Effects of in-crop nitrogen application on grain yield of wheat under waterlogged conditions

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Abstract
Waterlogging is a major constraint for wheat production in the high-rainfall zone (HRZ) of south-eastern Australia. During waterlogging, significant quantities of nitrogen (N) derived from fertilisers can be lost, reducing potential supply to the crop. A field experiment was conducted to quantify the effectiveness of different in-crop N application rates in reducing the effects of pre-anthesis waterlogging on wheat grain yield. The experiment was designed with two water regimes (waterlogged and rainfed) and four rates of in-crop N (urea) fertiliser (nil N, 70,140 and 210 kg N ha^{-1}). The waterlogged regime was irrigated from mid-tillering (GS23) to flag-leaf emergence (GS39). In-crop N fertiliser rates were split; 70% at early-tillering (GS21) and 30% at flag-leaf emergence. At grain maturity, tiller number, ear number, above-ground biomass, grain yield and harvest index were determined. Results demonstrated that tiller numbers, ear numbers, above-ground biomass, grain number and grain yield significantly increased with increasing rates of N applied compared to nil N under both water regimes. Pre-anthesis waterlogging significantly delayed heading, anthesis and maturity (3-5 days) and significantly reduced tiller numbers (21%), ear numbers (11%) and above-ground biomass at anthesis (15%). This reduction was less under high N rates. Adequate soil moisture availability for grain filling in a dry spring followed by pre-anthesis waterlogging significantly increased grains per ear (24%) and this increase was greater at high rates of N application. Grain yield and above-ground biomass at maturity were not significantly affected by waterlogging at low N rates but increased 8-17% at high N rates. Pre-anthesis waterlogging significantly reduced grain protein content at low N rates but there was no significant effect of waterlogging on grain protein content at high N rates due to increased N uptake. Overall, adequate supply of N fertilizer before and after waterlogging can alleviate the detrimental effect of pre-anthesis waterlogging on wheat grain production.

Key Words
waterlogging, N fertilizer rate, wheat, pre-anthesis, tillering, flag-leaf emergence

Introduction
Wheat is the dominant crop in the High Rainfall Zone (HRZ) of south-eastern (SE) Australia, with a mean yield of 2.9 t/ha (http://yieldgapaustralia.com.au/). However, simulation modelling has suggested that potential yields of more than double these figures are possible (Sylvester-Bradley *et al.*, 2012), which have been demonstrated in field trials (Christy *et al.*, 2015). Hostile soil physicochemical conditions in HRZ, particularly oxygen-limited conditions during winter waterlogging are believed to result in large losses of nitrogen (N) through denitrification (Harris *et al.*, 2015b). Oxygen depletion in waterlogged soils reduces root growth and restricts nutrient uptake. In wheat, the adverse effects of waterlogging reduce tillering, shoot growth, delay maturation and eventually reduce yield (de San Celedonio *et al.*, 2017). Options for managing waterlogging damage to crops are currently limited and additional management options are needed. Subsurface drainage and raised beds appear to be effective in some situations, but may not be financially viable (Manik *et al*., 2019). Nitrogen fertiliser application can improve plant growth and development under waterlogged conditions (Anderson and Garlinge, 2000). Some controlled-environment studies have found that application of additional N fertiliser under waterlogging can increase grain yield by 20% through increase in plant height, tiller number and spikelet number (Robertson *et al*., 2009). Studies in field-grown, rainfed crops (wheat, canola) have confirmed this effect in some situations, but not in others (Harris *et al.*, 2015b; Manik *et al*., 2019). The evaluation of the potential of N fertiliser application in reducing the adverse effects of waterlogging on wheat under field conditions has received little attention. There is currently no evidence to quantify the effect of different N application rates on grain yields under waterlogging in HRZ of

SE Australia. This study investigated whether supplying optimum N fertilizer amounts can alleviate the adverse effects of waterlogging on wheat grain production in HRZ of SE Australia.

Methods

The study was conducted in the 2018 growing season at the Agriculture Victoria research farm in Hamilton, Victoria. (142°4'15" E, 37°49'27"S). Soil type at the experimental site was Ferric-Eutrophic Brown Chromosol (Isbell, 2002) that is prone to waterlogging. The experiment comprised a randomized split-plot design with three replicates. There were two water regimes with four in-crop N fertiliser treatments randomised within these. Two experimental blocks were located 30 m apart on the upper and lower parts of the paddock that differed in their expected susceptibility to waterlogging and were selected for two water regimes (waterlogged and rainfed). Irrigation (~100 mm) was applied to the lower block through a travelling spray irrigator to increase the depth and duration of waterlogging during winter; from July 23rd/mid tillering (GS 23; Setter and Carlton, 2000) to September 21st/flag-leaf emergence (GS 39). N fertiliser treatments included four rates: nil N, 70, 140 and 210 kg N/ha. These N rates were calculated based on the maximum yield potential and the starting soil mineral N content (10.4-10.7 mg kg^{-1}). Fertiliser was surface-applied by hand as urea with 70% at early-tillering (GS 21) and the remaining 30% at GS 39. Winter wheat (*Triticum aestivum* L.) cv. Trojan was sown on raised beds on 21 May. The crop was drilled at a depth of 30 mm and a seed rate of 100 kg/ha with 150 mm row spacing in plots 4 m long and 1.5 m wide. All treatments received a basal application of 50 kg/ha mono-ammonium phosphate fertiliser (10 kg N and 22 kg phosphorus/ha) and were treated with 400 mL/ha Flutriafol at sowing.

Climatic measurements were recorded from a weather station near to the experimental site. Piezometers containing Odyssey® water level sensors were used to measure the depth of the water table in the waterlogged and rainfed blocks throughout the growing season (May-December). At stem elongation (GS 31), anthesis (GS 65) and final harvest (GS 92) plants within a 0.3 m^2 quadrat in each plot were hand harvested at ground level and processed for biomass and yield determination. At GS 31 and GS 65, green leaf number was determined along with the number of tillers and ears (GS 65). All plant components (dead leaves, green leaves, ears and stems) were oven dried to a constant weight at 60°C and weighed. At final harvest, each sample was processed for tiller number and ear number. The ears were dried, threshed and weighed to determine grain yield, non-grain biomass, 1000 kernel weight and harvest index (ratio of grain yield to total-above ground biomass). The straw and grain were analysed for N concentration using Leco combustion to determine grain protein content (%N x 5.83) and total N uptake (grain yield x %N in the grain + straw yield x %N in the straw)/100. Data were analysed using Analysis of Variance to determine N treatment effects and interactions with the water regime using GenStat 18th edition (VSN International Ltd., 2016). Treatment means were deemed significant at 5% least significant difference (*l.s.d*).

Results

The 2018 growing season was relatively dry and the total annual rainfall was 650 mm which was lower than the long-term average (705 mm). The rainfall over spring (Sep-November) was 101 mm which was significantly lower than the long-term average (197 mm). The depth of the water table in the waterlogged regime varied from 5 to 40 cm below the surface throughout July-Sep whereas it varied from 5 to 60 cm in the rainfed regime. The rainfed regime was also waterlogged, but the depth of the water table stayed in the top 30 cm for a shorter duration in winter (mid July-mid Aug), declined rapidly and stayed below 30 cm after that. The severity of waterlogging which is determined by the depth of the water table and its duration was significantly higher in the waterlogged regime compared to rainfed. The response of wheat to N fertiliser application depended on waterlogging. In the waterlogged regime, tiller number, ear number, grain number, grain yield and biomass increased in response to N fertiliser application up to 210 kg N/ha, whereas in the rainfed regime, these parameters asymptoted ($P < 0.05$) at 70-100 kg N/ha. Pre-anthesis waterlogging significantly ($P < 0.05$) reduced tiller numbers, ear numbers and above-ground biomass at anthesis at low N rates but none of these attributes were significantly affected by waterlogging at high N rates. There was a significant interaction between waterlogging and N fertiliser application in response to tillering, ear production and biomass at anthesis. The rainfed treatment had more tillers (12-30%), ears (3-18%) and above-ground biomass at anthesis (7-22%) compared with their respective N treatments under the waterlogged treatment (Fig. 1 a, b and d). The waterlogged plants had significantly more grains per ear (12-31%) compared with their respective N treatments under the rainfed regime. This increase was greatest at high N rates (Fig. 1e). At maturity grain number, grain yield and above-ground biomass were not significantly affected by waterlogging at low N rates but increased (8-17%) at the high N rates (Fig. 1c and f). The harvest index of waterlogged plants were greater than that of rainfed plants for each respective N treatment (Table 1). There was a significant interaction between waterlogging and N application for the grains per ear, grain number, grain yield, biomass at maturity and harvest index (Fig. 1 and Table 1). Total N uptake and grain protein content increased in response to N fertiliser application. Pre-anthesis waterlogging significantly reduced grain protein content at low N rates but there was no significant effect of waterlogging on grain protein content at high N rates due to increased N uptake. There was a significant interaction between waterlogging and N fertiliser application in response to total N uptake and grain protein content (Table 1). There was a significant interaction between waterlogging and N fertiliser application on crop phenology. Heading, anthesis and crop maturity were significantly delayed (3-5 days) under waterlogging whereas high N rates significantly accelerated heading, anthesis and crop maturity under both water regimes compared to nil N. Grain weight and duration of grain filling were not significantly affected by the interaction between pre-anthesis waterlogging and N application rates (Table 1).

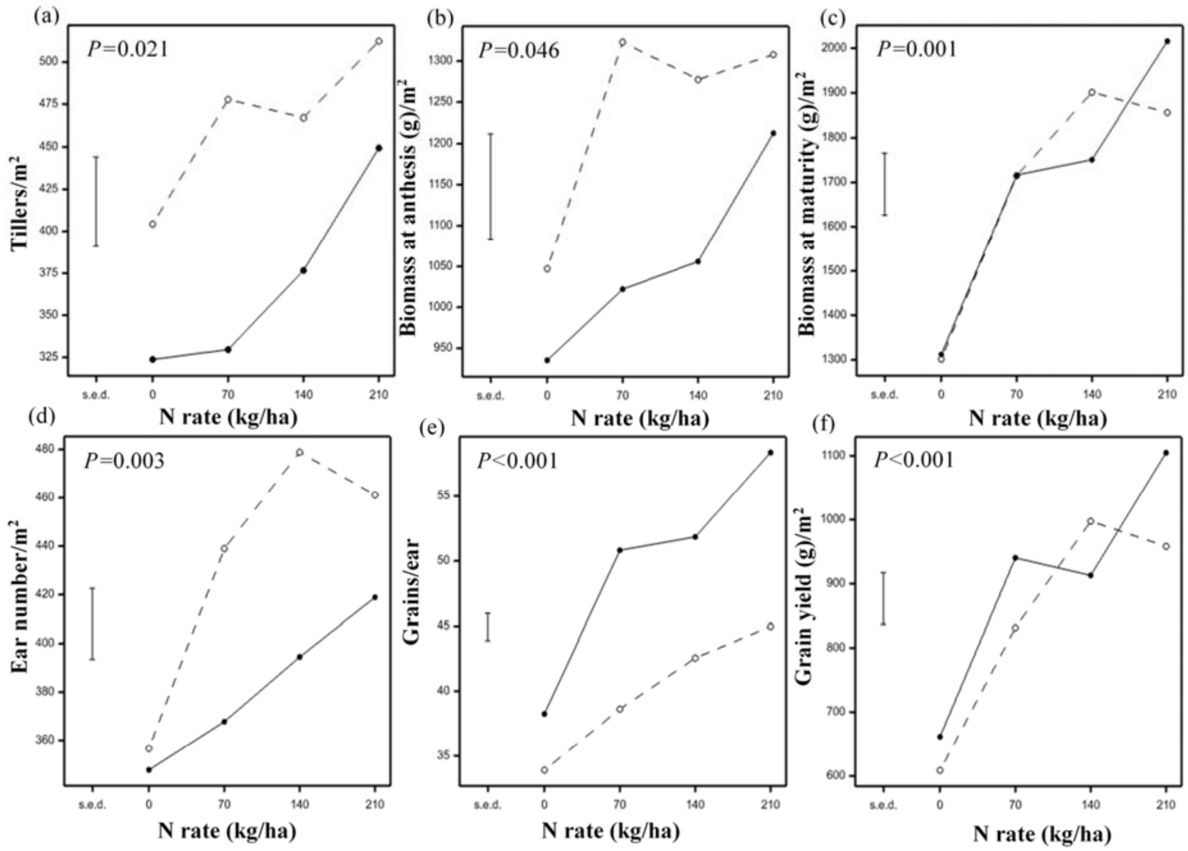

Figure 1. Changes in number of tillers (*a*), above-ground biomass at anthesis (*b*), above-ground biomass at maturity (*c*), number of ears (*d*), grains per ear (*e*) and grain yield (*f*) under different N rates in waterlogged (—●—) and rainfed (-○-) treatments. Error bars (—) are standard errors of differences (s.e.d) of means (*n*=3). Significance levels represent the Site*N rate interaction.

Discussion

The longer period of high water table in the waterlogged regime caused a reduction in plant growth and biomass at anthesis compared to the rainfed regime. The results of this study indicate that there is a significant reduction in tillering, ear and biomass production at anthesis as a response to pre-anthesis waterlogging and reduced N uptake, but there was an increase in grains per ear resulting in no significant effect of waterlogging on grain yield, grain number or biomass at maturity. Although waterlogging damage was greatest at early growth stages similar to the findings of de San Celedonio *et al.* (2017), later dry seasonal conditions allowed the crop to recover and compensate for any early damage. Therefore, the extent of waterlogging damage depends on the growth stage of the plant at the time of waterlogging, severity of the waterlogging, the ability of the plant to recover and later seasonal conditions. Application of N fertilizer after waterlogging, combined with access to sufficient soil moisture reserves following waterlogging, may have provided favourable conditions for plant recovery and grain-filling in seasons with a dry spring finish. Reduced grains per ear in the plants grown under rainfed block may have been due to greater shading associated with more tillers and due to dry conditions in spring. Under high N rates, waterlogged crops which had low tiller numbers and ear numbers were able to recover and maintained yield through more grains per ear. This is consistent with the findings of Anderson and Garlinge (2000). Therefore, application of higher rates of N fertilizer provides a strategy to offset the impacts of waterlogging on grain production in HRZ. The increase in wheat growth and grain yield in response to increased N application was largely due to increased tillering, ear and biomass production and grain numbers per ear. The growth and yield increases were greater when N is applied in N deficient waterlogged soils. Significant delay in heading was mainly due to waterlogging and possibly N deficiency caused by waterlogging.

Table 1. Crop phenology, yield attributes and nitrogen uptake under different water regimes and nitrogen rates

Treatment	N rate	Days to heading (DAS)	Grain filling period (Days)	Grain number (m^{-2})	Grain weight (mg)	Harvest index	Grain protein content (%)	Total plant N uptake (kg/ha)
Rainfed	0	141	55	12040	50.7	0.46	15.4	180
	70	137	57	16944	49.3	0.48	15.9	253
	140	134	57	20375	48.8	0.52	16.5	308
	210	133	56	20745	46.3	0.51	17.1	316
Waterlogged	0	141	55	13339	49.8	0.49	16.7	239
	70	138	57	18598	50.6	0.53	9.3	259
	140	138	56	20136	45.2	0.52	15.0	292
	210	137	57	24442	45.1	0.54	15.4	445
l.s.d.		3.7	2.2	2505	6.09	0.031	3.47	74.8
Significance (*p<0.05*)	Site* N rate	**	ns	***	ns	**	**	***

Abbreviations: DAS, days after sowing; ns, not significant (>p.0.05); * p<0.05; ** p<0.01; *** p<0.001

Conclusions

Pre-anthesis waterlogging reduced tiller numbers, ear numbers and above-ground biomass at anthesis relative to the rainfed treatment with the effects generally more evident at the lower N rates. However, these crops were able to compensate through more grains per ear, particularly at the higher N rates. Adequate soil moisture reserves following waterlogging, may have provided favourable conditions for plant recovery and grain-filling in seasons with a dry spring finish. Therefore, waterlogging does not cause adverse impacts on wheat grain yields in a dry season. Overall, high levels of N fertiliser alleviate the detrimental effect of pre-anthesis waterlogging and to achieve yield potential in HRZ environments. More work is needed on the degree of recovery depending on the severity of waterlogging and more strategic timing of N and costs of amelioration.

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