Effects of timing of drought stress on grain yield of feed wheat

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Abstract

In New Zealand, recurrent and variable droughts are a major cause of season to season variation in wheat grain yields. Furthermore, many of the wheat growing areas are prone to summer droughts. The importance of timing and severity of drought for early autumn-sown wheat in summer drought-prone regions have not been explored. An experiment with different drought timing and severity was established in a rain-out shelter at Lincoln, Canterbury, New Zealand, in autumn of 2013 on a deep Templeton silt loam soil with a water holding capacity of about 190 mm/m depth. This included six irrigation treatments: 1. Full irrigation (Full) 2. Nil irrigation (Nil) 3.Very early drought (VED) 4. Early drought (ED) 5. Mid-season drought (MD) and 6. Late drought (LD). The most sensitive component to both severity and timing of drought stress was the grain yield; with a yield of 7.6 t/ha for the Nil treatment compared with 10.1 t/ha for the MD, LD and Full treatments and 10.8 t/ha for the early drought treatments. These findings suggest that with irrigation, farmers should avoid droughts late in the season and can reduce the total amount of water applied by imposing drought earlier in the season. Moreover, some seed quality parameters such as screenings and thousand seed weight were also sensitive to severity and timing of drought stress, implying that the end use of the crop should be considered when deciding irrigation strategies. These results also demonstrate that full replacement of ET_o may not be the most profitable option, with a similar yield achieved when only 50% of the water deficit was replaced. As this experiment was on a single genotype, single site and season, the results will need to be confirmed by repeating this study for another season, at multiple sites.

Additional keywords: *Triticum aestivum*, harvest index, screenings, thousand seed weight, water use, water use efficiency

Introduction

In New Zealand, recurrent and variable droughts are a major cause of season to season variation in wheat (*Triticum aestivum* L.) grain yields (Jamieson *et al.*, 1995a). Furthermore, much of the Canterbury region, where most wheat is grown, is prone to summer droughts, with potential evapotranspiration (ET_o) twice the mean rainfall.

Feed wheat planting dates are getting progressively earlier and yields are gradually increasing. However, most of the reported results of drought effects on cereals (Jamieson *et al.*, 1995 a, b, c; Martin *et al.*, 2001) have been for either winter or early spring sown crops. Limited information exists on the water use and water stress responses of autumn-sown feed wheat. There is also uncertainty regarding the importance of timing of drought events. Reports on other crop species have shown they are sensitive to timing when droughts are imposed, e.g., pigeon peas (*Cajunus cajan* L.) (Nam *et al*., 2001) and cowpeas [*Vigna unguiculata* (L.) Walp. syn. V. C sinensis] (Turk *et al*., 1980). Jamieson *et al.* (1995a) attributed the reduction of grain yield in barley (*Hordeum vulgare* L.) to reduced grain size and number of grains when drought was imposed early, and to reduced grain size and increased screenings when drought was imposed later in the season. Previous research on wheat (Jamieson *et al.*, 1995a) and oat (*Avena sativum* L.) (Martin *et al*., 2001) suggested little effect of the timing of water stress, but only to the overall severity of the drought stress. However, this view is widely challenged in the industry and anecdotal evidence from analyses of data from oat crops grown in a rain-out shelter in Canterbury suggests that timing can affect grain yield differentially. In particular, early drought gave smaller leaves which shaded the base of the canopy less, resulting in greater tiller survival, more heads, more grains and a higher yield than fully irrigated treatments. Later drought stress gave greater tiller mortality, fewer heads, fewer grains and rapid canopy senescence all of which contributed to lower grain yields than fully irrigated treatments. The harvest index (HI) was unaffected by the treatments.

The objectives of this experiment were two-fold: to measure the (*i*) water use and water stress responses of an early sown feed wheat and (*ii*) effects of different timings of drought on yield components of feed wheat.

Materials and Methods

The experiment was conducted in a mobile rain-out shelter (Martin *et al*., 1990) located at The New Zealand Institute for Plant & Food Research Limited, Lincoln (43° 37’ S, 172° 28’ E), Canterbury, New Zealand. The site was situated on a deep (>1.6 m), well drained Templeton silt loam, with a plant available water-holding capacity of about 190 mm/m of depth (Jamieson *et al*., 1995a). These soils are classified as Immature Pallic soil in New Zealand soil taxonomy (McLaren and Cameron, 1996); *Udic Ustochrept* (USDA Soil Taxonomy). Physical characteristics of the soil have been reported by Martin *et al.* (1992). The site had been under a perennial ryegrass (*Lolium perenne* L.) crop for the previous 3 years. Plot size was 3.6 m wide × 5.0 m long, with 1.0 m between plots. Wheat (cv ‘Wakanui’) was sown at row spacing of 0.15 m, giving a total of 21 rows per plot. ‘Wakanui’ wheat was released in 2009, is resistant to most leaf diseases (Luisetti Seeds, 2014) and currently occupies the largest area of autumn sown forage wheat in Canterbury region.

The experiment was a latinised row-column design generated using CycDesign version 4.1 (VSN International Ltd, UK), with four replications. There were 24 plots laid out in an eight column by three row grid. There was a single treatment factor consisting of six irrigation treatments (Table 1): 1. Full irrigation (Full), 2. Nil irrigation (Nil), 3. Very early drought (VED), 4. Early drought (ED), 5. Mid-season drought (MD) and 6. Late drought (LD). The design was structured such that each replicate (block) consisted of a 2 column by 3 row grid, but further constrained so that each treatment occurred at least once but no more than twice in each row. These constraints were imposed to account for any spatial trends and to help cancel out potential effects of pre-existing treatment effects on the site resulting from previous experiments. These spatial trends were highlighted by variation in soil nitrogen (N) among the 24 plots, which ranged from 141 kg N/ha to 381 kg N/ha in the top 1 m depth.

The site was prepared by deep ploughing (150 mm), followed by power harrowing. Twenty soil samples to a depth of 300 mm were randomly taken from the experimental area on 14 March 2013, evenly mixed, and a representative 100 g sample taken for analyses. Average soil test results were as follows: pH 5.8, phosphorus (Olsen P) 24, potassium (K) 220, calcium (Ca) 1250, magnesium (Mg) 80, sodium (Na) 65, and sulphate sulphur (S) 6 mg/kg soil and available N 160 kg/ha. The amounts of soil nutrients were determined as ‘MAF quick-test units’ (Mountier *et al.*, 1966) and converted into mg/kg dry soil using the following conversion factors: P, ×1.1; Ca, ×125; K, ×20; Mg, ×5; Na, ×5; S, × 1.0 (Chapman and Bannister, 1994). Basal fertiliser, at 250 kg/ha Super Sulphur 30 (0-7-0-30.1) was applied through the drill at sowing. During the season 200 kg N/ha as urea (46% N), was applied in two even splits on 26 September 2013 and 13 November 2013.

Initially, irrigation treatments were imposed on 16 May 2013 (52 days after sowing; DAS), applying sufficient water to return the soil to field capacity (Table 1). However, the site received 180 mm of rainfall between 16 and 23 June 2013, which led to run off and seepage into the experimental site. The 50 mm of water shown as irrigation on the 27 June (Table 1) was an estimate of the amount of water the plots received as a result of this flooding, which was assumed to be uniform across the site. The amount was estimated from soil moisture content measurements, using neutron probes, prior to and immediately after the event and the expected water use estimated from Penman potential evapotranspiration. Irrigation treatments were resumed again on 12 September (172 DAS). Each plot had its own trickle irrigation supply, with emitters spaced 150 mm × 150 mm apart. All the irrigation treatments with the exception of the controls (Nil, Full) received similar amounts of irrigation (average 223 mm) with drought imposed at different times of the growing period.

Agrichemicals were applied to the crop when needed so that crop yield was not compromised by weeds, insects or disease infection.

Measurements

A single neutron probe (NP) access tube and time domain reflectometer (TDR) wave guide was installed in each plot following seedling emergence for the duration of the experiment. Measurements of volumetric soil water content were made for each plot at one to four-weekly intervals beginning on 23 April to 25 September 2013 depending on the weather, and weekly intervals thereafter until 25 January 2014. Measurements were made in 200 mm increments to a depth of 1600 mm. The 0-200 mm depth was measured using TDR, while all other measurements were made using the NP. It was assumed that drainage losses were negligible for the soil type of this experiment, as reported by Jamieson *et al.* (1995a).

Table 1: The timing of key growth stages (GS; Zadoks *et al.*, 1974) and events, irrigation treatments[1] (and amount applied; mm), and biomass harvests (H) for 'Wakanui' wheat grown at Lincoln, Canterbury in the 2013–14 season.

		Irrigation treatments[1]						
Date	GS/Events	Full	Nil	VED	ED	MD	LD	H
25 March 2013	Sowing							
18 April								
16 May		25.0			25.0	25.0	25.0	
30		9.0			9.0	9.0	9.0	
13 June		12.0			12.0	12.0	12.0	
27	Trial flooded	50.0	50.0	50.0	50.0	50.0	50.0	
4 July								H1
29 August	GS31							
3 September								H2
12		30.0			30.0	30.0	30.0	
19		11.1				11.1	11.1	
26	Fertigation	16.9	4.6	4.6	4.6	16.6	16.9	
3 October		14.2				14	14.2	
10		16.2					16.2	
17	GS40	17.0					17.0	
22								H3
24		19.1					19.1	
31		20.6						
4 November	GS51							H4
7		22.9						
14	GS60	25.5						
18								H5
21	GS70	26.2		26.2				
28		28.8		28.8				
2 December								H6
5		29.5		29.5				
12		30.2		30.2	30.2			
17								H7
19		30.3		30.3	30.3	30.3		
26 December		31.5		31.5	31.5	31.5		
6 January	GS90							
25 January 2014								H8
Total water applied		466	55	223	230	221	221	

[1]Full= Full irrigation, Nil= Nil irrigation, VED=Very early drought, ED=Early drought, MD=Mid-season drought and LD=Late drought.

Seasonal crop water use (WU) was calculated from the change in volumetric soil water content (ΔSWC) during the measurement period and irrigation (I) as shown in Equation 1:

$$WU = \Delta SWC + I \qquad \text{Equation 1}$$

Total WU was determined for all treatments throughout the growing period. Water use efficiency (WUE; kg/ha/mm) was calculated as the relationship between grain yield at the final harvest and total WU.

A total of eight dry matter (DM) harvests (Table 1) were taken at seven to eight weekly intervals for the first three harvests, with the third coinciding with the start of the booting phase (GS40), and then at two weekly intervals thereafter to GS 90. The final biomass and grain harvest was on 25 January 2014. The size of the quadrat sample varied with the GS of the crop: 0.4 m lengths of 7 rows (0.42 m^2) per plot for all the sequential DM harvests, followed by 1 m^2 (2 × 0.5 m^2) quadrats per plot for final harvest. At all harvesting events, three outside rows in each plot were used as buffer rows and a 0.3 m space as a buffer between consecutive harvests, in each plot. Plant density and total fresh mass per quadrat were determined in the field at each harvest. A 10 plant sub-sample was used to determine number of live and dead tillers, and leaf and stem partitioning. The total sub-sampled leaf laminae were used to determine leaf area, using a leaf area meter (LI-COR model LI-3100; Lincoln, Nebraska, USA). The total leaf area per quadrat was determined, and then used to calculate leaf area index (LAI; m^2/m^2). Dry mass was determined after drying at 60°C to constant weight.

The crop was covered with bird netting 2 m above the ground from 12 November 2013 to maturity to prevent birds from eating the grain. The Nil and LD treatments matured earlier, and were harvested 10 days earlier than the rest of the treatments. All harvests were completed by hand and for the final harvest, the ear samples were threshed in a Saatmeister Kurt Pelz mill to separate the grain from the chaff. The proportion of screenings (%) was determined on a 200 g grain sub-sample per plot passed through a 2.1 mm screen.

Data analyses

Analyses were carried out in GenStat (version 14, VSN International Ltd, UK). The least significant difference (LSD) at α=0.05 was used to separate means. Where values showed $P<0.1$, a trend is indicated in the text. A mixed model fitted with restricted maximum likelihood (REML) (Gilmore *et al.*, 1995) was used. Random effects fitted were row and column. As the samples were sequential and linked to growth stages, sampling date was fitted as a fixed term. The fixed treatment effect was partitioned to allow testing of orthogonal contrasts to establish where differences between treatments existed: Nil versus the rest, Full versus the rest (excluding Nil), ED versus LD, VED versus ED and MD versus LD (Table 2). Assumptions of normality and homoscedasticity (Jarque and Bera, 1980) were tested and deemed appropriately met for dry matter and yield component data. For cumulative water use (WU), the most appropriate model for the correlation structure of measurements taken through time (selected by testing the change in deviance) was the ante-dependence model (Gabriel, 1962) that allows analysis of data collected at unequal time points. However, for the LAI, there was no evidence for a correlated structure, or that the ante-dependence correlation model improved the fit of the model. Therefore, the model that allows a separate variance at each time was used. The fixed effects then assessed response of treatment over the course of the trial given the structure defined above.

Table 2: Total biomass and grain yield (14% moisture), water parameters [WU (mm); WUE (kg grain/ha/mm)] and yield components [fertile tillers (FT; per m^2), harvest index (HI; g/g), screenings (SN; %) and thousand seed weight (TSW; g)] for 'Wakanui' wheat grown under different timing and severity of irrigation at Lincoln, Canterbury, New Zealand in the 2013-14 season.

Treatment[1]	Yield (t/ha)		Water parameters			Yield components		
	Biomass	Grain	WU	WUE	FT	HI	SN	TSW
Nil	21.2	7.6	331	24.2	797	0.32	0.5	45.5
VED	23.9	10.7	453	23.7	831	0.39	0.3	50.7
ED	24.7	10.8	486	22.2	851	0.39	0.7	43.7
MD	24.9	10.0	473	20.9	818	0.35	0.9	42.1
LD	26.1	10.2	557	18.5	890	0.34	2.0	36.4
Full	26.4	10.1	750	13.1	879	0.34	1.8	36.8
LSD	1.8	1.0	25	2.4	64	0.04	0.8	2.4

[1]Full= Full irrigation, Nil= Nil irrigation, VED=Very early drought, ED=Early drought, MD=Mid-season drought and LD=Late drought.

Results

The Nil treatment differed (P≤0.02) from the mean of the other five treatments for all indicators, being lower for all except WUE and thousand seed weight (TSW) (Table 2). Once the Nil effect was accounted for, there was also evidence that the Full treatment was different (P≤0.03) from the mean of the remaining treatments, being greater for total DM yield, WU, and fertile tillers (FT; tillers with a grain bearing head) and lower for grain yield, harvest index (HI), WUE and TSW. Similarly, once the Nil and Full treatments had been accounted for, there was evidence of significant differentials (P≤0.06) between the VED and ED treatments, and the MD and LD treatments, for all indicators except FT (Table 2); higher for the VED and ED treatments for grain yield, HI, WUE and TSW, and lower for total DM and WU compared with the MD and LD treatments. Since there were no grain yield differences among the MD and LD treatments and the Full, it implied that the Full yielded less grain than the VED and ED. The ED vs. VED showed significance (P≤0.001) for WU and TSW, while the MD vs. LD showed significance (P≤0.02) in their effects for FT, WU and TSW. Overall, TSW showed a strong decrease (P<0.001) with increasing irrigation with the opposite trend being seen for WU.

As expected, the total biomass increased (P<0.001) with water supply, from 21.0 t/ha for the Nil treatment to 26.4 t/ha for the Full treatment (Table 2). Furthermore, the grain yield increased (P<0.001) 30-40% with water supply compared with the 7.6 t/ha for the Nil treatment. There were no differences in grain yield between the VED and ED, averaging 10.7 t/ha and among the MD, LD and Full treatments, averaging 10.1 t/ha. Furthermore, the average grain yield for the early drought treatments was greater (P<0.1) than for the MD, LD and Full treatments.

The number of FT was greater (P=0.02) for the irrigated treatments (Table 2), with an average of 854 tillers per m^2 compared with the 797 for the Nil treatments. There were no differences in FT among the irrigated treatments. The proportions of screenings were greater (P=0.003) in the LD and Full treatments at an average of about 1.9% compared with the < 1% for the remaining treatments. The TSW differed (P<0.001) among the treatments, being highest for the VED treatments and decreasing with increasing water supply for the other treatments (Table 2).

The cumulative WU increased (P<0.001) with time and treatments (Figure 1; Table 2) and at the end of the season was highest for the fully irrigated crops. Water use increased 36-127% with water supply, from 331 mm for the Nil treatment to 750 mm for the Full treatment. The calculated WUE decreased (P≤0.02) with water supply, by between 2.2% for the VED to 46% for the Full treatment compared with the Nil treatment.

The peak LAI of 7.6 m^2/m^2 was achieved at the end of October 2013 (Figure 2). LAI was consistently higher (P<0.001) for LD and Full treatments than the Nil and VED treatments, from October to the beginning of December. The ED and MD were intermediate.

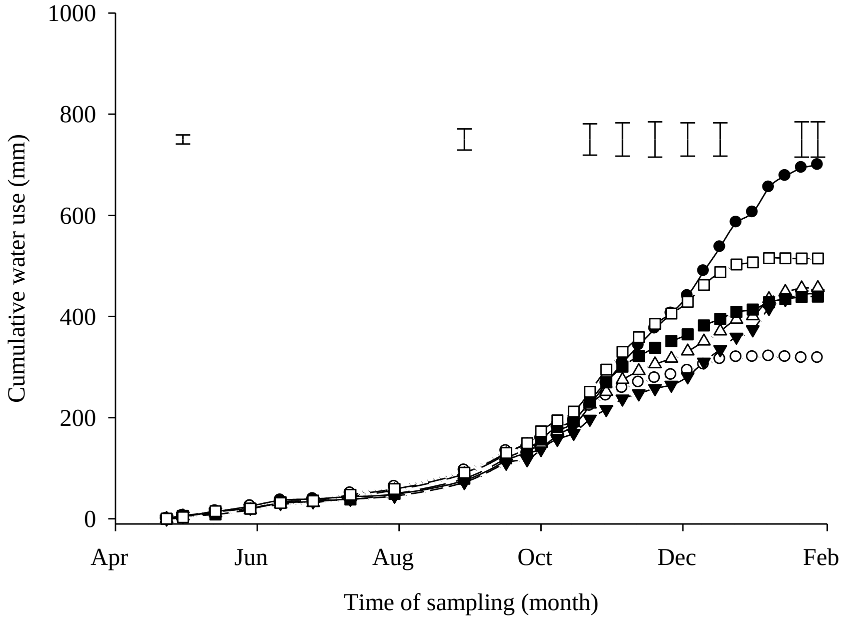

Figure 1: Cumulative water use (WU, mm) for autumn-sown wheat grown under different irrigation regimes: ○, Nil; ● Full; ▼ Very early drought; Δ Early drought; ■ Mid-season drought and □ Late drought at Lincoln, Canterbury, New Zealand in the 2013-14 season. Bars represent the least significant differences ($LSD_{0.05}$).

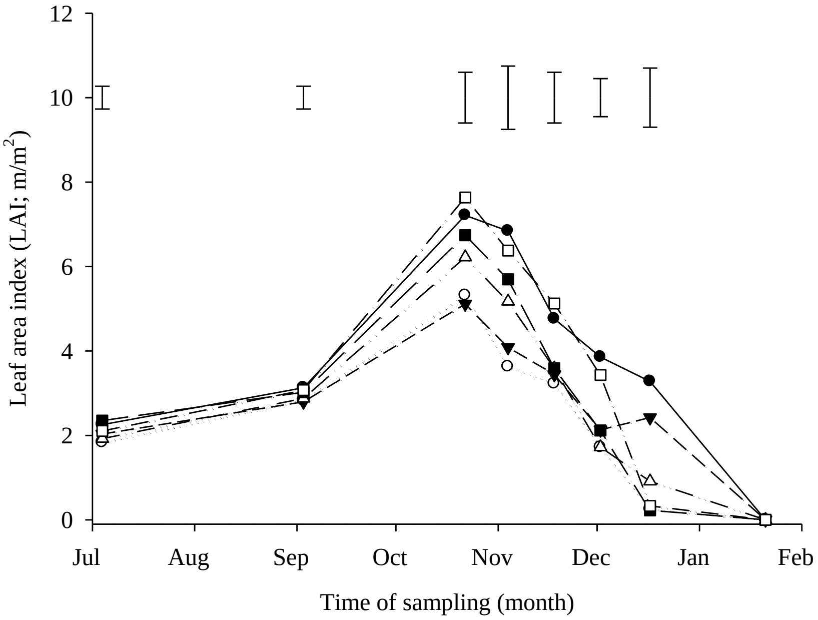

Figure 2: Cumulative leaf area index (LAI, m^2/m^2) for autumn-sown wheat grown under different irrigation regimes: ○ Nil; ● Full; ▼ Very early drought; Δ Early drought; ■ Mid-season drought and □ Late drought at Lincoln, Canterbury, New Zealand, in the 2013-14 season. Bars represent the least significant differences ($LSD_{0.05}$).

The TSW decreased with increasing total DM (Figure 3, Table 2) by about 2 mg for every increase of 1 kg in total DM. This was the opposite of the relationship between the total DM and number of FT (Table 2). The total grain yield decreased with increasing LAI, at a rate of 170 kg/ha for every 0.1 m^2/m^2 increase in LAI. However, the relationship between FT and WU, and that between TSW and WUE were positive and moderately correlated (R^2 of 0.59 and 0.61, respectively). The number of FT increased at a rate of 21 tillers per m^2 with each increase of 100 mm in WU, while the TSW increased by 1.1 mg for every 1 kg grain DM/ha/mm in WUE.

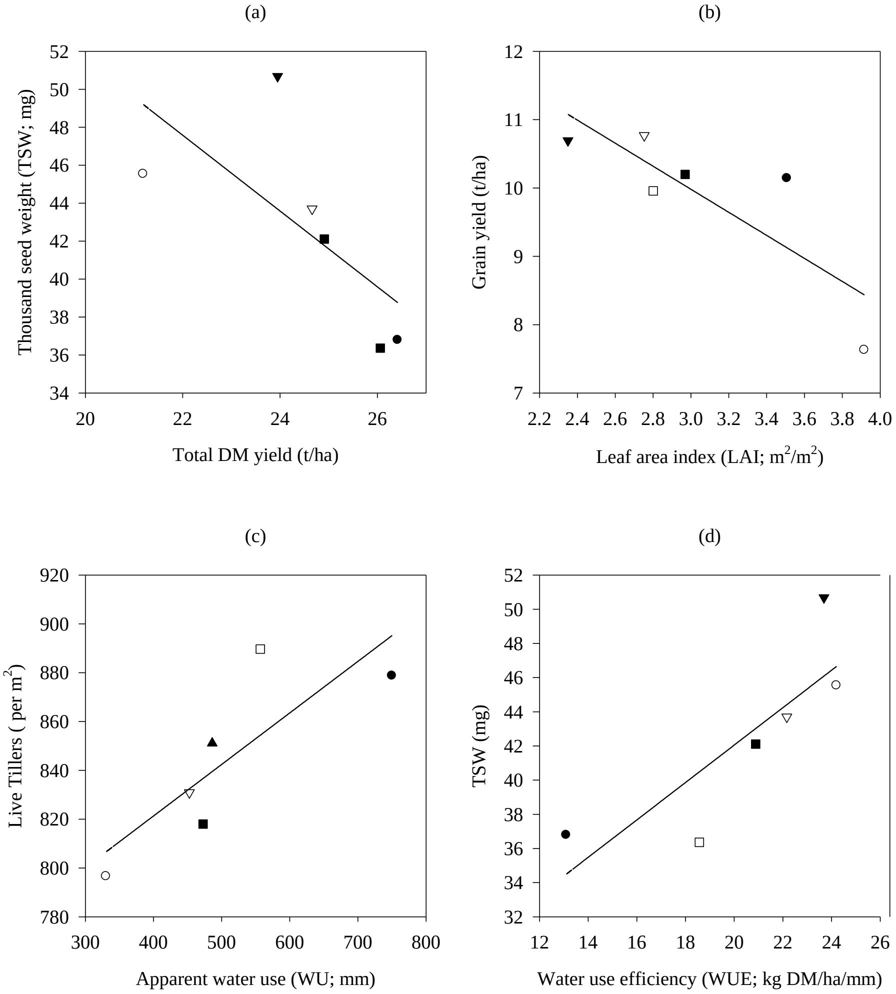

Figure 3: Relationships between: (a) thousand seed weight and total DM (Y=-2*x*+91; R^2=0.47), (b) grain yield and mean leaf area index (Y=1.7*x*+15; R^2=0.68), (c) fertile tillers and water use (Y=3.2*x*+2183; R^2=0.67) and (d) thousand seed weight and water use efficiency (Y=1.1*x*+21; R^2=0.69) for wheat crops grown under different irrigation treatments: ○ Nil; ● Full; ▼ Very early drought; Δ Early drought; ■ Mid-season drought and □ Late drought at Lincoln, Canterbury, New Zealand, in the 2013-14 season.

Discussion

The application of drought treatments varied by as much as seven weeks (Table 1). This resulted in differences in grain yield of 30-40% (Table 2) higher in irrigated treatments than the 7.6 t/ha for the Nil treatments. These differences were attributed to both timing and severity of drought stress. Grain yield was higher in the VED and ED treatments than MD and LD, and also higher in the irrigated than Nil treatments. The response to timing of drought stress was inconsistent with reports for oats (Martin *et al.*, 2001), and wheat and barley (Jamieson *et al.*, 1995a) where there was no responds to timing of irrigation. However, the response to timing of drought was consistent with the review by Farooq *et al.* (2014), who reported that the most critical stage at which drought impedes wheat production was during the flowering, and grain filling phases (terminal drought). The impacts of terminal drought have also been reported in other crop species, e.g., pigeon peas (Nam *et al.*, 2001) and cowpeas (Turk *et al.*, 1980). These authors also concluded that terminal droughts, coinciding with reproductive stages, have the greatest effect in grain yield. The LD treatment in the current experiment was imposed at the start of the reproductive stages (GS 51) (Zadoks *et al.*, 1974) and resulted in lower grain yield than drought treatments imposed earlier (VED, ED) in the season. There were no differences in grain yield between MD (booting, GS 40) and LD (reproductive stage) (Table 1, 3). The implication was that drought stress imposed before booting had no effect on grain production (Table 2).

The lower yield in the Nil treatment could be attributed to reduced WU (Figure 1; Table 2) and the resultant low numbers of fertile tillers (FT) and HI. The number of FT increased linearly with WU (Figure 3; R^2=0.59), which is in contrast to our hypothesis that ED would result in more FT than for LD. However, the differences in WU among the irrigated treatments (Figure 1) did not translate into grain yield (Table 2) as the grain yield increased with WU up to an average of about 470 mm, and decreased with higher WU (LD, Full). The implication was that an average of 223 mm water applied to the drought plots was adequate to attain maximum grain yield in these deep soils. This was 50% of the total water applied in the Full treatment (full ET_o replacement); thus, farmers can use this knowledge to save water, time and money by deficit irrigation. Although the LAI was lower (Figure 2) for the early drought treatments (VED, ED), this did not result in more FT per unit area than the LD and Full treatments (Table 2) as hypothesised. However, the LD and Full treatments which had higher LAIs (Figure 2) had lower grain yield than the early drought treatments, even though there were no FT differences among the irrigated treatments. The main drivers of the grain yield were therefore the HI and TSW, which were higher for the VED and ED treatments. The implication for this is that LAI also affects other yield components, such as HI and TSW. These results support current industry concerns on the effect of timing of drought, and our hypothesis that early drought would result in better yield than late drought. Moreover, it should be noted that this site was on a deep soil with a high water holding capacity (approximately 190 mm/m depth; Jamieson *et al.*, 1995a) and severe drought was not achieved. This, coupled with the June flooding, meant that the amount of water stored in this deep soil may have reduced the effects of both timing and severity of drought. Timing of drought could be more important on shallow soils with lower water holding capacities, which are typical of the areas where cereal production is common, particularly in Canterbury, where more severe drought occurs.

As expected, the WUE for the grain yield decreased with WU (Table 2). However, the overall WUE was inconsistent with those reported previously, higher than values reported by Ram *et al.* (2013) and comparable to French and Schultz (1984a) and Kirkegaard *et al.* (2007). The WUE of wheat grain established by French and Schultz (1984a) of 20 kg/ha/mm has hsitorically been used as the maximum value for wheat in Australia. Recently, Sadras and Leawson (2013) have updated the value to 24 kg/ha/mm, the increase attributed to genetic improvement. The WUE for the grain yield (Table 2) under deficit irrigation, excluding the LD are comparable to these values. Ram *et al.* (2013) reported a decrease of WUE from 17.3 to 11.8 kg DM/ha/mm for wheat crop using 300 mm and 537 mm/ha, respecitvely. These WUE values are lower than reported in the current experiment at similar WU (Table 2). The overall WUE reported here for the crops under deficit irrigation are also higher than the ≤ 20 kg DM/ha/mm reported by French and Schultz (1984a) across 61 sites in Southern Australia. However, the WUE in Table 2 was consistent with the 19-25 kg DM/ha/mm (French and Schultz, 1984b; Kirkegaard *et al.*, 2007), when WU was determined for the whole soil column to 1650 mm.

Although timing of droughts had minimal effects on grain yield, Table 2 also shows that irrigation timing may be critical to meet some crop seed quality requirements. Even though the level of screenings are low, the proportion in the LD (2%) and Full (1.8%) treatments were at least double those of the other treatments (≤0.9%). The overall, low levels of screenings are consistent with those reported for wheat (0.7-2.5%) by (Jamieson *et al.*, 1995a), but lower than the 30-41% reported for oats (Martin *et al.*, 2001 and barley (Jamieson *et al.*, 1995a). These differences in screenings between wheat and the other cereals may be a species characteristic. The higher screenings in the LD treatments (Table 2) were consistent with reports for oats and barley (Martin *et al.*, 2001; Jamieson *et al.*, 1995a). The overall low HI (Table 2) could be attributed to the fact that 'Wakanui' a forage wheat cultivar, was bred to produce vegetative dry matter and possibly at the expense of seed yield compared to the HI reported in literature (e.g., Kirkegaard *et al.*, 2007), for grain wheat cultivars, that are bred to produce high seed yields. Both the TSW and HI were higher when drought was imposed earlier in the season, and this together with the low screenings in those treatments may imply that if farmers are going to apply deficit irritation, then the recommendation is to impose drought earlier in the season (Table 1). Furthermore, terminal droughts have been associated with reduced wheat yields in some situation (Farooq *et al.*, 2014).

Conclusions

Flooding of the site and the uncertainty of the actual amount of water entering treatments compromised the results of this study. As this experiment was completed on a single genotype, single site and season, the results will need to be confirmed by repeating this study for another season. However, there was evidence that the grain yield was more sensitive to medium and late drought stress, and therefore if farmers are to apply deficit irritation, then the recommendation is to impose drought earlier in the season. Moreover, some seed quality parameters, such as screenings and TSW, were sensitive to timing of drought stress and therefore the end use of the crop should be considered when deciding irrigation timing and intensity. These results also show that full replacement of ET_o may not be the most profitable option, with similar yield achieved when 50% of the water was replaced.

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