others)				0.001 (0.011)				
N Trt (Linear)				0.623 (0.060)				

(Chakwizira et al. 2013; 2014b; Matthew et al. 2011). However, lower yields are commonly reported in commercial paddocks (Milne et al. 2014); these have been attributed to agronomic difficulties with growing these crops, e.g., sowing dates (Chakwizira et al. 2013; Stocker et al. 2016) or location/site properties, e.g., soil type/depth (Chakwizira et al. 2013). For example, late sowing at Riverton (Southland) reduced canopy development (Table 4) resulting in yield reductions. Also, there were two other sites (Fordell and Opunake) with reduced season duration (<200 days) because of early grazing, and consequently a reduced yield especially in low N treatments. In the second season, the low yield (16–18.4 t DM/ha) at the Cambridge site was primarily because of bacterial leaf spot in late summer and autumn period that caused significant canopy senescence, hence the reduced canopy cover (Table 4) at mid-season harvest. This resulted in little biomass increase between the mid-February harvest and the final harvest. Interpretations of potential yield response should, therefore, be made within the context of other agronomic factors that may be limiting growth.

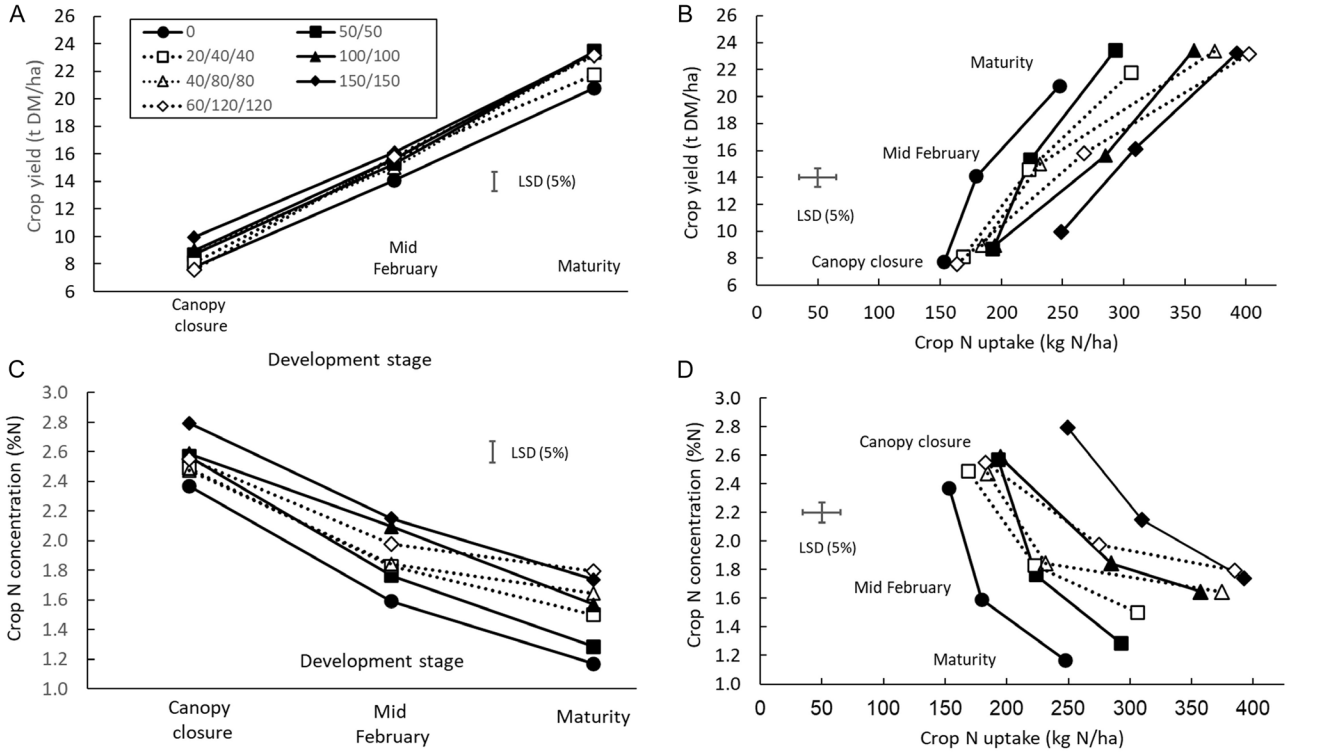


FIGURE 4 | Combined site analysis showing effects of nitrogen (N) fertiliser rate and timing on whole fodder beet (leaf + bulb) yield, %N and N uptake during the growth cycle. Nitrogen fertiliser was applied in either two (50/50, 100/100 or 150/150 kg N/ha) or three (20/40/40, 40/80/80 or 60/120/120 kg N/ha) split timings sowing, canopy closure, or mid-February.

In both seasons, the control treatment had generally lower yields, compared with the N fertilised treatments ($P < 0.05$). Reduced biomass yield under lower N supply conditions has been reported in other studies in Canterbury (Chakwizira et al. 2014a; 2016a), when background soil N was limiting. The background soil N fertility was higher at sites selected for the second season compared with the first season, which explained the lack of response in the second season.

Previous studies have shown that biomass yield responded to fertiliser N when the starting soil mineral N levels were 80 kg N/ha or less to depth of up to 0.15 and 0.30 m (Chakwizira et al. 2014a; 2016a), respectively. The process of determining critical soil levels for N fertility should consider other factors in addition to the lab-determined values, such as depth to stones or compacted layer and organic matter content.

Given that N availability is a complex soil characteristic, we have opted for simplified rules for N management with the soil test results being used as the prime sources for decision making. Growers and advisors may adjust the recommendations based on local knowledge and historical data for paddocks. The current industry standard for sampling of cropping soils is 0–15 cm and there is reluctance from farmers and advisors to change to deeper profiles because of practical difficulties of sampling and processing. Deeper soil mineral N sampling may recover mobile N returned to soils during grazing of a previous crop and may be missed in shallow sampling. Additionally, if sampling is done after deep ploughing, then the original surface layer with high soil mineral N content may be buried below the 0–15 cm sampling layer, leading to underestimation of the true mineral N content available for uptake.

The dilution of N concentration as the crop matured (Figure 4C) and lower N concentrations in bulbs and petioles compared with leaf lamina (Figure 5) has been reported previously (Chakwizira et al. 2016c). This has been attributed to increased carbohydrate accumulation as the season progressed. The reported N concentration and resulting crude protein (CP) content of 6.25–10.6% at final harvest was lower than animal requirements for wintering and well below the levels required for lactating animals without supplementation (Dalley et al. 2017).

The observation that yield was not adversely affected by reduced N fertiliser and the lower CP levels in fodder beet fed in winter are economic (reduced production costs) and environmental (reduced N return to soil) advantages compared with high CP crops such as forage kale (Fletcher and Chakwizira 2012; Malcolm et al. 2016). The range of N uptake was from 250 kg N/ha for control N treatments to >500 kg N/ha, when 300 kg N/ha was applied. The crop was able to take up significant amounts of N if supplied at high fertiliser N rates, but the high uptake was also likely to be problematic when grazed and when the N is excreted and recycled.

Nitrogen stress was manifested in reduced leaf area expansion for the control crops, which was observed at the canopy closure and mid-season harvest, or by increased leaf senescence later in the growing season (Chakwizira et al. 2016c). This pattern of response was consistent in the current trials (Table 4). GLA development and duration of green canopy were not affected by the rate or timing of N fertiliser applied after canopy closure. This occurred because leaf senescence rates were more responsive to developmental aspects of canopy expansion (e.g., time of canopy closure) than environmental factors or resource supply as reported by Chakwizira et al. (2016b). Therefore, the current New Zealand

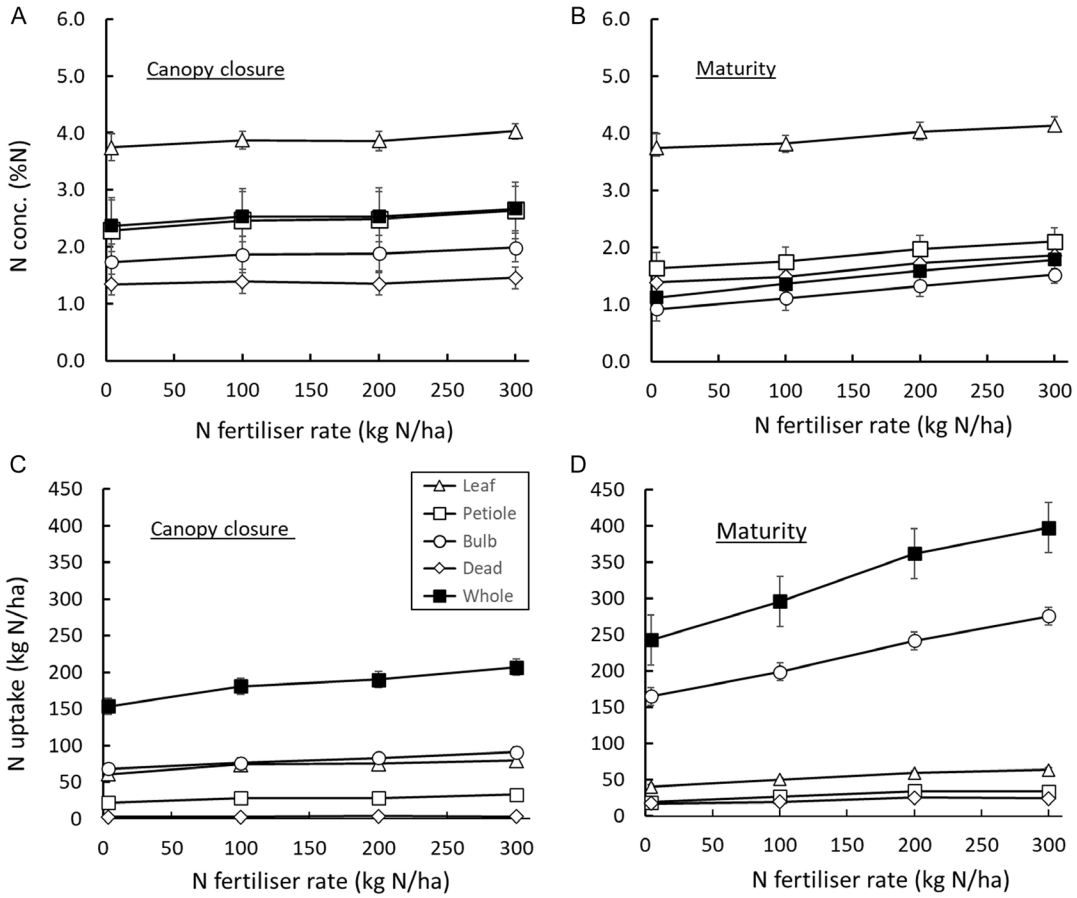


FIGURE 5 | Mean nitrogen (N) concentration (plots A and B) and N uptake (plots C and D) at canopy closure (H1) and maturity (H3) harvests for fodder beet leaf, petiole, bulb, dead material and whole plant in response to fertiliser N rate. Points are means over sites and seasons. Data for 25/25/0 kg/ha N rate treatment in season 2 were omitted. Rates of fertiliser were grouped according to total N applied (irrespective of number of split applications). Error bars are SEM for location x season means. Error bars not shown are hidden by data symbols.

industry standard of early N splits, while not having a major effect on yield, is still considered important for assisting early canopy development and early canopy closure. This was expected to result in longer GLA durations by maintaining high green leaf health after canopy closure. Factors such as disease incidence in autumn caused significant yield loss (e.g., at Cambridge) and steps need to be taken to manage the presence of disease in future crops.

In the current study, some of the crops did not attain $GLAI_{crit}$ (Table 4), which for fodder beet is estimated at a LAI of 3–4 m^2/m^2 (Chakwizira et al. 2016b). Relationships between accumulated yield and the integral radiation intercepted by the leaf canopy are documented (Chakwizira et al. 2018b). This meant that these crops were not intercepting maximum radiation, thus not operating at their yield potential, hence the low biomass yield, particularly at the Riverton and Opunake sites. Canopy opening through early senescence in autumn occurred in most crops, also contributing to crops not reaching their yield potential. This, coupled with the decreasing temperature in autumn, has previously been reported to reduce DM accumulation in fodder beet crops (Chakwizira et al. 2014a, 2016a). A lack of N response at the Cambridge site in the second season was partly because of the higher general soil fertility (Table 3), but more importantly the appearance of bacterial leaf spot contributing to considerable leaf area loss and cessation of bulb growth.

The best indicator of soil N fertility status in this study was the total available N (mineral N + AMN) in the 0–30 cm soil layer, but sampling to 15 cm depth gave a satisfactory estimate of the potential N availability for comparative purposes. If the AMN (0–15 cm) is <80 ppm and mineral N is <80 kg N/ha, then a yield response to N fertiliser could be expected. These conditions were satisfied for the South Canterbury (Ōrarī) site, but there was no yield response. This was an irrigated site, and therefore conditions for organic N mineralisation could have been adequate. This is further supported by the total N uptake for the control treatment of 341 kg N/ha, most of which must have been derived from mineralisation of organic N. These results support the use of a presowing soil test for both soil mineral N and AMN to manage starting N and in-season N fertiliser applications. In future, with the introduction of a new PMN test (Curtin et al. 2017) coupled with local soil temperature and water content data giving improved estimates of seasonal soil N supply (Beare et al. 2022), there is an opportunity to develop revised guidelines for N fertiliser management that better matches N supply with fodder beet N demand. Furthermore, fodder beet has been shown to extract water from depths >1.4 m (Chakwizira et al. 2014b) and therefore significant amounts of nutrients were potentially available from deeper soil layers, which would not be accounted for in current protocols. As a compromise, we therefore recommend presowing soil testing to 30 cm depth.

5 | Conclusions

The trials over two growing seasons and in multiple regions found there were no responses to urea-N fertiliser above an application rate of 100 kg N/ha. The critical rate for which there was a yield response was dependent on the initial soil N status at crop establishment. A fertiliser response can be expected for yield if the AMN (0–15 cm depth) is <80 ppm and mineral N is <50 kg N/ha. If the AMN was >80 ppm in the top 15 cm, basal applications of 50 kg N/ha were required at sowing and no further N required thereafter. In the absence of a presowing AMN test, basal N fertiliser of 50 kg N/ha was recommended if the mineral N was <50 kg/ha. This can be reduced to 25 kg N/ha if the mineral N is 50–75 kg N/ha in the top 15 cm, and otherwise no N fertiliser is required. We conclude that the fertiliser requirement of fodder beet crops should be managed within the background of data on soil nutrient availability, preferably both available mineral N and a measure of the mineralisable N (either AMN or the new PMN test). Important management practices for maximising yield include the use of N fertiliser for earlier crop canopy closure and enhanced canopy duration during bulb development and therefore improved efficiency of radiation capture. Late season N application was not effective in promoting a yield gain but did influence the whole plant N concentration.

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Conflicts of Interest

The authors declare no conflicts of interest.

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