Impact of genotypic variations in transpiration rate on Australian wheat productivity

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Abstract

Crop water productivity has been receiving special attention in regards to productivity and food security. Limited-transpiration rate (LTR) at high vapour pressure deficit (VPD) has potential to improve drought adaptation. The quantification of the impact of LTR on water consumption, biomass accumulation and yield formation requires the use of dynamic crop modelling to simulate physiological and environmental processes at a suitable time scale and across environments. Here, a new module for the new generation of Agricultural Production Systems sIMulator (APSIM-NextGen) was developed and evaluated, which enables the simulation of atmospheric (VPD) and edaphic water effects on transpiration, biomass production and yield. The module was used to assess the potential of the LTR trait at improving transpiration efficiency at 60 sites across the Australian wheatbelt. Results showed that selection for the LTR trait could result in a 2.5% increase in grain yield nationally through significantly higher transpiration efficiency. Greatest productivity gains were found in eastern part of the wheatbelt where crops rely heavily on stored soil moisture and saving water mid-day (i.e. under high VPD) allows crops to consume it at more critical stages later during the crop cycle.

Key Words

Limited-transpiration rate, transpiration efficiency, genotypic variation, APSIM Next Generation.

Introduction

Increasing yield is of utmost importance to provide sustainable food security to the growing population. Higher transpiration efficiency (TE), usually defined as crop mass production per unit of water transpired (Sinclair, 2018), appears as a promising mechanism to increase crop yields in drought-prone environments where crops rely heavily on stored soil water (Sinclair et al., 2005; Chenu and Fletcher, 2015; Messina et al., 2015; Kulkarni et al., 2017; Christy et al., 2018; Sinclair, 2018). Transpiration is driven by two major factors being the gradient in vapour pressure between the dry atmosphere and the wet interior cell chamber of leaves (i.e. the vapour pressure deficit, VPD) and the resistance to gas diffusion driven by stomata aperture. Stomatal conductance controls water and CO_2 fluxes from and into leaves so that increased stomatal conductance typically enhances CO_2 flux and biomass assimilation but at the cost of higher transpiration rate and water loss.

One approach to select genotypes for enhanced TE under water-deficit conditions is to identify genotypes with increasing stomatal resistance at elevated VPD. This trait, usually referenced to as the limited-transpiration rate (LTR; Sinclair *et al.*, 2005), keeps transpiration rate from continually increasing (especially at mid-day when highest VPDs occur) and allows conservation of soil water. The conserved water in soil profile early in a growing season can be valuable to support crop physiological activity at more sensitive growth stages later in the season (e.g. Sinclair *et al.*, 2005; Schoppach and Sadok, 2012; Lobell *et al.*, 2013; Devi *et al.*, 2014; Messina *et al.*, 2015) when water deficit is more likely to develop in many Australian cropping environments (Chenu *et al.*, 2013).

To assess the impact of reduced transpiration rate at high VPD on crop growth and development, a new transpiration efficiency module was developed for APSIM NextGen (Holzworth *et al.*, 2018) improved for canopy development (Zheng *et al.*, 2019). The performance of the new module was tested for a broad range of conditions. The impact of variations in transpiration-rate response to VPD on wheat yield was simulated and the potential of breeding for lower LTR, i.e. higher TE, was explored across the Australian wheatbelt.

Material and Methods

A new transpiration module

A new transpiration module was implemented to the improved version of APSIM NextGen Wheat from Zheng *et al.* (2019). The new module simulates photosynthesis using the Soil-Plant-Atmosphere System Simulation (SPASS) developed by Wang (1997), with a few modifications, such as a downscaling to hourly time step with the temperature diurnal pattern from Parton and Logan (1981). Hence, the model simulates hourly potential biomass assimilation. VPD is calculated as the difference between hourly saturated vapour pressure (SVP) and SVP at minimum temperature (Messina *et al.*, 2015) and is used to calculate hourly transpiration as follows:

Eq (1) $$TR_{pot,t} = \frac{\Delta DM_{pot,t} \times VPD_t}{TEc} \qquad \text{sunrise} \leq t \leq \text{sunset}$$

where TR_{pot} is the potential transpiration driven by radiation interception (mm), ΔDM_{pot} is the hourly potential increase in dry matter (i.e. amount of CO_2 fixed by photosynthesis; g m^{-2}), TEc is the transpiration efficiency coefficient (kPa g_C^{-1} m^{-2} mm_{water}^{-1}), and t is time. The potential transpiration is then adjusted based on the level of evaporative demand and soil water stress when applicable. First, VPD-limited hourly transpiration ($TR_{VPD-limited}$) is calculated as follows for $VPD_t > VPD_{ref}$:

Eq (2) $$TR_{refVPD} = \frac{\Delta DM_{pot,refVPD} \times VPD_{ref}}{TEc}$$

Eq (3) $$TR_{VPD-limited,t} = \min(TR_{pot,t}, TR_{refVPD})$$

where VPD_{ref} is the threshold VPD above which transpiration rate levels off (kPa), TR_{refVPD} is the transpiration rate at VPD_{ref} (mm hr^{-1}), $\Delta DM_{pot,refVPD}$ is the interpolated hourly growth at VPD_{ref} (g m^{-2}). TEc was converted from APSIM v7.9 and set at 0.006 (g m^{-2} mm^{-1} kPa) from crop emergence to maturity. Then, soil-water-limited hourly transpiration ($TR_{water-limited}$) is calculated. Hourly transpiration is capped starting from the maximum $TR_{VPD-limited}$ at midday until the total plant available soil moisture can meet the crop daily water demand. Finally, actual hourly increase in dry matter (ΔDM) is calculated based on $TR_{water-limited}$, as follows:

Eq (4) $$\Delta DM_t = \frac{TR_{water-limited,t} \times TEc}{VPD_t}$$

The performance of the new module was evaluated in five experiments in Gatton, Australia in which *cv.* Hartog was cultivated under a wide range of management practices, i.e. irrigation, N application rates, stubble management, row spacing, and planting dates.

Simulation setup

Daily weather data for 1988-2017 were obtained at 60 selected sites in four major wheat-producing regions across the Australian wheatbelt (Figure 2a; Chenu *et al.*, 2013; Jeffrey *et al.*, 2001). Five sowing dates, five initial soil moisture levels at sowing, and local N application rates were adopted at each site to represent local wheat cropping systems (see Table 1 in Chenu *et al.*, 2013). Atmospheric CO_2 concentration was updated daily according to observations (Ziehn *et al.*, 2016).

Simulations were run for *cv.* Hartog (which transpiration was not restricted by VPD) , and a virtual genotype with a transpiration rate capped for VPD greater than 1.3 kPa, i.e. a VPD threshold above which significant genotypic variations in normalised transpiration rate were observed (K. Chenu, unpublished data).

Results and Discussion

Model performance with the new transpiration module

The model with the new transpiration module, with no re-calibration of genotypic parameters, performed relatively well across the range of conditions tested (Figure 1). In-season LAI and biomass, and final yield were better reproduced with the new module than without it (data not shown).

Impact of reduced transpiration rate at high VPD

The model with the new transpiration module was used to assess the potential of a genotype capping its transpiration rate above 1.3 kPa. Across the Australian wheatbelt, such a trait gave an average yield advantage between -9.5 to 19.7% depending on the location (Figure 2b). The regional yield increases in the East, South, South-East and West were estimated to be on average 4, 2.2, 1.3 and 1.3%, respectively, and 2.5% nationally (Figure 3). The probability of positive yield gains across the wheatbelt was around 54%, and yield loss greater than 5% where only simulated in ~16% of the conditions, mainly in the West (Figure 23, inset). Largest yield gains due to the water-conservation trait were simulated in Queensland and New South Wales (up to 340 kg ha^{-1}), where crops often rely heavily on stored soil moisture.

The water-conservation trait was typically more advantageous under drier situations as long as the water saved during the early vegetative phases could compensate the losses in biomass accumulation by enhancing grain filling and harvest index (Figure 3). By contrast, in high yielding conditions (i.e. absence of substantial drought), yield was typically reduced due to lower transpiration rate. Similar results were found in other studies, e.g. in the US (Sinclair *et al.*, 2010) and Africa (Sinclair *et al.*, 2014) on soybean.

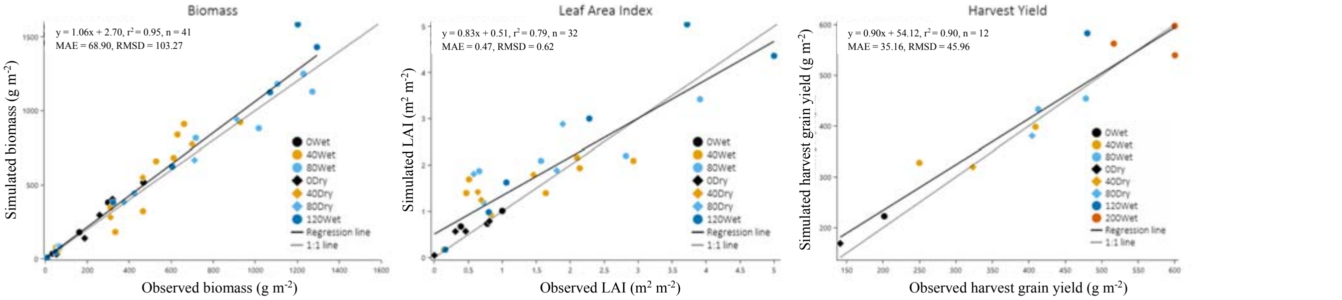

Figure 1. Simulation of in-season biomass (left), leaf area index (LAI; middle) and grain yield (right) by APSIM NextGen with the new transpiration module in five experiments in Gatton, Australia. In the legends, the umbers depict the amount of N applied (in kg ha^{-1}) and wet/dry denotes full irrigated and rainfed conditions, respectively.

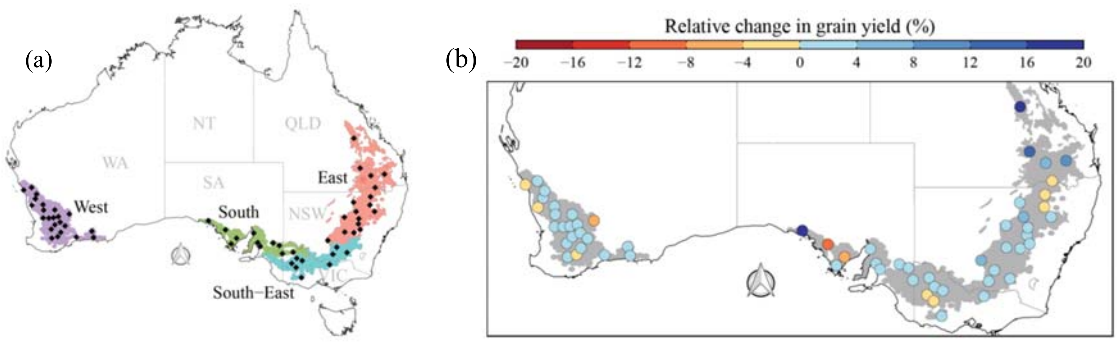

Figure 2. The Australian wheatbelt and the 60 studied sites (left) and yield advantage of the water-conservative virtual genotype (i.e. *cv*. Hartog with limited transpiration at high VPD) compared with *cv.* Hartog (right).

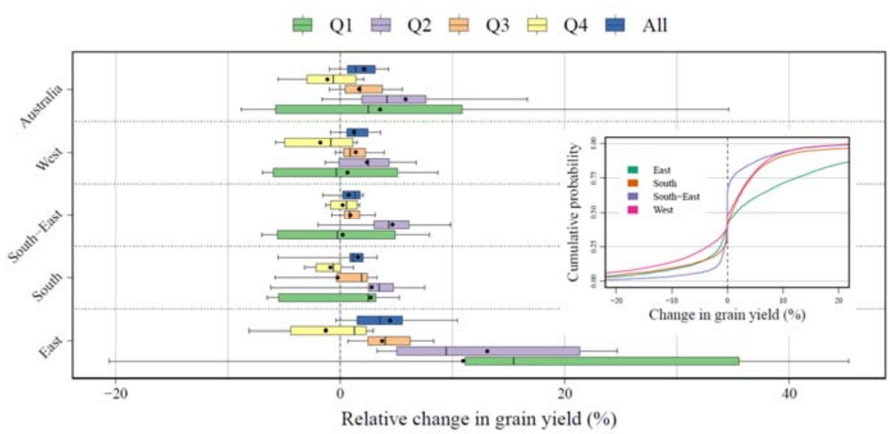

Figure 3. Relative yield advantage of the virtual water-conservative genotype compared with *cv.* Hartog in major wheat-producing regions (Figure 2a) and across the Australian wheatbelt. Q1-Q4 show the quartiles of grain yield quartiles (low to high) of the reference cultivar Hartog. Inset shows cumulative probability of yield advantages.

Limited transpiration at high VPD, which mimics a partial closure of the stomata under elevated VPD, resulted in reduced photosynthetic rate, biomass accumulation and ultimately crop biomass at maturity in ~57% of simulations. Nationally, reduced transpiration rate for VPD >1.3 kPa led to a major reduction in cumulative transpiration, estimated at 9% across the Australian wheatbelt, and a 1.4% reduction in crop biomass at maturity which in turn led to higher transpiration efficiency (7% on average) and harvest index (4% on average).

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