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The impact of water and nitrogen limitation on maize biomass and resource-use efficiencies for radiation, water and nitrogen

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ABSTRACT

The impact of limited water and nitrogen (N) supply on maize productivity and on the utilisation efficiency of key production resources (radiation, water and N) was quantified in two field experiments during consecutive seasons in Canterbury, New Zealand. In experiment 1 crops were subjected to five N treatment rates (0–400 kg N/ha) and, in experiment 2, to three N (0 to 250 kg/ha N) and two water regimes (dryland and fully irrigated) using a rain-shelter structure. Limited N and water reduced yield and affected resource-use efficiencies. Total biomass ranged from 8 Mg DM/ha for dryland nil N crops to up to 28 Mg DM/ha for fully irrigated and N fertilised crops. Radiation use efficiency declined with N and water limitation from a maximum of 1.4 g DM/MJ to 0.6 g DM/MJ. Transpiration water use efficiency was higher in water stressed crops than irrigated crops (50–70 kg DM/ha/mm) and increased linearly with N fertilizer rates in proportion to the increase in radiation use efficiency. The crop conductance decreased from 0.19 mm/MJ in irrigated crops to 0.07 mm/MJ in dryland crops with negligible response to N fertilizer rates. Nitrogen use efficiency declined with N input rates from 100 to 150 kg DM/kg N, being inversely related to the efficiency of both water and radiation use. Dryland crops recovered 25% less N from applied fertilizer than irrigated crops. These results highlight that benchmarks of resource efficiency need to consider the level of intensification of the production system and illustrate trade-offs between yield targets and the efficiency of water and N use, that depend on the scale of analysis. To establish a balance between economic returns and environmental impacts, these trade-offs need to be managed depending on the relative values assigned to the use-efficiency of each input resource in relation to crop productivity.

1. Introduction

The global demand for food is projected to increase by more than 70% by 2050 (Tilman et al., 2011). In order to minimise the need for further expansion of cultivated lands, this production increase needs to be partially achieved through the intensification of crop productivity, i.e. more produce per unit of cultivated land (Mueller et al., 2012). Much of the enhancement in crop productivity in the last half century has been achieved by increasing rates of agronomic inputs (Borlaug, 2003). However, to optimise use of increasingly limited resources and to avoid adverse environmental impacts, future yield increases will need to focus on increasing the efficiencies with which inputs such as fertiliser and irrigation water are utilised in agricultural systems (Tilman et al., 2002).

When plant growth is unconstrained by water, nutrients and biotic stresses, total above-ground biomass dry-matter (DM) yield (Y_{dm}, g DM/m^2) is determined by the product of total solar radiation (R_0, MJ/m^2), the fraction of this radiation that is intercepted by the crop canopy (f_R, 0–1) and the efficiency (ε_R, g DM/MJ R_i) by which intercepted radiation is converted into biomass via photosynthesis (Monteith, 1972). However, in many production systems worldwide, yields are limited both by water and nitrogen (N) availability. Under these conditions, both f_R and ε_R can be reduced through stresses on canopy expansion and photosynthesis rates, respectively (Lemaire et al., 2008) and contribute to low Y_{dm}. Intensively managed cropping systems achieve high yields using irrigation and

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fertiliser to maintain water and N supplies at levels adequate to satisfy crop demands. However, water (ε_W, kg DM/ha/mm) and N (ε_N kg DM/kg N) use efficiencies tend to decrease as N and water inputs increase beyond crop demand, compromising farm profitability and increasing the risk of negative impacts on ecosystems, such as from eutrophication, nitrous oxide emissions and leaching of nitrate to groundwater (Tilman et al., 2002).

To determine the best management practices to optimise both yields and resource use efficiencies it is important to understand how crop production and resource efficiency-coefficients respond to both optimum or limiting water and nutrient supplies. This understanding can support the setting of benchmarks to evaluate and improve future agricultural systems in order to balance the need to increase yields and the efficiency of resource use (Kant et al., 2011; Mulvaney et al., 2009; Sadras and Angus, 2006). Information regarding the effects of water and N on yield and multiple resource use efficiencies (ε_R, ε_W and ε_N) is usually pieced together from distinct datasets with contrasting scales of analysis (e.g. leaf, plant or crop level), crop species, and experimental conditions (e.g. controlled or field environments). For example, previous analysis reported on relationships between ε_R and ε_W in lucerne (Brown et al., 2012) and wheat (Caviglia and Sadras, 2001) in the field and mixed stands of annual weeds in pot trials (Hirose and Bazzaz, 1998). For wheat, a strong positive linear relationship between ε_W and ε_R indicated that the rate of transpiration per unit of intercepted radiation (i.e. crop conductance, g_c, mm/MJ) was conservative across contrasting N availability (Caviglia and Sadras, 2001). The relationships between ε_R and ε_N were also studied in wheat under controlled environment (van den Boogaard et al., 1995); and between ε_W and ε_N for maize (*Zea mays*) in pot trials (Eghball and Maranville, 1991).

In this study, we quantify these relationships for field grown maize crops under a wide range of water and N supply. Maize is the most produced grain cereal worldwide (FAOSTAT, 2013) and also a key forage option for the New Zealand pastoral-based livestock industry (de Ruiter et al., 2009). Under unconstrained growth conditions, maize crops have inherently higher potential biomass production than temperate cereals, such as wheat, due to the C_4 photosynthetic metabolic pathway that increases the efficiency of radiation, water and nitrogen use (Ghannoum et al., 2011; Sage and Zhu, 2011). There is a well established positive relationship between Y_{dm} and ε_R (Muchow and Sinclair, 1994) in maize and indication of an inverse relationship between ε_N and ε_W from controlled environment trials (Eghball and Maranville, 1991). Nevertheless, there is limited information regarding how N and water supply interact to influence multiple efficiencies in maize crops and how these compare with previous reports for other crops. In this paper, we first report on the relationships among total biomass, ε_R, ε_W and ε_N for field maize crops subjected to limited water and N supply in Canterbury, New Zealand. Then, by analysing how resource capture and conversion efficiency are influenced by crop physiological characteristics (e.g. leaf area index, g_c and specific leaf nitrogen) we provide insights on the mechanisms explaining use-efficiency patterns in response to water and nitrogen limitation.

2. Materials and methods

2.1. Field management and experimental design

Data from two experiments in which the maize hybrid Pioneer 39G12 was sown in consecutive growth seasons (2011–2012 and 2012–2013) and adjacent sites (spaced by around 350 m) at Lincoln, Canterbury, New Zealand (43°37′ S, 172°28′ E) were used in this study. The soil is similar in both sites being a deep (>1.7 m) Templeton silt loam (New Zealand Soil Bureau, 1968) or *Udic Ustochrept* (USDA Soil Taxonomy) with an available water holding capacity of around 190 mm/m of depth (Martin et al., 1992, 2004). The depth of the groundwater table for both sites was not identified through core sampling or neutron probe measurements (Section 2.2.2), indicating that saturated soil layers are deeper than the effective root zone for maize, in agreement with regional surveys (Hanson and Abraham, 2009).

In the first experiment (E1, 2011–2012) fully irrigated crops were sown on 31st October 2011 at a population of 12.5 plants/m^2 and row spacing of 0.76 m. A complete randomised design, with five N application rates (0, 50, 100, 200 and 400 kg/ha), was established with 4 replicates. Pre-trial soil tests showed that available P and K where moderately high (Olsen P 19 mg/kg; available K 160 mg/kg). Even so, base fertilizer of 250 kg triple superphosphate (20.5% P) and 200 kg/ha potassium chloride (KCl; 52% K) was applied on 31 October 2011 to ensure that P or K did not constrain plant growth. Nitrogen treatments were applied in the form of urea (46% N) in split applications with 50% at plant emergence (17 November 2011) and 50% at the 6th expanded leaf stage (29 December 2011).

In the second experiment (E2, 2012–2013), the same maize hybrid was established under a mobile rain-shelter structure (Martin et al., 2004) located 350 m west of the first season site. Crops were subjected to fully irrigated and dryland (i.e. not irrigated and protected from rainfall) conditions using the rain-shelter. Briefly, the rain-shelter consists of a greenhouse-like structure (55 m long × 12 m wide) that is positioned in a “parking-mode” ∼50 m from experimental plots. During rainfall events, the rain-shelter automatically moves along metal rails to cover the experimental area, enabling total control of water inputs through a drip irrigation system. Prior to the experiment establishment on 19 October 2012, base fertilizer in the form of 488 kg/ha of triple superphosphate (100 kg P/ha and 68.32 kg Ca/ha) and 100 kg/ha of KCl (50 kg K/ha) was applied on the entire experimental area. Prior to the experiment, the soil was intentionally depleted of N by removing above-ground biomass through sequential harvests of an unfertilised perennial ryegrass pasture (*Lolium perenne*) followed by an unfertilised oat (*Avena sativa*) crop. On 23 October 2012, the maize crop was sown at a density of 12 plants/m^2 with 0.71 m row spacing. Six experimental treatments combining two water regimes (dryland or fully irrigated) and three nitrogen application rates (0, 75 and 250 kg/ha) were arranged in a randomised complete block design with 4 replicates giving 24 plots (3.6 m × 5.0 m). For fully irrigated crops, water was applied weekly to replenish evapo-transpiration measured at the site (Section 2.2.2). The N fertilizer was applied as urea (46% N) in either two or three splits depending on treatment. The first urea application was at sowing (0, 25 and 50 kg N/ha), the second at the sixth expanded leaf stage (0, 50 and 100 kg N/ha) and the third at crop anthesis (0, 0 and 100 kg N/ha) for the respective N treatments. In both experiments, crops were frequently monitored and agrichemicals were applied at commercial rates as required to minimise biotic stress (George et al., 2013 for details). Damage resulting from biotic stresses (insect, pathogen and weed pressure) was negligible in both experiments.

2.2. Measurements

2.2.1. Site weather and initial soil conditions

Daily weather variables (solar radiation, maximum and minimum air temperatures, vapor pressure deficit, Penman potential evapo-transpiration and rainfall) were accessed from measurements at the Broadfields weather station (National Institute of Water and Atmospheric Research – NIWA 17603) which is located ∼200 m from the rain-shelter site (Fig. 1).

Total soil moisture through the 1.6 m soil profile (Section 2.2.2) was estimated at ∼240 mm in Experiment 1 in the early stages of crop establishment (8 December 2011) and 330 mm in Experiment