Drought response and water use efficiency of forage brassica crops

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Abstract

Forage brassicas are used as supplementary feed crops throughout New Zealand. The availability of sufficient soil water often limits yield. This limitation can be expressed as the product of total water use (WU; mm) and the efficiency with which water is used (WUE; kg DM ha^{-1} mm^{-1}) by the crop. Quantitative data describing the WU and WUE of forage brassicas is not available for New Zealand conditions. This paper reports the results of an experiment that investigated the yield and water use of summer turnips and rape to varying levels of water availability. 'Barkant' turnips and 'Titan' rape were sown at the rain-out shelter at Lincoln, Canterbury, where they were supplied with four irrigation treatments: 1. the previous weeks evapotranspiration (ET) replaced each week; 2. the previous weeks ET replaced 2 out of every 3 weeks; 3. the previous weeks ET replaced every second week; and 4. irrigated during mid-growth to replace the previous weeks ET. Final yields ranged from 12 t DM ha^{-1} for the fully irrigated treatments to 5.5 t DM ha^{-1} for the most severe drought treatment for both species. Both crops extracted water to at least 1.0 m depth. The WUE was 32.3 kg DM ha^{-1} mm^{-1} for rape and 34.1 kg DM ha^{-1} mm^{-1} for turnips; this was not affected by drought treatment for either crop. Two additional data sets with 'Gruner' kale were also analysed. This analysis estimated a WUE of 34.1 kg DM ha^{-1} mm^{-1} for kale. This value can be used to estimate brassica yields in water-limited environments. The data from these experiments will be used to develop and test a mechanistic model of forage brassica growth.

Additional keywords: irrigation, kale, rape, rooting depth, turnips

Introduction

Forage brassicas are grown widely throughout New Zealand to supplement pasture when pasture growth rates are low (de Ruiter *et al*., 2009a). They are widely used by the dairy, sheep and beef industries. At least 300,000 ha of forage brassicas are sown each year from Northland to Southland (de Ruiter *et al*., 2007). Forage brassica crops used in New Zealand include: winter crops such as kale (chou molier - *Brassica oleracea* L.), swedes (*Brassica napus* L. subsp. *rapifera* Metzg.) and bulb turnips (*Brassica rapa* L. subsp. *rapa*) and summer crops such as rape (*Brassica napus* L.), leafy turnips (*Brassica rapa* L. subsp. *rapa*), and bulb turnips.

Across the wide range of environments in which forage brassicas are grown, there is a large variation in yield between both seasons and sites. Yields can range from 20-25 t DM ha^{-1} in a well-grown kale (Brown *et al*., 2006; Fletcher *et al*., 2007) or swede crop to approximately 6 t DM ha^{-1} (or less) for water-stressed crops (Wilson *et al*., 2006). Even though soil fertility and pest and disease pressures limit yield, most often the yield-limiting factor is the availability of soil water. Irrigation is only applied in a few situations, e.g. kale crops in Canterbury.

The yield of a water limited crop can be expressed as (Hay and Porter, 2006; Passioura and Angus, 2010):

$$Y=WU\times WUE\times HI \qquad \text{(Equation 1)}$$

Where WU is the total amount of apparent water use by the crop (mm), WUE is the water use efficiency of this extracted water (kg DM ha^{-1} mm^{-1}) and HI is the harvest index. For forage brassicas the whole crop is potentially used by the grazing animal. Therefore, HI can be ignored. WU includes both transpiration from the crop canopy and evaporation from the soil surface. Clearly, evaporation is 'unproductive' water loss and needs to be minimised to maximise yield (Passioura and Angus, 2010). In the analysis presented in this paper, it is assumed that once the canopy has closed soil evaporation is small compared to transpiration, and is therefore negligible.

Total crop WU depends on the water-holding capacity of the soil, how full it is at sowing, crop rooting depth (deeper rooting crops will have access to more stored soil water than shallow rooted crops), and water inputs from rainfall and irrigation. WUE is relatively conservative for a crop at a given location but humidity, experienced by a crop, can have a marked effect on WUE (Passioura and Angus, 2010). At high humidity the atmospheric 'demand' for water is much lower than at low humidity and therefore the amount of photosynthesis per unit of water transpired increases. Thus, in arid environments WUE is likely to be lower than in humid environments. In Australia, Jacobs *et al*. (2004) reported WUEs of 6-45 kg DM ha^{-1} mm^{-1} for 'Vollenda' turnips. Neilsen (2000) studied the response of four forage brassicas to irrigation and found WUE ranged from 15 to 38 kg ha^{-1} mm^{-1} with clear differences between species. Summer turnips had the greatest WUE, and leafy turnips and kale the lowest. The reasons for these differences are unclear.

Despite widespread use of brassicas, there are no published WUE data for forage brassicas for New Zealand conditions. However, for irrigated dairy pastures Martin *et al*. (2006) identified 20 kg DM ha^{-1} mm^{-1} water as an appropriate benchmark for Canterbury. Meanwhile Moot *et al*. (2008) reported WUEs ranging from 7 to 40 kg DM ha^{-1} mm^{-1} water for a range of pastures in New Zealand. In their study the application of sufficient N was important in achieving a high WUE.

This paper reports the results of an experiment that investigated the yield and water use of summer turnips and rape to varying levels of water availability. The objective was to determine responses of key yield forming processes to the various drought levels imposed. In particular, the water extraction patterns and apparent WUE are determined for each crop. Additional data are used from previous kale experiments to determine a WUE for this crop. In these additional data sets, water stress was not a treatment; however, frequent measurements of water use and crop yield were made enabling the calculation of WUE.

Materials and Methods

Experiments 1 and 2

Experiments 1 and 2 were sown side-by-side in the mobile rain-out shelter (43° 38' S, 172° 30'E) facility at Plant & Food Research, Lincoln (Martin *et al.*, 1990; Martin *et al.*, 1992; Jamieson *et al.*, 1995). The rain-out shelter automatically excludes rainfall from the experimental site, enabling soil water availability to be closely controlled by differential irrigation treatments. The soil at the site is a Templeton silt loam over sand, and key physical characteristics are described by Martin *et al.* (1992). Both experiments consisted of four irrigation treatments and three replicates (total of 12 plots per experiment) laid out in a randomised complete block design. Experiment 1 was sown with 'Barkant' turnips at 2 kg ha^{-1} and Experiment 2 was sown with 'Titan' rape at 4 kg ha^{-1}. Apart from this, the agronomic management and treatment structures of the two experiments were the same.

The experiments were sown into a cultivated seed bed on 19 November 2008 using a Taege drill with Öyjord cone seeder. Row spacings were 150 mm. Each plot measured 3.6 m x 5.0 m, with 1.0 m between plots. After sowing, irrigation was managed in common across the site until 5 December 2008. After this a drip irrigation system was installed and the four irrigation treatments were established. Treatment 1 was irrigated each week to replace evapotranspiration (ET); Treatment 2 was irrigated to replace ET two out of every three weeks; Treatment 3 was irrigated to replace ET every second week; and Treatment 4 was irrigated to apply 45 mm, once during mid-growth. The irrigation timings and amounts for each treatment are outlined in Table 1. Treatment 1 had a total of 328 mm of water applied, Treatment 2 had 223 mm applied, Treatment 3 had 189 mm applied and Treatment 4 had 100 mm applied (Table 1).

Fertiliser was applied so that soil fertility did not limit growth. The forecasting system described by Wilson *et al.* (2006) was used to choose the appropriate fertiliser rates. Base fertiliser of 45 kg N ha^{-1} and 50 kg P ha^{-1} was applied at sowing in the form of di-ammonium phosphate (18:20:0:0); boron was also applied at 15 kg ha^{-1} as boronate. These were broadcast on the soil and then incorporated at sowing. Two further side dressings of 50 kg N ha^{-1} were applied as liquid urea (46:0:0:0) using the drip irrigation system on 24 December 2008 and 13 January 2009.

Weeds were controlled, prior to sowing, by applying Tridan 480 (a.i. Trifluralin @ 480 g l^{-1}) at 1.7 l ha^{-1} on 12 November 2008. An aggressive pesticide programme was used for prophylactic control of a range of insect pests so that they did not affect crop growth. All seed was coated with Superstrike. On 20 November 2008, Diazinon 800 EC (a.i. Diazinon @ 800 g l^{-1}) was applied at 1 l ha^{-1}. On 11 and 30 December 2008 Lorsban (a.i. Chlorpyrifos @ 500 g l^{-1}) was applied at 1 l ha^{-1}. On 9 January 2009 Perfekthion S (a.i. Dimethoate @ 500 g l^{-1}) was applied at 700 ml ha^{-1}. Karate Zeon (a.i. Lambda-cyhalothrin @ 250 g l^{-1}) was applied at 40 ml ha^{-1} on 22 January 2009. On 27 January 2009 Perfekthion was applied at 500 ml ha^{-1}.

Neutron probe (NP) access tubes and time domain reflectometry (TDR) wave guides were installed following seedling emergence. Measurements of volumetric soil water content were made for each plot at weekly intervals beginning on 17

December 2008. Measurements were made in 200 mm increments to a depth of 1.6 m. The 0-200 mm increment was measured using TDR while all other measurements were made using NP.

Measurements of crop biomass were made at 7-day intervals, beginning on 22 December 2008. Two rows of crop, each measuring 1.2 m in length, were sampled from each plot. The number of plants was recorded and the fresh weight of the sample was recorded in the field. A 5 plant sub-sample was taken, weighed fresh and taken back to the laboratory. The sub-sample was separated into leaf, stem and bulb (for turnips only) fractions. The fractions were then dried in a fan-forced oven at 60°C for 2-3 days and their dry weight determined. A final harvest was taken on 10 February (83 days after sowing). A 2.1 m^2 area of crop was cut and weighed fresh in the field. Again a 5-plant sub-sample was taken back to the laboratory for partitioning and dry weight determination.

Table 1: Irrigation amounts (mm) and application dates for experiments 1 and 2.

Date	Treatment 1	Treatment 2	Treatment 3	Treatment 4	
23 Nov 2008	16	16	16	16	Irrigations
25 Nov 2008	12	12	12	12	before
30 Nov 2008	12	12	12	12	treatments
5 Dec 2008	8	8	8	8	established
17 Dec 2008	17	0	0	0	
22 Dec 2008	20	20	20	0	
24 Dec 2008	4	4	4	4	Fertigation
29 Dec 2008	35	35	0	0	
5 Jan 2009	46	0	46	0	
12 Jan 2009	45	45	0	45	
13 Jan 2009	3	3	3	3	Fertigation
19 Jan 2009	38	38	38	0	
26 Jan 2009	42	0	0	0	
2 Feb 2009	30	30	30	0	
Total	328	223	189	100	

Experiments 3 and 4

Experiments 3 and 4 involved a range of forage species in crop sequence experiments located at Lincoln (de Ruiter *et al*., 2009b; de Ruiter *et al*., 2009c). Only the data for the kale crops in those sequences are considered here. Both experiments used treated 'Gruner' kale seed sown at 4 kg ha^{-1}. Experiments 3 and 4 did not include water stress as a treatment, but sequential measurements of crop water use and biomass were made. Water use was measured using TDR and NP, as in Experiments 1 and 2. These data were used to estimate the WUE of kale. Herbicides and pesticides were applied so that weeds and insect pests did not affect growth. Experiment 3 ran from 2005 to 2007. Kale was sown on 26 October 2006 and 2 February 2007. Fertiliser N was either applied at normal (those typically used by farmers) or high rates. The 26 October 2006 sown crop received 260 kg N ha^{-1} and 385 kg N ha^{-1} fertiliser N for the normal and high N crops respectively. The 2 February 2007 sown crop received 135 kg N ha^{-1} and

235 kg N ha^{-1} fertiliser N for the normal and high N crops respectively. Experiment 4 ran from 2007 to 2009. Kale was sown on 25 October 2007 and grown until 6 March 2008. This crop received a total of 303 kg ha^{-1} of fertiliser N. A full description of Experiment 4 is provided by de Ruiter *et al*. (2009b).

Calculations and statistical analysis

All statistical analyses were made using Genstat v.11.1 (VSN International Ltd, UK). Crop yield and partitioning for Experiments 1 and 2 were analysed separately using ANOVA with the randomised complete block design.

For each of Experiments 1-4 WUE was calculated by linear regression of the sequential crop biomass measurements against apparent crop water use. Linear regression with groups was used to test if slopes (WUE) and intercepts differed among treatments. Apparent crop water use was calculated by the difference in volumetric soil water content between the current day and the start of the experimental measurements plus any inputs from irrigation or rainfall. It was assumed that drainage losses were negligible. Measurements of soil water were not available from the start of each dataset; therefore, comparing total water use was inappropriate. However, the relationship between biomass and apparent WU was still valid. For this reason the linear regressions were not forced through the origin. When WU and crop biomass measurements were on different days, WU was estimated by linear interpolation between two subsequent measurements.

Results

Drought effects on yield and partitioning

Drought had a marked effect on yield of both turnips ($P<0.01$) (Figure 1a) and rape ($P<0.05$) (Figure 1b). For the turnips, the fully irrigated crop (Treatment 1) had a yield of 11.9 t DM ha^{-1}. This was reduced to 7-8 t DM ha^{-1} for the partial irrigation treatments (Treatments 2-3), and reduced further to 5.5 t DM ha^{-1} for the most severe drought treatment (Treatment 4). The fully irrigated rape crop (Treatment 1) had a yield of 10.7 t DM ha^{-1}. This was reduced to 7-9 t DM ha^{-1} for the partial irrigation treatments (Treatments 2-3), and reduced further to 5.2 t DM ha^{-1} for the most severe drought treatment (Treatment 4).

Drought had no effect on dry matter partitioning in turnips (Figure 1c). It did, however, have a marked impact ($P<0.001$) on the partitioning of dry matter in rape crops (Figure 1d). For the fully irrigated rape crop, the harvested biomass was 64% stem with the remaining 36% as leaf. While for the crop subjected to the most severe drought treatment the harvested biomass was 48% stem with the remaining 52% as leaf.

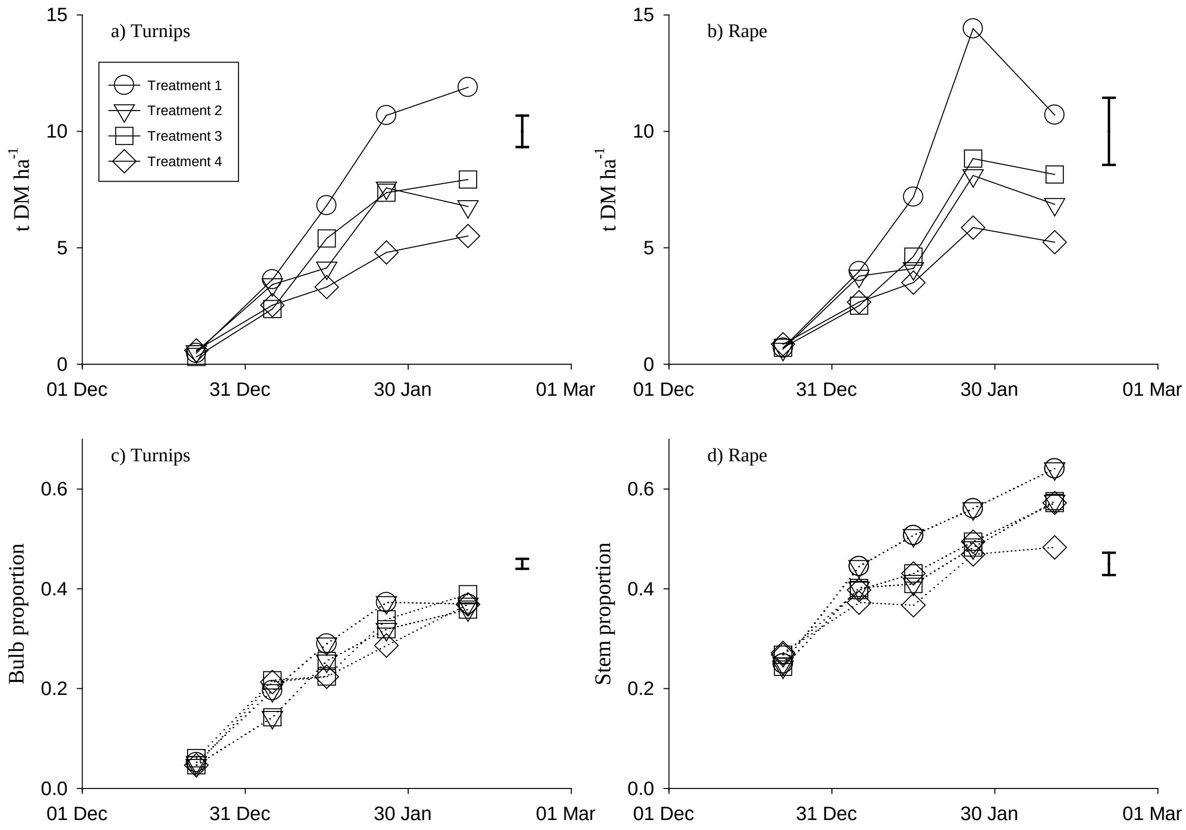

Figure 1: Yield (t DM ha^{-1}) development of turnip (a) and rape crops (b); and proportion of yield as bulb (c) or stem (d) for each crop; in response to four irrigation treatments. Error bars represent the 5% LSD with 6 error degrees of freedom for the final harvest date. The irrigation treatments are outlined in the text.

Water use

The potential water extraction of turnips and rape is demonstrated by the crops exposed to the most severe drought treatment (Figure 2). Extraction patterns are not shown for the other treatments because the addition of irrigation confounds their interpretation. By 12 January 2009 (54 DAS) the turnip crop was extracting considerable amounts of water from about 700 mm depth, while the rape crop was extracting water from as deep as 900 mm. However, for both crops most of the soil water extraction occurred in the top 500 mm of soil. By 10 February (83 DAS) both crops had extracted water from as deep as 1000-1200 mm. However, most of the water extraction between 12 January and 10 February occurred at depths between 500 and 900 mm. During this period no further extraction occurred from the 0-300 mm depth.

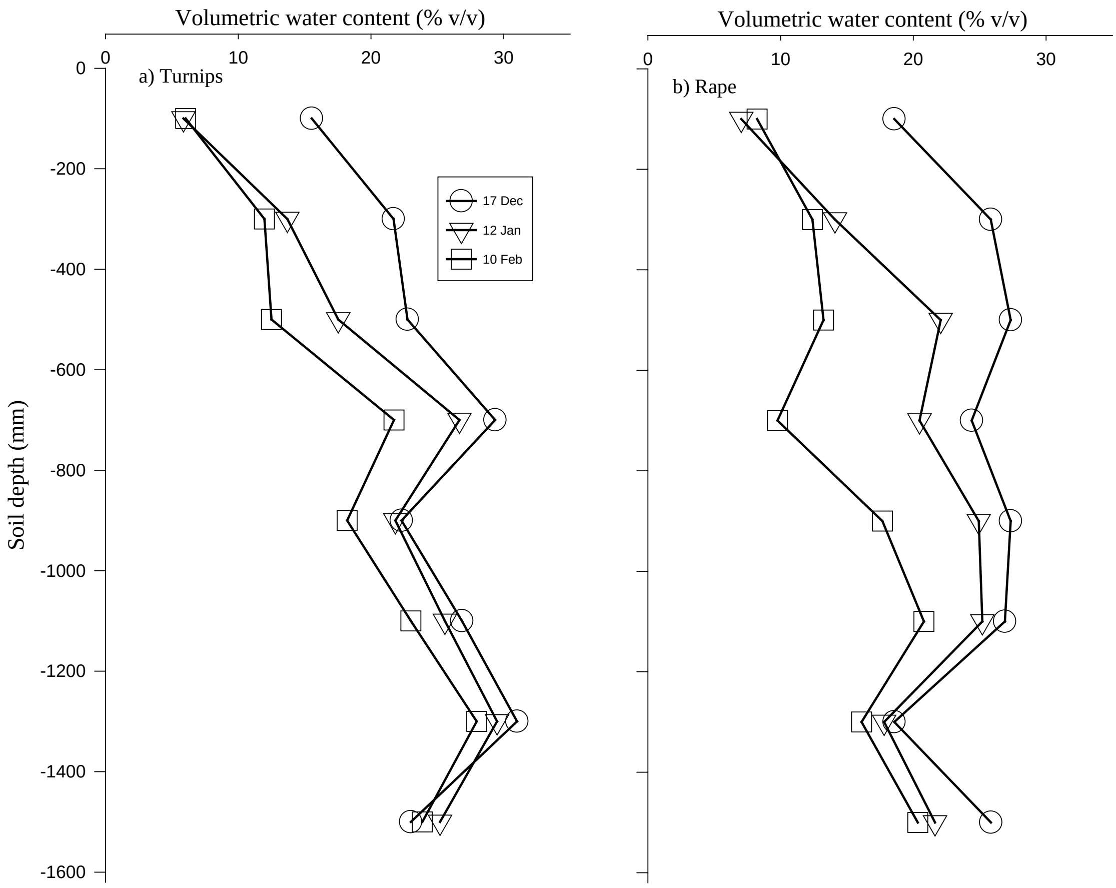

Figure 2: Water extraction patterns for Treatment 4 (one mid-season irrigation) of 'Barkant' turnips in Experiment 1 (a) and 'Titan' rape in Experiment 2 (b). For clarity volumetric soil water data are only provided for three selected dates (17 December 2008, 12 January and 10 February 2009).

Water use efficiency

For the turnip and rape crops WUE was not affected by irrigation treatment. Therefore, a single regression was used for each experiment (Figure 3). For turnips the WUE was 34.1 kg DM ha^{-1} mm^{-1} (R^2 = 0.95) and for rape it was 32.3 kg DM ha^{-1} mm^{-1} (R^2 = 0.79).

The analysis of the data sets from Experiments 3 and 4 found no differences in WUE for either sowing date or N treatment. The WUE was 34.1 kg DM ha^{-1} mm^{-1} (R^2 = 0.95). There were differences ($P<0.001$) among treatments for the intercepts of the regressions. For the normal N treatment of Experiment 3 the intercept was -3.3 t ha^{-1} for the October sowing and -0.1 t ha^{-1} for the February sowing. For the high N treatment of Experiment 3 the intercept was 1.4 t ha^{-1} for the October sowing and 2.5 t ha^{-1} for the February sowing (Figure 4 a). For Experiment 4 the intercept was -0.5 t ha^{-1} (Figure 4 b).

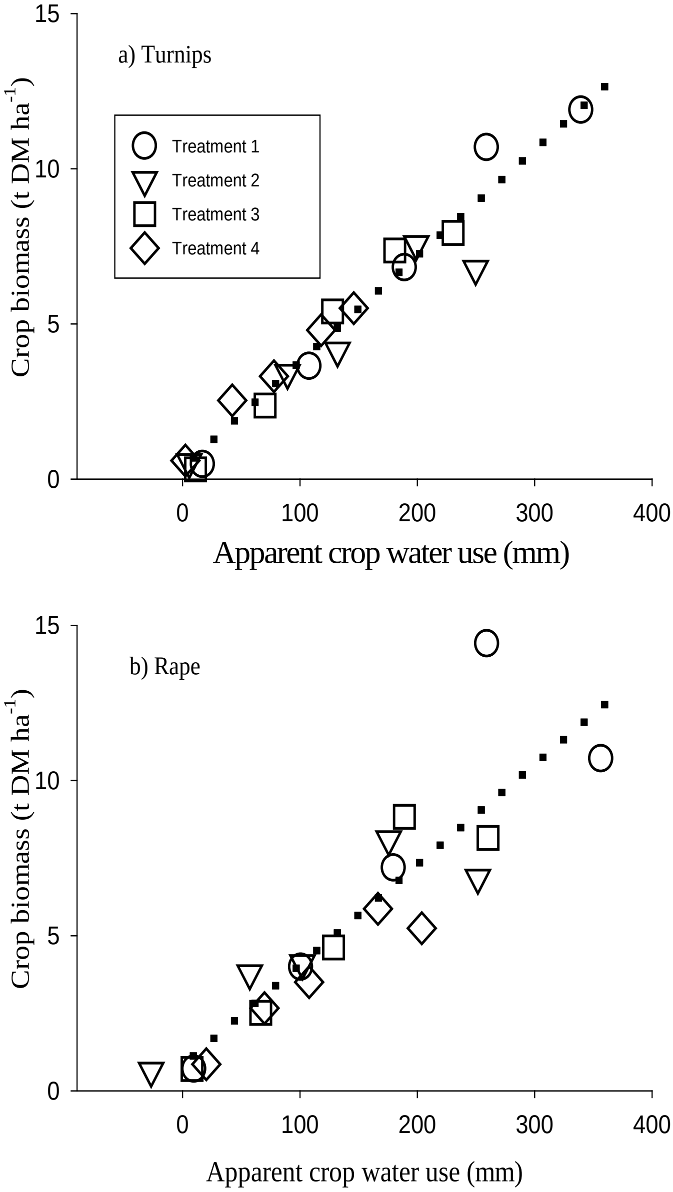

Figure 3: Relationship between apparent water use and crop DM for 'Barkant' turnips in Experiment 1 (a) and 'Titan' rape in Experiment 2 (b). The regression line in each graph represents the WUE. There were no significant differences between irrigation treatments so a single regression is used for each experiment.

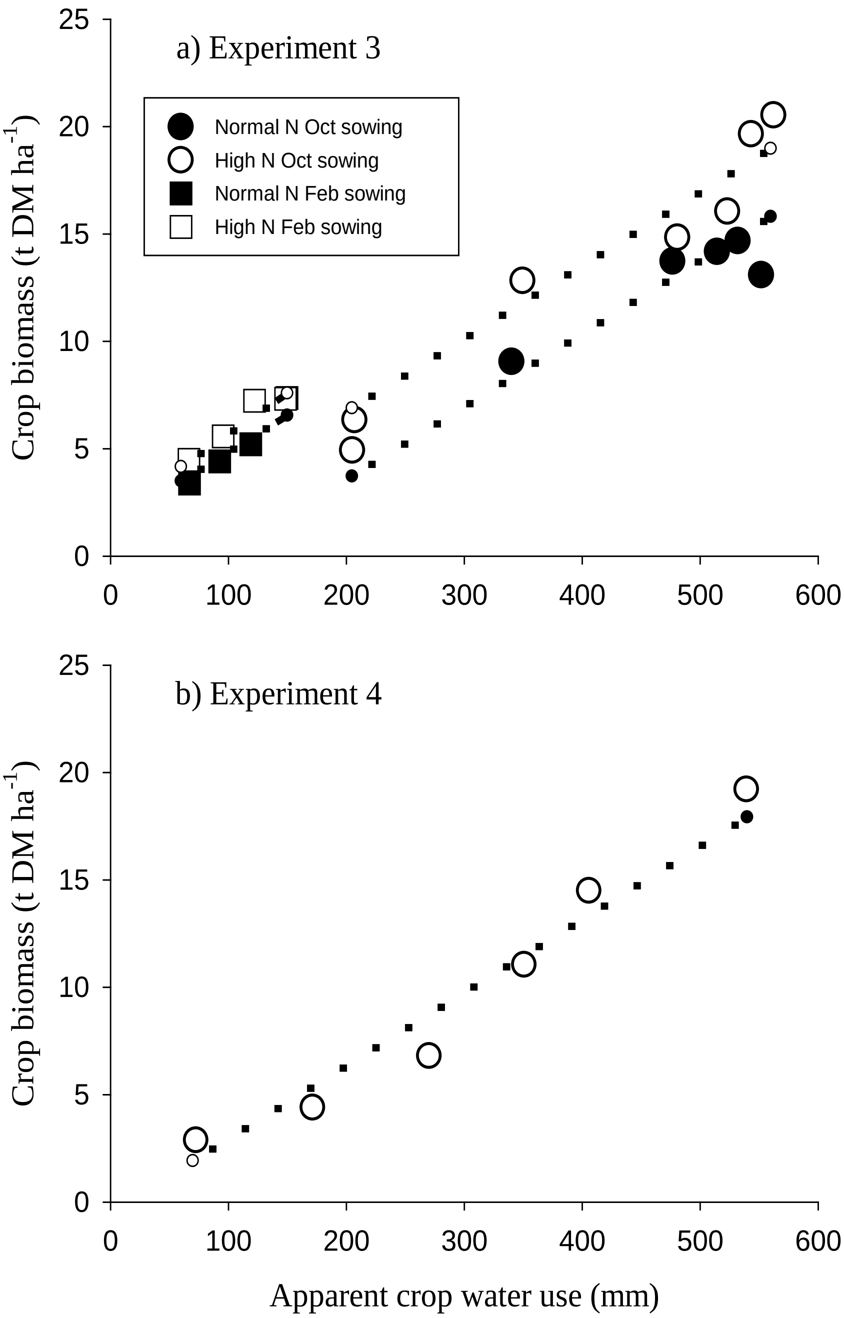

Figure 4: Relationship between apparent water use and crop DM for 'Gruner' kale Experiments 3 (a) and 4 (b). The regression lines (R^2 = 0.95) had a single slope (0.03405; P<0.001) but different (P<0.001) y-intercepts (-3.3, -0.1, 1.2, and 2.4 t DM ha^{-1} for the October sowing of normal N, and high N and the February sowing of normal N, and high N respectively and -0.5 t DM ha^{-1} for Experiment 4).

Discussion

Overall, these results demonstrate the importance of adequate soil water for high yielding forage brassica crops (Figure 1). For the most severe drought treatment (Treatment 4, receiving 100 mm irrigation in total) the yield was approximately half that of the fully irrigated treatment (Treatment 4, receiving a total of 328 mm of irrigation). These results are specific to the environment and soil in this study, but they demonstrate the dominant effect that water availability for forage brassica yields. Most brassica crops are grown without irrigation, and farmers need to take account of water limitations when they choose fertiliser rates and make their feed plans.

Growers can use the approach in Equation 1 to estimate their water-limited yield. The apparent WUE was conservative (approximately 34 kg DM ha^{-1} mm^{-1}) across the forage brassica species (Figures 3 and 4), drought treatments (Figure 3) and sowing dates (Figure 4a); therefore, it is only necessary to estimate the total amount of water available to the crop throughout the season. To do this will require knowledge of initial soil moisture, soil depth (and water holding capacity), within season rainfall and any irrigation inputs. For example, consider an unirrigated kale crop sown into a 0.5 m deep silt loam (140 mm of plant available water per m depth) at field capacity, receiving a further 250 mm of rainfall during the season and with 50 mm of soil evaporation (unproductive water use), then the water-limited potential yield would be 9.2 t DM ha^{-1} (Equation 2). In contrast, if irrigation was available and a further 160 mm was added as irrigation then the water-limited potential yield would increase to 14.6 t DM ha^{-1} (Equation 3).

Equation 2:

$$0.5\text{ m} \times 140\text{ mm m}^{-1}\text{ soil} = 70\text{ mm} + 250\text{ mm (rain)} - 50\text{ mm (soil evaporation)} = 270\text{ mm total water} \times 34\text{ kg}\left(\text{DM ha}^{-1}\right)\text{mm}^{-1} = 9{,}180\text{ kg DM ha}^{-1}$$

Equation 3:

$$0.5\text{ m} \times 140\text{ mm m}^{-1}\text{ soil} = 70\text{ mm} + 250\text{ mm (rain)} - 50\text{ mm (soil evaporation)} = 270\text{ mm} + 160\text{ mm (irrigation)} = 430\text{ mm total water} \times 34\text{ kg}\left(\text{DM ha}^{-1}\right)\text{mm}^{-1} = 14{,}620\text{ kg DM ha}^{-1}$$

This example illustrates how irrigation can increase yields of forage brassicas. Applying irrigation to the crops in Experiments 1 and 2 increased yields (Figure 1) by making more water available for extraction (WU), with no change in apparent WUE. However, most forage brassica crops in New Zealand do not have supplemental irrigation available. In these environments farmers need to maximise the water available to the crop (WU) in order to increase yields. Farmers can use a number of approaches to achieve this. By making sure that the rooting environment is optimum for root growth they can maximise rooting depth and, therefore, the soil water available to the crop (Passioura and Angus, 2010). Also choosing a deeper rooted crop will ensure the crop has physical access to the available water thereby increasing WU (de Ruiter *et al.*, 2009a; Passioura and Angus, 2010). Although both rape and turnips extracted water to a soil depth of 1000-1200 mm, there was an indication that rape was extracting more soil water from depths between 700 and 1000 mm. By the end of the season the most severe drought treatment of the turnip experiment had an apparent WU of 550 mm, whereas for the rape experiment the most severe drought treatment had an apparent WU of 590 mm (Figure 3). This may be why rape is often preferred by growers for summer-dry environments (de Ruiter *et al*., 2009a). Growers can use a fallow period before sowing forage brassica crops to ensure that the soil profile is at or near field capacity (Passioura and Angus, 2010). During a fallow no water is being used by a crop therefore, soil moisture tends to accumulate. They can avoid using the shallowest soils on their properties. Perhaps the greatest gains could be made by minimising the unproductive use of soil water. This includes both soil evaporation losses and water use by weeds. Weeds can be controlled using appropriate herbicide applications. Soil evaporation can be minimised by ensuring a healthy crop canopy (de Ruiter *et al*., 2009a) through pest control and appropriate fertiliser use. This will mean that canopy development is rapid and soil evaporation is limited (Passioura and Angus, 2010). For example, in Experiment 3 (Figure 4a) the high N treatments consistently had about a 1-2 t DM ha^{-1} higher yield than for the normal N treatments for the same apparent WU, even though they had similar WUE. This higher yield most likely reflects the more rapid canopy closure in these high N treatments and the subsequent reduction in soil evaporation. Direct drilling of crops as opposed to cultivation may also minimise soil evaporation through the retention of stubble from previous crops (Passioura and Angus, 2010).

Early in the season, before crop canopy closure, a considerable part of total WU comes from soil evaporation. As the season progresses the importance of soil evaporation reduces due to the crop canopy being closed, increasing apparent WUE. This may explain the apparent increase in WUE of kale throughout the season in Experiment 4 (Figure 4b). Alternatively, as the season progressed towards autumn, humidity would have increased, further increasing WUE.

The results for WUE in Figures 3 and 4 compare with other reported values of WUE. Jacobs *et al*. (2004) presented WUE ranging from 5 to 50 kg DM ha^{-1} mm^{-1} for turnips grown in Australia. However, their calculations were based on a single end-of-season harvest. Furthermore, their estimates of WU were only for the top 450 mm of soil. Significant volumes of water were likely extracted below this depth (Figure 2). If this was taken into account it is likely that their estimates of WUE would have dropped considerably. Like our results, Neilsen *et al*. (2000) found a WUE of 38 kg ha^{-1} mm^{-1} for ‘Barkant’ turnips. However, they also recorded WUEs for rape and kale of 20 and 15 kg ha^{-1} mm^{-1} respectively. This difference between species was not evident here (Figures 3-4). Their estimates were based on responses to applied irrigation rather than direct measures of water use, which may have biased the results. Furthermore, their WUE estimates were based on a single end-of-season harvest.

The WUEs for forage brassicas reported here (Figures 3 and 4) are considerably higher than the benchmark of 20 kg DM ha^{-1} mm^{-1} for pasture in New Zealand (Martin *et al*., 2006). They were also in the upper ranges of the WUE values presented by Moot *et al*. (2008) for a range of dryland pasture crops. This indicates that a well grown forage brassica crop offers considerable potential to increase total forage production in water-limited pasture production systems.

Conclusion

Water availability had a major impact on the growth of forage brassicas. All crops, whether drought stressed or not, produced 32-34 kg DM ha^{-1} for each mm of water used. Farmers can use this value in conjunction with soil water storage and rainfall to estimate their water-limited yield potential. This can then be used to schedule appropriate fertiliser application rates (de Ruiter *et al*., 2009a) and plan feed requirements.

Growth and water use data from these experiments will be used to further develop and validate a mechanistic forage brassica simulation model (Zyskowski *et al*., 2010).

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