StressMaster: a web application for dynamic modelling of the environment to assist in crop improvement for drought adaptation

Karine Chenu[1], Al Doherty[2], Greg J. Rebetzke[3], Scott C. Chapman[3]

[1] *The University of Queensland, QAAFI, 203 Tor Street, Toowoomba, 4350 Queensland, Australia*
[2] *Agri-Science Queensland, DAFF, QPI&F, APSRU, 203 Tor Street, Toowoomba, 4350, Australia.*
[3] *CSIRO Plant Industry, PO Box 160, Canberra, ACT 2601*
[4] *CSIRO Plant Industry, QBP, 306 Carmody Road, St. Lucia, 4067 Queensland, Australia*
correspondence: karine.chenu@uq.edu.au

Highlights: Drought frequently limits crop production. A modelling approach was used to characterise the water deficit that wheat plants experience over the cropping season in targeted environments. Using this insight, the StressMaster application assists in decision-making in managed environment trials to increase the probability of attaining a seasonal drought pattern that represents the targeted environments.

Keywords: Environment characterisation, drought, water deficit, mega-environment, wheat, APSIM model, StressMaster.

INTRODUCTION

While a multitude of studies are proclaiming the identification of new genes or QTL for improved abiotic-stress tolerance, a significant contribution from these findings to released varieties is yet to be realised (e.g. Richards et al., 2010). Phenomics platforms are being developed to provide new insights into gene function and environmental responses (e.g. Granier et al., 2006) but the number of genotype x environment combinations to be tested is beyond the capacity of any platform. Drought affects gene expression and physiological processes to a different extent depending on the timing and the intensity of the stress (e.g. Fischer et al., 2011). As a consequence, genes and traits can have positive or negative effect on yield, depending on the environment (e.g. Chenu et al., 2009; Tardieu, 2012), highlighting the need to phenotype in the target environments whenever possible. Within a limited geographic area, spatial and temporal variations in rainfall occurring over diverse soil types gives rise to an almost unlimited number of drought patterns that crops might experience. There is thus a need to characterise the environment of the 'target populations of environments' (TPE) to identify major stress patterns and provide focus to research and breeding experiments (e.g. Chapman et al., 2000).

In the case of complex abiotic stress(es) such as drought, environment characterisation is difficult given that (i) plants are sensitive to a water deficit during most of their growth cycle, with different processes involved at different stages, so that a characterisation over time is required; (ii) the stress is influenced by the crop itself (i.e. by plant growth and transpiration, and by any factors that may affect them), the soil characteristics and water supply (rainfall, irrigation), which makes the stress pattern difficult to quantify (timing and intensity) even at a local scale; and (iii) both soil characteristics (e.g. available soil water) and rainfall patterns vary spatially and over time, which makes characterisation challenging over long-term periods and large geographic areas.

Modelling tools open opportunities to resolve this challenge, as they can be applied to multi-site long-term characterisation, thus leading to more comprehensive environmental sampling than conventional field studies (e.g. Hammer and Jordan, 2007). Secondly, they allow the simulation of the stress *per se* by accounting for the interactions between the plants and their environments (*e.g.* Chelle et al., 2005; Chenu et al., 2007 and 2008). By capturing the feedback between plant growth and soil water depletion, a functional modelling approach has been shown to characterise water deficits better than standard indices based on climatic data (Muchow et al., 1996).

The aim of this study was to analyse the drought patterns of wheat crops across the large and contrasting Australian wheatbelt TPE over 123 years. The goals were to (i) identify the nature of the main water deficits (timing, duration, intensity), (ii) analyse the spatial and seasonal variation in frequency of occurrence of the main water-deficit patterns, and (iii) develop an application to assist in-season water management and target representative stress in field trials.

SIMULATIONS

The APSIM crop model (e.g. Keating *et al.*, 2003) was used to simulate crop drought patterns for the check variety 'Hartog' across the Australian wheatbelt over 123 years. To represent the Australian wheat cropping system, the major production area was divided into 22 regions and 60 locations, each representing between 130 000 and 230 000 hectares of planted wheat (averaged data from 1975-2000, 2005 and 2006; source: Australian Bureau of Statistics). The simulations used weather records for 1889-2011 (SILO Patched Point Dataset; http://www.longpaddock.qld.gov.au/silo/).

The daily drought pattern was calculated for each crop based on a water-deficit index ("water supply/demand ratio") which indicates the degree to which the soil water extractable by the roots ("water supply") is able to match the potential transpiration ("water demand"). For each environment (site x year x sowing date x initial soil water x climatic scenario), this daily index was centred around flowering and averaged over 100°Cd from emergence to 450°Cd after flowering. A statistical analysis was used to cluster the seasonal water-deficit patterns into a few environment types.

Developed to allow water-management at irrigated trials, the APSIM-based web-application 'StressMaster' simulates the drought pattern that wheat crops have experienced in a specific trial up to the current date and predicts the likely future drought pattern for the remainder of the season based on historical climatic records. Different irrigation and fertilisation scenarios can be tested in the application to assess their influence on future drought events. The crop-cycle stress patterns for each scenario are classified based on which environment type they were most similar to, i.e. based on the minimum sum of squared differences between the water-deficit pattern under consideration compared to the water-deficit pattern of the environment types. Users can then decide which management scenario to apply to their trial to increase their chance to obtain the desired experimental environment type.

RESULTS AND DISCUSSION

In characterising the target population of environments, four main drought-environment types that contrasted in the timing and intensity of the stress were identified across the wheatbelt (Fig. 1). The frequency of these environment types was subject to spatial (Fig. 2) and temporal variation (data not shown), with a tendency for higher frequency of severe stresses during the last decade (Chenu et al., 2013).
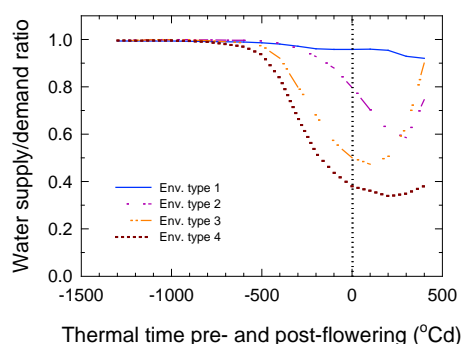

Fig. 1. Simulated water-stress index for the four environment types identified across the Australian wheatbelt. The stress index corresponds to the ratio of soil water supply to crop water demand and is represented. Adapted from Chenu et al. (2013).
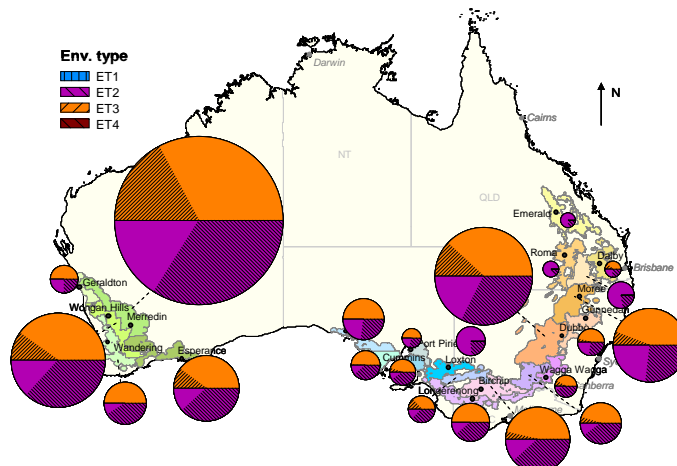
Fig. 2. Map of the frequencies of each environment type (pie charts) across the Australian wheatbelt. Data simulated for the check variety Hartog over 123 years for the different regions of the wheatbelt. The size of the pie charts is proportional to the wheat-planted area in the associated region. Adapted from Chenu et al. (2013).

High spatial and temporal variations in rainfall in Australia present a risk for plant breeders, who typically select germplasm based on 3-5 years of multi-site trials, i.e. based on environment conditions which may differ greatly to the conditions that newly released cultivars will experience during the 5-20 years of their commercial life. Environmental characterisation can help reduce this risk by assisting in (i) selecting trial locations (e.g. Trethowan et al., 2003; Rebetzke et al., 2013); (ii) weighting genotype performance by the

representativeness of their growing environment with respect to the TPE; (iii) unravelling genotype-environment interactions to better interpret genotype performance in the main environment types (e.g. Löffler et al., 2005; Chenu et al., 2011).

In order to quantify the value of genes, traits and germplasms in target environments, modelling can also help design managed drought environments within breeding programs or physiology/genetics based research projects (*e.g.* Bänziger et al., 2006; Rebetzke et al., 2013). The StressMaster application has been implemented to assist management decision-making and increase the probability of attaining the desired environment types (Fig. 3). Based on information concerning the soil, the climate (weather station in the field or nearby), the genotype, and the management used (*e.g.* sowing date, depth, fertilisation), StressMaster simulates in "real time" the drought pattern that plants have experienced up to "today", and predicts their future drought pattern based on historical climatic records used for the rest of the season. The application is being used to define irrigation regimes at the national (GRDC funded) Managed Environment Facilities in Australia, where wheat benchmarking germplasm and diverse populations varying for potential adaptive traits are currently phenotyped (Rebetzke et al., 2013).
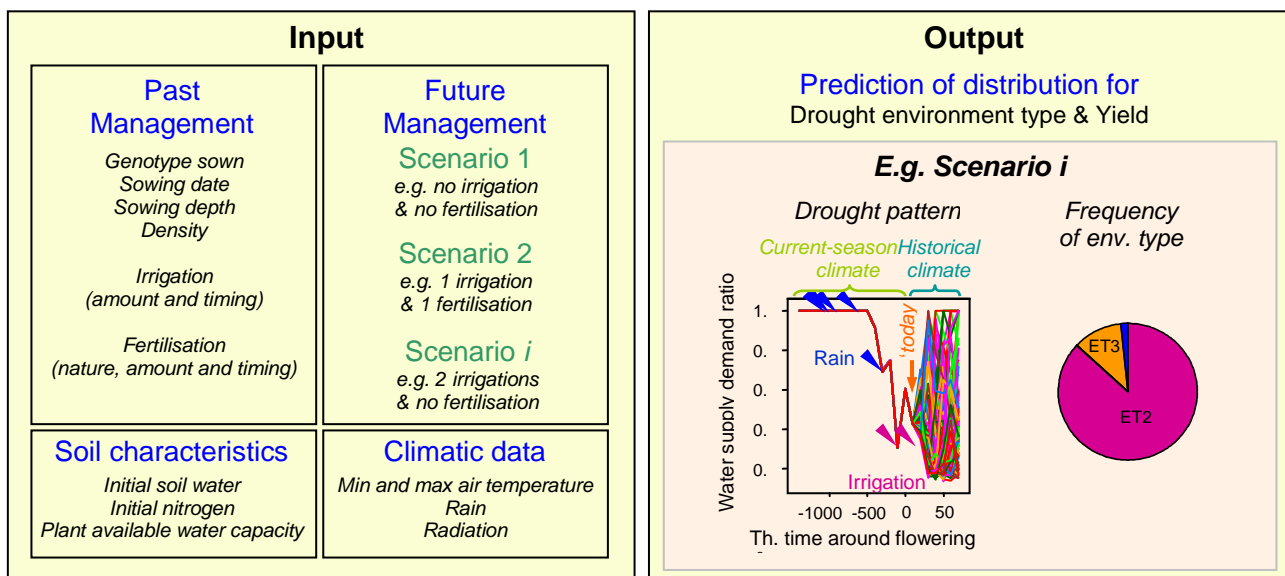

Fig. 3. Schematic view of the StressMaster application where soil, climatic and management information are input to simulate in 'real time' the frequency of drought-environment type and the yield distribution for various irrigation-fertilisation scenarios.

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