The impact of crop modelling on plant physiological research and breeding – an example.

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Abstract

The process of developing a new cultivar with improved yield and its evaluation under field conditions often takes 10-12 years. In addition, the impact of a specific trait on yield in any climatic region, rainfall zone, soil types and particularly growing season will require many more site-by-season (years) trials to be assessed, and may still not cover the full range of environments experienced by the cultivar after release.

As an alternative, a comprehensive crop simulation model that takes into consideration the dynamics of crop-soil-weather interactions and captures the principles inherent in such a system can assist plant breeding in the evaluation of the impact of specific traits on yield across a range of climates, soil types and seasons.

An example is given where water-soluble carbohydrate (WSC) was proposed as a trait to confer drought tolerance and a crop simulation model was used to investigate the contribution of WSC to grain yield in the Mediterranean environment of Western Australia. Simulation results stressed the importance of pre-grain filling WSC in grain yields under terminal drought and supported industry funded projects in western and eastern Australia aimed to identify genotypes with better pre-anthesis accumulation and mobilisation of WSC to the grain. Genotypes have been identified with high stem WSC at anthesis and are currently being used in wheat breeding programs to improve grain yields under water-limited conditions.

Keywords

Crop modelling, G x E x M, terminal drought, water soluble carbohydrates, wheat genotypes

Introduction

Wheat grain yields in rainfed agriculture of Australia and in other similar environments of the world are often low and vary substantially from season to season. Water soluble carbohydrates (WSC) stored prior to grain filling have been shown to be an important contributor to grain yield in such environments, in particularly under terminal drought (Nicolas and Turner 1993; Palta *et al.* 1994; van Herwaarden *et al.* 1998a). WSC may also be important for osmotic adjustment under drought and saline conditions to increase water uptake from the soil. In addition, the negative impact of nitrogen deficiency or late-in-season diseases on grain yield which reduce the photosynthetic capacity of a crop can be reduced through the availability of WSC stored prior to grain filling (Blacklow and Incoll 1981). Quantifying the contribution of WSC to grain yield has been hampered by large seasonal variability under field conditions (see review by Setter *et al.* 1998). An example is outlined were a crop simulation model was used to quantify the contribution of WSC to grain yield under conditions of large seasonal variability and how the results were linked with crop physiological research and breeding for improving grain yields in the Mediterranean environment of Western Australia.

Methods

The Agricultural Production Systems Simulator (APSIM) (McCown *et al.* 1996) for wheat (APSIM-Nwheat version 1.55s) is a crop simulation model, consisting of modules that incorporate aspects of soil water, N, crop residues, crop growth and development and their interactions within a wheat/soil system that is driven by daily weather data. Yield is calculated as a function of temperature, solar radiation, water and N supply. Documented model source code in hypertext format can be viewed at www.apsim-help.tag.csiro.au.

Two simulation experiments were carried out. The first assumed that the potential contribution of WSC to grain yield being a proportion of biomass at the beginning of grain filling. To analyse the impact of this proportion, it was varied between 20% and 40%. In a second experiment, the potential contribution of WSC to grain yield was related to biomass accumulation from 150 degree-days before the beginning of grain filling to grain filling. To analyse the impact of this growth period on the contribution to grain yield, it was varied between 75% and 90% of all biomass accumulation in this period. Both assumptions were simulated with long term historical weather record.

Results and Discussion

Based on a conceptional framework by Fischer (1994) and evidence from field experiments (Nicolas and Turner 1993; Palta *et al.* 1994) a simulation experiment was set up to quantify the contribution of WSC to grain yield under the seasonal variable growing conditions at Moora (81 historical seasons) in the Mediterranean environment of Western Australia (Setter *et al.* 1998). A simulated increase in the availability of WSC partially compensated for the loss in photosynthetic capacity on grain yield under terminal drought. The simulation results indicated that doubling the amount of WSC from 20% stem biomass (average of 20% determined from field experiments by van Herwaarden *et al.* 1998a, b) at beginning of grain filling to 40% would increase grain yields by 19% on average, and in some seasons by up to 81% (Setter *et al.* 1998) (Figure 1).

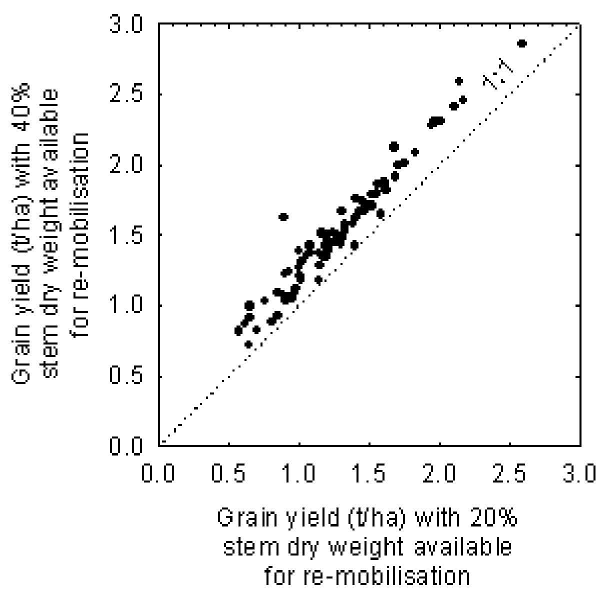

Figure 1: Simulated grain yields with 40% of stem dry weight at the beginning of grain filling being available for remobilization to the grain versus 20%, for 81 years of historical weather records at Moora, Western Australia, after Setter *et al.* (1998).

Supported by these simulation results, the Grains Research and Development Corporation (GRDC) funded a physiological research project at the Western Australian Department of Agriculture (DAW548) together with an AusAid scholarship at the University of Western Australia to identify differences in stem WSC and its impact on yield in a range of genotypes.

In this project, WSC of 40 genotypes were measured under field conditions in artificial light, shading, water supply and N treatments. A correlation between stem WSC at anthesis/two weeks after anthesis and grain yield was found with significant variations between genotypes. Low stem WSC (as low as 11%

of stem weight at anthesis/2 weeks after anthesis) were recorded in most Western Australian cultivars compared to other Australian and international material. Four genotypes were eventually identified with high stem WSC (38-44% of stem weight at anthesis/2 weeks after anthesis) and finally recommended for use in breeding (Conocono 2002).

These four genotypes are currently used in the Wheat Breeding Program for the Western Region (GRDC project DAW516) at the Western Australian Department of Agriculture. Double haploid crosses are being made for screening in the next season in order to identify whether single or multiple genes control the high stem WSC. After that, high stem WSC lines will be crossed into the Western Australian cultivars with superior agronomic characteristics. The double haploids will also be used to develop molecular markers to further reduce breeding time by screening several crops per year instead of one per season.

The impact of crop modelling on breeding via crop physiology highlights the potential contribution that crop modelling can make to other disciplines. However, such a linkage is not a static one-way process. Since the time of the original simulation study about five years ago to the inclusion of new traits into the current breeding program new understanding of the physiological mechanisms related to WSC has emerged from collaboration with the research at CSIRO Plant Industry in Canberra. The simplistic view that a proportion of biomass at or shortly after anthesis is available for remobilization to yield during grain filling is supported in general by many observations (e.g. van Herwaarden *et al.* 1998a; b), but can be off by half of this percentage in specific situation, also supported by the same data. In addition, in a glasshouse experiment by Palta (unpubl. data) where water deficit was induced from ear emergence to maturity reducing net photosynthesis to near zero resulted in grains of 7-9 mg compared to 42-43 mg in the well watered treatment. These results suggested that most of the WSC available for retranslocation to yield during grain filling are accumulated in the period shortly before and after anthesis and this is in agreement with earlier suggestions (Schnyder 1993) and recently confirmed with new studies (Conocono 2002). The original CERES model (Ritchie *et al.* 1985) did consider the accumulation of WSC by devoting all biomass accumulation shortly before grain filling to a pool which could later be translocated to grain yield. The crop simulation model APSIM-Nwheat kept this basic structure of the CERES model but extended the period of the contribution of pre grain filling WSC to yield to shortly before anthesis. This approach, based on crop physiological results (van Herwaarden *et al.* 1998a, b), enabled simulation studies to reproduce a number of observed pre-grain filling stored WSC amounts which were retranslocated to the grain (Figure 2).

Using this approach but with different genetic potential to store WSC during the critical time around anthesis (shortly before anthesis to the beginning of grain filling) confirmed the importance of WSC for grain yields under Australian growing environments which experience terminal drought. However, it also highlighted that an increase in storage capacity may have little or no effect on grain yield in seasons where water and nitrogen do not limit yield or when early drought restricts pre-anthesis growth and grain number. In the first situation crops fill grain from current photosynthesis due to a longer leaf area duration and only call on WSC reserves during periods of peak assimilate demand. In the latter scenario periods of pre-anthesis drought limit the crops ability to accumulate WSC and genotypic differences may not be expressed.

Nitrogen is often used restrictively by farmers in terminal drought environments to conserve water for the period of grain filling. However, the recent simulation experiment suggested that this can also limit the ability to store WSC if pre-anthesis growth is reduced (Asseng and van Herwaarden 2002). Increasing the capacity to accumulate WSC well before anthesis for translocation to yield during grain filling would overcome the limitation and improve yields under these conditions.

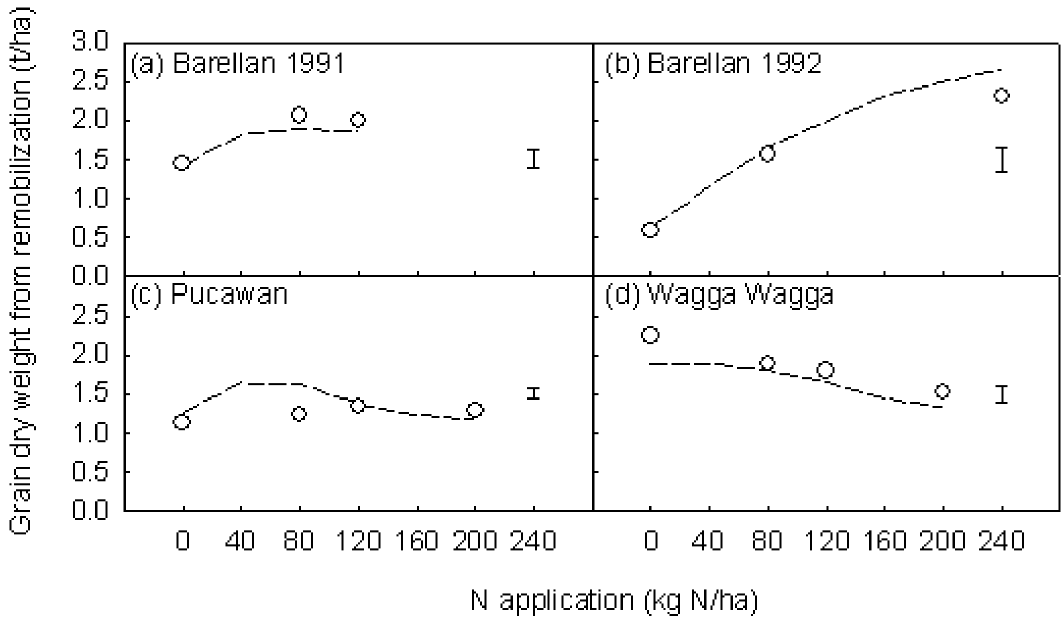

Figure 2: Simulated (lines) and observed (symbols) remobilization of pre-grain filling stored dry matter for (a) Barellan 1991, (b) Barellan 1992, (c) Pucawan 1991 and (d) Wagga Wagga 1991, New South Wales. After Asseng and van Herwaarden (2002). Bars indicate l.s.d.

Conclusion

The impact of crop modelling on plant physiological research and breeding can be three-fold. Firstly, crop simulation modelling enables the quantification of the potential impact of proposed research in crop physiology and new traits for crop breeding to improve yields under variable growing conditions, as shown with high stem WSC. Secondly, by further extending the simulation experiments allows a suitability analysis of specific traits for specific growing environments (e.g. soil type, rainfall region, climatic region). Thirdly, the evaluation of new cultivars after their release in multi-location field trails can be supported by simulating crop growth for any possible growing condition.

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