Understanding nitrogen and water stress mechanisms on maize crops

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Abstract

Nitrogen and water are the two most critical production resources that farmers can manage to ensure high yields, low environmental impacts and low production costs in maize crops. Optimum water and nitrogen management guidelines can be derived from the understanding of physiological mechanisms responsible for nitrogen and water deficiency in maize. The maize hybrid 39G12 was subjected to six treatments combining three nitrogen rates (0, 75 and 250 kg/ha) and two water regimes (dryland and irrigation to replace total evapotranspiration) under an automated rain-shelter facility at Lincoln, Canterbury. Total biomass yields ranged from 8 to 28 t dry matter per hectare. Yield differences were partially explained by a reduction in intercepted light from 1,987 MJ/m^2 for the irrigated treatments to 1,328 MJ/m^2 for the dryland treatments. Light interception was mostly mediated through a reduction in leaf expansion rates, causing reductions in the leaf area index (LAI) from an average of 4.83 in the irrigated treatments to 2.94 in the dryland treatments. The remaining yield effect was explained by a decline in radiation use efficiency (RUE) from 1.6 to 0.7 g dry matter per MJ of intercepted light, as nitrogen and water deficits were increased. Differences in phyllochron were only slightly increased in the extreme stress treatments.

Additional keywords: *Zea mays*, irrigation, leaf appearance

Introduction

Maize (*Zea mays*) is one of the most productive and high quality forage crops available for New Zealand livestock systems (de Ruiter *et al.*, 2009). This is particularly important for the growing dairy industry in which maize silage is a common supplement feed; in the 1999-2000 season 47% of dairy farms in the Waikato used maize silage (Kolver *et al.*, 2001). Nitrogen and water are the two most critical input resources that farmers can manipulate to achieve multiple goals such increasing productivity (total biomass per area) and nutritive value (grain content in total biomass) and reducing costs and environmental footprints in maize cropping operations (Hargrove *et al.*, 1988). The design of best management practices to optimise these often conflicting targets relies on the understanding of maize physiological responses under different New Zealand environmental conditions. This requires combined use of data from field experimentation to quantify maize responses and computer simulation modelling to assess implications under a wide range of management and climate conditions (Teixeira *et al.*, 2011). Although water and nitrogen deficiency both limit maize yields, this effect can be either associated with reductions in the interception of sunlight or the efficiency of its conversion into biomass (Stone *et al.*, 2001). The physiological mechanisms involved include reduced rates of leaf area expansion and leaf photosynthesis respectively (Cakir, 2004; Massignam *et al.*, 2011). There are very few studies in New Zealand that have investigated these responses for the combined effect of limiting nitrogen and water. In this study, the results from a field experiment using a rainfall exclusion facility (rain-shelter) in which maize crops were subjected to a wide range of nitrogen and water stress conditions are described. Maize yields were analyzed as the product of (i) the total amount of intercepted solar radiation (Ri, MJ/m^2), (ii) the radiation use efficiency (RUE, g DM/MJ) and the crop harvest index (HI) (Monteith, 1972). The aim of this study was to gain insights into the isolated and combined effects of a wide range of resource limitation for maize crops grown in Canterbury and to explore underlying driving mechanisms. This knowledge can be used to improve the understanding of maize responses to limiting growth factors and consequently the science within maize models used in New Zealand.

Materials and Methods

Site description, experimental design and trial set-up

A field trial with the maize hybrid 39G12 (comparative relative maturity of 78) was planted on 23 October 2012 in the Plant & Food Research rain-shelter facility site at Lincoln, Mid Canterbury (43° 37' 12" S, 172° 28' 12" E). The rain-shelter enables total control of water supply to the crop through a 5 m tall moveable “glass-house type” structure that covers the entire field trial area (12 m x 54 m) automatically during rainfall events. The shelter retracts automatically once rainfall has stopped to ensure light conditions are not influenced by the structure (Martin *et al.*, 1990; Martin *et al.*, 2004). The soil is a deep Templeton silt loam (NZ classification: typic immature pallic soil), previously managed to have low nitrogen content (approximately 7 kg N in the top 150 mm) at the time of sowing. From 5 October 2012 to 19 October 2012 the trial area was cultivated using conventional implements. Prior to cultivation the trial area was sprayed with the non-selective herbicide; Lion 470 DST at 4 l/ha with 200 l water/ha. On 25 October 2012 a pre-emergent herbicide and insecticide mix of Lasso Micro-tech at 5 l/ha, Bruno at 2 l/ha and Lorsban 50 EC at 560 ml/ha was sprayed on the trial area. On 27 November 2012 Emblem Flo at 1 l/ha with 300 l water/ha was sprayed on the trial area to kill broadleaf weeds. Compound fertiliser containing 100 kg P/ha, 68 kg Ca/ha and 50 kg K/ha was incorporated into the soil on 19 October 2012 over the entire trial area to minimise risks of other nutrient deficiencies.

The trial was set as a randomized block design, with six treatments replicated four times. Maize rows were 0.71 m apart. The intended sowing rate was 120,000 plants/ha and the established plant population was approximately 122,000 plants/ha. Each plot was five maize rows (3.55 m) wide by 5.00 m long. All destructive harvests and crop measurements occurred in the middle three rows and the outside two rows were treated as buffer rows. Treatments were a factorial combination of two irrigation treatments (dry and fully irrigated) and three added nitrogen treatments (0 kg N/ha, 75 kg N/ha and 250 kg N/ha). Water was applied weekly, on the fully irrigated treatments only, to replenish accumulated evapotranspiration (ET) since the previous irrigation event. Nitrogen as urea (46% N) was split applied at sowing, sixth leaf (V6) and anthesis using fertigation with <5 mm of water per plot at each application (Table 1).

Table 1: Timing and rates of nitrogen application. V6 = the ligule was present on the sixth leaf.

Nitrogen Treatment	After sowing 15 November 2012 (kgN/ha)	V6 20 December 2012 (kgN/ha)	Anthesis 31 January 2013 (kgN/ha)
0N	0	0	0
75N	25	50	0
250N	50	100	100

Measurements

Total biomass, grain yield (kg dry matter/ha) and leaf area index (m^2 green leaf per m^2 soil) were measured at grain maturity. The fresh weight of 21 plants cut 30 mm above ground level was recorded, then a five plant subsample was dissected into weighed components (green leaf, dead leaf, stem, husk, grain and rachis), dried to constant weight in a forced air oven at 60°C and results presented as dry matter (DM). Leaf area index (LAI) was calculated from data collected by using a belt meter (Licor Li-3100 area meter). Radiation interception was measured weekly using a ceptometer (Decagon Sunfleck Ceptometer). Specific leaf nitrogen (SLN, g N/cm^2 of leaf) of leaf position 12 was estimated from three SPAD (Minolta SPAD 502 Chlorophyll Meter) measurements on three plants per plot at the time of anthesis and converted to SLN through a calibration curve based on combustion analysis (Dumas method using a Leco TruSpec CN) of 16 individual leaf samples.

Results and Discussion

Total maize biomass ranged from 7.7 to 28.3 t DM/ha in response to water and nitrogen treatments (Table 2). In the irrigated treatment nitrogen limitations were able to create a very wide range of biomass yields. Although both treatments reduced ($P<0.01$) total biomass, the pooled effect of water was nearly twice as great as the nitrogen effect on total biomass (58% and 31% difference between extreme treatments, respectively). There was a positive response of total biomass and grain yields to nitrogen supply for the irrigated treatments ($P<0.05$) and a positive trend ($P<0.10$) for the dryland treatments. Harvest index (HI) was highest at 0.54 for the irrigated treatment, at the highest applied N level. In contrast, nitrogen stress reduced HI for dryland conditions with a minimum HI of 0.45 observed for the low N dry treatment. These values are in the upper range of HI previously reported for maize grown in different regions and managements in New Zealand (Wilson *et al.*, 1995).

Table 2: Total biomass and maize grain yield from the final biomass harvest at grain maturity.

Irrigation Treatment	Nitrogen Treatment	Total biomass (kg DM/ha)	Grain yield (kg DM/ha)	Harvest index (HI)
Dry	0N	7,677 c	3,464 c	0.45 c
Dry	75N	11,051 c	5,264 c	0.47 bc
Dry	250N	11,928 c	6,202 c	0.51 b
Irrigated	0N	20,208 b	10,995 b	0.54 a
Irrigated	75N	24,427 ab	12,803 ab	0.52 a
Irrigated	250N	28,339 a	15,209 a	0.54 a

Means followed by different letters are different at a 5% significance level.

Differences in total biomass were mainly explained (R^2>0.89) by the reduction in radiation interception (R_i) in response to water stress (Figure 1). Pooled radiation interception ranged from 1,987 MJ/m^2 for irrigated crops, reducing to around 1,328 MJ/m^2 for the dryland crops, without significant impact (P<0.19) of nitrogen treatments on R_i. On the other hand, nitrogen stress was an important factor, reducing the radiation use efficiency (RUE) in conjunction with water stress (Figure 1). The RUE decreased by nearly 2.5 fold, from 1.6 which is similar to previous results under optimal growth conditions (Lindquist *et al.*, 2005) to 0.7 g dry matter/MJ of intercepted radiation, in response to the combined effect of limiting water and N resources.

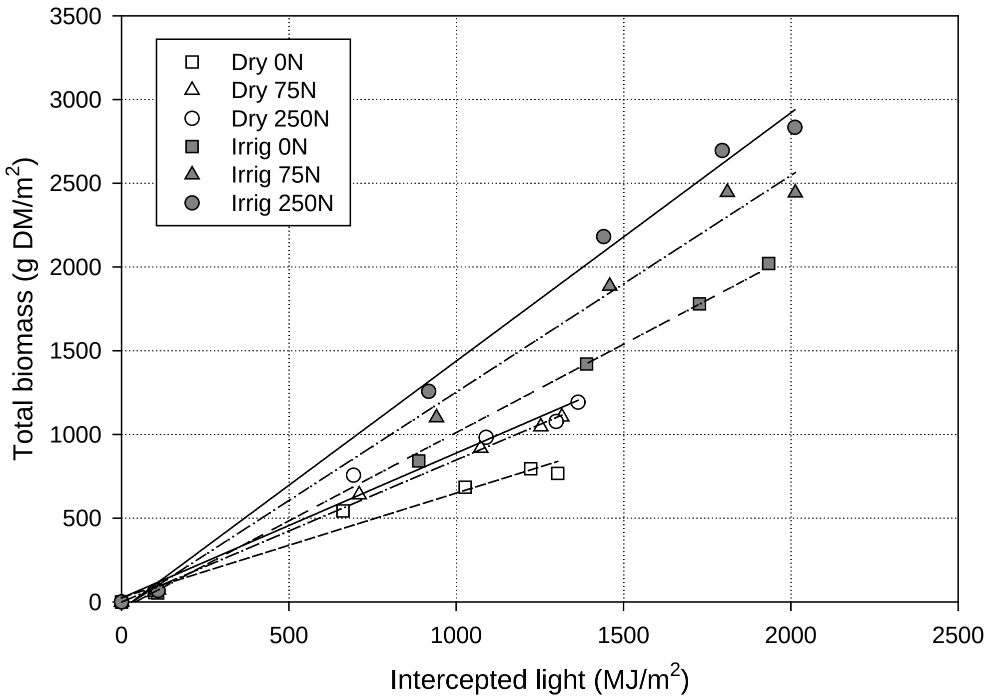

Figure 1: Total biomass of maize crops in response to accumulated intercepted radiation for crops subjected to three nitrogen concentrations (0, 75 and 250 kg/ha) and two water availability conditions under a rain-shelter facility (dryland or irrigated).

Leaf appearance rates were slightly lower (<7.8%, $P<0.05$) in the extreme water and nitrogen stress treatment (dryland 0N) than in unstressed crops (Table 3). Previous findings show that maize under pre-anthesis water stress did show a decrease in leaf appearance rates (NeSmith and Ritchie, 1992). However, the small range in phyllochron (40-44 °Cd/leaf, Table 3) in our results highlight the lower sensitivity of phenological development to resource limitation, in comparison with crop growth processes such as leaf expansion (Hodges, 1991). In large, most of the reduction in R_i could be attributed to limited rates of leaf area expansion, as indicated by the more than two-fold difference in leaf area index (LAI) among treatments at the time of anthesis (Table 3).

Table 3: Effect of irrigation and nitrogen on leaf appearance (phyllocron), leaf area index (LAI) at anthesis and specific leaf nitrogen (SLN) of leaf 12.

Irrigation Treatment	Nitrogen Treatment	Phyllocron (°Cd/leaf)	LAI[1] (m^2/m^2)	SLN[2] (g N/cm^2 leaf)
Dry	0N	44.02 a	2.45 d	0.62 c
Dry	75N	42.30 ab	3.05 c	0.71 bc
Dry	250N	41.47 ab	3.31 bc	0.70 bc
Irrigated	0N	43.10 ab	4.16 b	0.85 b
Irrigated	75N	40.87 ab	5.03 a	1.14 a
Irrigated	250N	40.58 b	5.31 a	1.24 a

Means followed by different letters are different at a 5% significance level.
[1]Leaf area index at the time of anthesis.
[2]Specific leaf nitrogen of leaf 12, counted from the base of the stem in this study.

The data suggests RUE reduction could be mostly explained by a decrease in the crop assimilation capacity of maize canopies due to low leaf nitrogen contents. This was indicated by the 50% decline ($P<0.01$) in specific leaf nitrogen (SLN) in response to both water and nitrogen stress (Table 3), in agreement with Muchow and Davis (1988).

Conclusion

These results quantify maize yield responses when co-limited by water and nitrogen supply. For the level of stress imposed, water limitation reduced both light interception and RUE, while the main impact of nitrogen stress was to reduce RUE. Water stress prevented full use of applied nitrogen, and vice-versa, highlighting the importance of balancing the amount of both resources to optimise yield, production costs and environmental footprint, such as from winter leaching of residual N that is not taken up by water stressed crops in summer. This detailed quantification of the physiological mechanisms that explain water and nitrogen stress on maize can be used to test and improve maize models validated for the cool temperate climate of Canterbury.

Acknowledgements

This study was funded by Plant & Food Research for the Land Use Change and Intensification Programme (LUCI). Thanks to Genetic Technologies Limited for providing the maize seed.

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