Harvest index for biomass and nitrogen in maize crops limited by nitrogen and water

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Abstract

Nitrogen (N) is one of the major yield-limiting nutrients for crop production. At high application rates the efficiency of N use is reduced and the risk of N loss in soil-plant systems is increased. The N taken up by maize crops is partitioned between vegetative (e.g. leaves and stems) and reproductive organs (e.g. grains) that have economic value. The ratio of grain N to total crop N, defined as the nitrogen harvest index (NHI), provides an indication of how efficiently the plant converts absorbed N into grain. Two field experiments with the maize hybrid 'Pioneer 39G12' were undertaken to investigate how N rate and irrigation affected NHI and grain quality of maize grown. Harvest index (HI) and NHI increased with increasing water supply, from 0.47 to 0.53 (HI) and 0.43 to 0.60 (NHI), for the dryland and irrigated crops, respectively. However, neither HI nor NHI was significantly affected by N rate. The grain N concentration (Ng%) increased from 0.97% to 1.1% with water supply, and from 0.92% for the N control to 1.25% for the 200–250 kg N/ha crops in both experiments. However, Ng% did not significantly increase at the higher rates of fertiliser N. The NHI was closely related to HI, which suggests that management options to improve the HI of maize crops would also improve the crops' ability to utilise N. The response of both HI and NHI to moisture stress, but not fertiliser N, highlights the importance of soil moisture in crop production in this environment, due to its influence on N uptake. Treatments with high water availability caused higher NHI values in crops and therefore we conclude that water management was of more value than N fertiliser rates for increasing NHI up to reported critical thresholds up to ±0.65.

Key Words: *Zea mays* L., cropping systems, ecophysiology, expanded leaf stage, 'Pioneer 39G12'.

Introduction

Nitrogen (N) and water are the most limiting factors for maize (*Zea mays* L.) grain yield worldwide (Moser et al., 2006). As modern agriculture is becoming more concerned with yield, the nutritional quality of the crop and the environmental impact of crop production (Uribelarrea et al., 2007), the efficient use of fertiliser N and water are becoming more critical. The nitrogen harvest index (NHI), the ratio between N uptake in grain and N uptake in grain plus straw or shoot (Muchow, 1988), is an important guide to understanding N and water limitations to crops. Improvements in NHI through the adaptation of N fertilisation and irrigation strategies depends on understanding N uptake and assimilation. Such understanding of the ecophysiology of N uptake, its distribution within the crop, and crop growth (Lemaire, 2001) can be used as the basis for developing functional approaches for crop-based models to understand N dynamics in different ecosystems. For maize crops, NHI has been used as an indicator of N dynamics (Fageria, 2014; Muchow, 1988). Increased NHI is strongly correlated to improved grain N concentration (Ng%) (Fawcett and Frey, 1982). Similarly, Ng% has been used as a measure of grain quality (proteins = Ng% ^{x} 5.6) (Mariotti et al., 2008). Proteins are important constituents of crops grown for food in poorer regions of the world (McNeal et al., 1968), hence the importance of the Ng% of maize, which constitutes a greater part of the diet in these regions. We quantified NHI and the Ng% of maize grown under constrained N and soil water conditions in New Zealand.

Materials and Methods

Site description and experimental design

Data were derived from two field experiments that have been described in detail in previous publications (George et al., 2013; Teixeira et al., 2014), on total biomass and grain yield, and resource [water, radiation and N] use efficiencies. Briefly, maize hybrid 'Pioneer 39G12' was sown in consecutive growth seasons (2011–2012 and 2012–2013) and at adjacent sites at Lincoln, Canterbury, New Zealand (43°37’34.4”S, 172°28’13.4”E, 18 m a.s.l). The soil at both sites was a deep (>1.6 m) Templeton silt loam (Hewitt, 2010) or Udic Ustochrept (USDA Soil Taxonomy) with an available water-holding capacity of around 190 mm/m of depth (Martin et al., 1992). For the first experiment (A, 2011–2012), the initial total mineral N to a depth of 1.0 m was ~167 ± 10 kg N/ha and for the second experiment (B, 2012–2013), initial soil mineral N to 1.5 m depth ranged from 24 to 79 kg N/ha, with less than 36 kg/ha in the top 0.6 m. Experiment A was fully irrigated and sown on 31 October 2011 at a population of 12.5 plants/m^2 and in row spacing of 0.76 m. It was a randomised complete block design (RCBD), with five N application rates (0, 50, 100, 200 and 400 kg/ha), and four replicates. In Experiment B, also a RCBD with four replicates; crops were sown at 12 plants/m^2 (0.71 m row spacing) on 23 October 2012, under a mobile rain-shelter structure (Martin et al., 2004) located 350 m west of Experiment A site. Crops were subjected to three N application rates (0, 75 and 250 kg/ha) under both fully irrigated and dryland conditions (i.e. not irrigated and protected from rainfall using the rain-shelter). Nitrogen treatments were applied as urea (46%) in split applications, with 50% allocated at plant emergence (17 November 2011) and 50% at the sixth expanded leaf stage (29 December 2011) in Experiment A. In Experiment B, N treatments were applied in either two or three splits, depending on treatment: the first application was at sowing comprising 0%, 33% and 20% of the total N, the second at the sixth expanded leaf stage comprised of 0%, 67% and 40%, and the third at crop anthesis comprised of 0%, 0% and 40% of the total (0, 75 and 250 kg/ha), respectively.

Soil water monitoring and irrigation

Absolute soil moisture content (SMC$_A$; mm) (Teixeira et al., 2014) was estimated from volumetric soil moisture content (SMC$_V$; %) taken at the top soil layer (0–0.20 m) with a Time Domain Reflectometer Trase system, Model 6050X1 (Soil Moisture Equipment Corp., Santa Barbara, USA). From 0.20 to 1.60 m soil depth, SMC$_V$ was measured in 0.2 m increments, using a neutron probe Troxler model 4300 (Research Triangle Park, NC, USA). Total soil moisture through the 1.6 m soil profile was estimated at ~240 mm in Experiment A in the early stages of crop establishment (8 December 2011) and 330 mm in Experiment B, with 55 and 86 mm in the top 0.4 m, respectively.

In Experiment A, the site received 274 mm of rainfall through the growing period. Additional 210 mm was added as irrigation. For Experiment B, the experimental area was protected from rainfall events with a rain-shelter structure. Irrigation here refers to fully irrigated plots (774 mm/season), dryland plots received 101 mm of irrigation between October and November to enable even crop germination and 8.5 mm subsequent as a carrier for N fertiliser. In both experiments, irrigation was based on estimated SMC$_A$.

Measurements

Final biomass and grain yield were determined on 30 April 2012 in Experiment A, and on 10 April 2013 in Experiment B. Plant density and total fresh weight per sample were determined. In both experiments, every effort was made to include all dead leaves in the DM analyses. A 2- to 3-plant subsample was retained to determine dry matter percentage after drying the material at 60^{o}C to a constant weight. Subsamples were ground with a Cyclone Mill (Udy Corporation, Fort Collins, Colorado, USA) prior to passing through a 1 mm screen and subsequent N analysis using the Dumas high temperature combustion method with a LECO TruSpec C/N analyser. Yield components [grains row numbers, grains per row, grains per ear and 1000-grain weight] were determined for Experiment B only, as the most of the parameter were not determine in Experiment A.

Data analyses

Analysis of variance was performed using GenStat v.17 (VSN International, Hemel Hampstead, UK). Significant interactions and main effects were separated post hoc using Fisher’s protected least significant difference (LSD) tests (α=0.05).

Results and Discussion

Both total dry matter and grain yield increased with increasing water and N supply (Figure 1a). Higher radiation interception and radiation use efficiency were observed in crops supplied with increased amounts of N and water (George et al., 2013; Teixeira et al., 2014).

Nitrogen supply had no significant effect on either harvest index (HI) or N harvest index (NHI) (Figure 1a, c) within the same water treatments. The HI of 0.47-0.53 was similar to the range of 0.43–0.50 reported for irrigated maize (Muchow, 1988; Moser et al., 2006) in sub-tropical and tropical environments, respectively, and the values reported for the ‘new’ and ‘old’ era published literature reviewed by Ciampitti and Vyn, (2013). Similar NHI across N rates has also been reported for irrigated maize (Muchow, 1988). The constant indices across N treatments indicated that dry matter and N accumulation in the grain are closely coupled to the mass and N content of the whole plant (Muchow, 1988). Therefore it follows that as biomass and plant N increase with greater N supply, grain yield and grain N will increase proportionately, with the final yield being determined by the length of the effective grain-filling period. In this study, Ng% was relatively stable at the final harvest, increasing from 0.92 to 1.25% with increasing N application from 0 to 250 kg N/ha (Figure 1b). Given the constant HI, this suggests that grain N content would also be higher at higher N rates, as observed (Figure 1b, d). The NHI increased with HI in two out of three situations investigated (Figure 1d), the positive relationship similar to Ciampitti and Vyn (2013).

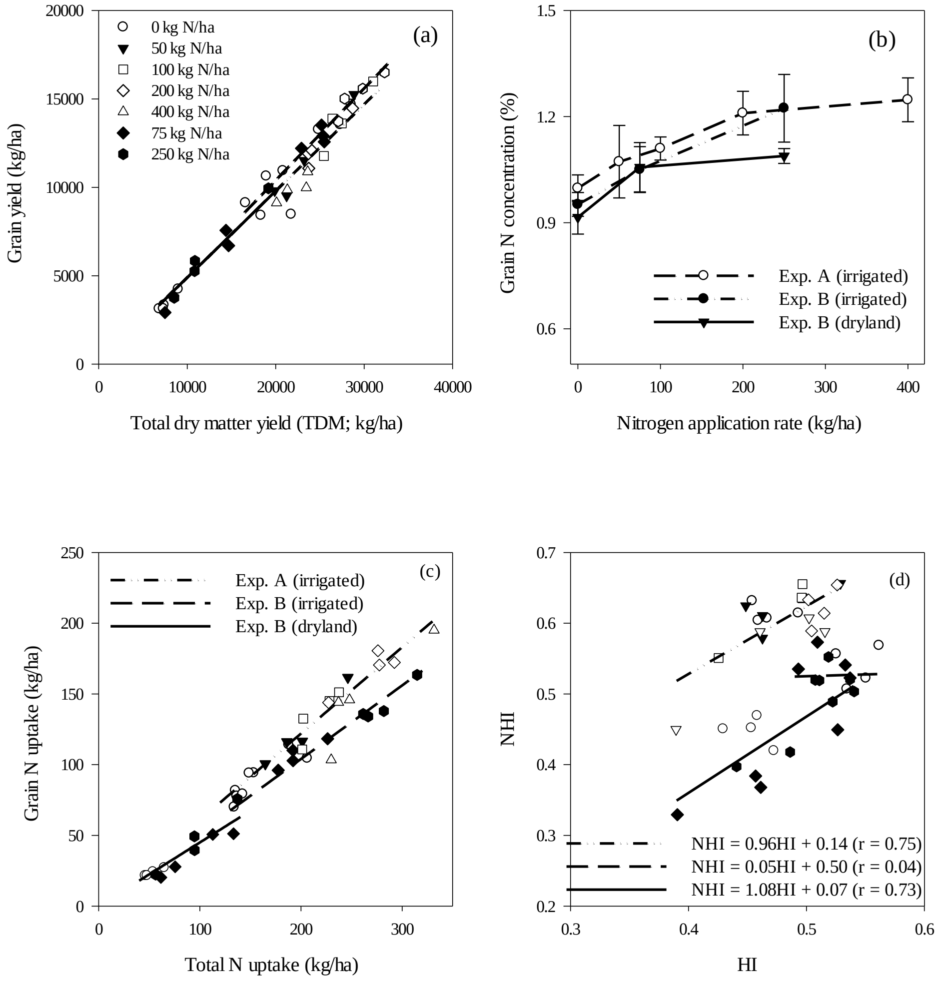

Figure 1: The relationship between grain and total yield (harvest index; HI) (a), (b) grain nitrogen (N) concentration and N application rate, (c) grain and total N uptake (N harvest index; NHI) and (d) the relationship between NHI and HI for maize crops grown under different irrigation (dotted lines; irrigated and solid lines; dryland) and N rates of application at Lincoln, New Zealand in two consecutive seasons (2011–2012, 2012–2013). Vertical bars are standard errors of differences of the means.

Both HI and NHI varied significantly (P<0.001) with water treatments in Experiment B (Figure 1a, c, d). The HI was lower at 0.47 for the dryland crops than the 0.53 for the irrigated crops. This could be attributed to the high (P<0.001) number of ears per plant, grains per ear and unit area for the irrigated compared with the dryland crops (Table 1). Furthermore the 1000-grain weight was also higher for the irrigated (250 g) than dryland (191 g) crops. Moser et al. (2006) reported higher yield components for fully irrigated than dryland maize crops. Surprisingly, Moser et al. (2006), reported higher HI for the dryland than the irrigated crops. This anomaly was attributed the difference in leaf shedding and loss under dryland conditions during harvesting, and also the large total biomass for the irrigated crops and the inefficient allocation of assimilates to the growing grain for these crops. The NHI values were 0.43 for the dryland treatments and 0.53-0.60 for the irrigated treatments (Figure 1c) for both experiments. The NHI for the irrigated crops was consistent with the 0.63.4±0.09 reported by Ciampitti and Vyn, (2013). These authors also showed that NHI was conservative under unlimited conditions. Low NHI for crops grown under dry conditions has been reported previously in other grain crops such as wheat (*Triticum aestivum* L.; Sarvestani et al., 2003), and these crops were also characterised by low N%, similar to that shown in Figure 1b.

Table 1: Yield components for maize crops grown under differing water and nitrogen rate at Lincoln, New Zealand in 2012-2013 season

Treatments	Ears/plant	Rows/ear	Kernels/row	Kernel /m^2	1000-kernel weight (g)
Grand mean	1.6	14	24	967	221
Water regime					
a) Fully irrigated	2.0	13	30	1294	250
b) Dryland	1.2	14	17	641	191
Nitrogen rate (kg N/ha)					
0	1.5	14	22	866	196
75	1.6	14	25	960	238
250	1.6	14	25	1076	228
F-tests					
Water (W)	***	ns	***	***	***
N rate (N)	*	ns	*	ns	***
W*N	ns	ns	ns	ns	ns

*P=0.05, **P=0.01 and ***P=0.001.

The Ng% increased (Figure 1b) from 0.97% to 1.1% with water supply, and from 0.92% for the N control to 1.25% for the 200–250 kg N/ha crops in both experiments. These figures agree with the mean of 0.98-1.1% reported by Ciampitti and Vyn, (2013). The low Ng% for the dryland crops was caused by the inability of these crops to take up sufficient N from the soil and/ or from the applied fertilisers to fully meet the demand of the growing crop. Overall, NHI differences with water supply (Figure 1c) are supported by the differences in Ng% across the N rates (Figure 1b). The increase of Ng% with both water and N supply (Figure 1b) meant that the associated protein content of the maize grain also increased, based on the established relationship between Ng% and protein content (Mariotti et al., 2008). The Ng% reached a maximum with application of about 250 kg N/ha in both experiments. Fertiliser N applied in excess of this rate would be of no economic value.

Conclusions

The Ng% increased with both water and N supply. The NHI was closely related to the amount of grain produced, suggesting that improving the HI of maize crops is one way to improve the ability of the crops to utilise N from both soil and fertiliser sources. NHI spanned the range of 0.43–0.60. Treatments with high water availability caused higher NHI values in crops and therefore we conclude that water management was of more value than N fertiliser rates for increasing NHI up to reported critical thresholds up to ±0.65.

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