A systems agronomy for sorghum in the Northern Grains Region

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Abstract
Over the last fifty years increases in grain yields have been the result of improvements from breeding, from agronomy and the cropping system, and from their interactions. There is also no doubt that the same drivers will be responsible for future yield gains. This calls for R&D efforts to be directed towards identifying and communicating optimum combinations of agronomic management (M) and cultivars (G), or crop designs (GxM), that make best use of available resources and expected seasonal conditions i.e. the environment (E). Our present understanding of crop stress physiology indicates that in hindsight, those optimum crop designs should be known, while the main problem is to predict relevant attributes of the environment (E), at the time of sowing, so that optimum GxM combinations could be informed. Here we tested our capacity to inform that "hindsight", by linking a crop model (APSIM-Sorghum) with outputs from two seasonal climate forecasting systems to answer *"What is the value of informing optimum crop designs?*" This was achieved by using the APSIM-Sorghum model and outputs from two seasonal climate forecasting systems (i.e. POAMA-2 and ACCESS-S1), to inform farmers' decisions at different time scales, ranging from weeks to a few months in sorghum cropping. Results showed that that by linking APSIM-Sorghum and POAMA-2 to inform optimum crop designs at sowing could increase average sorghum profits by up to 143 AU$ ha^{-1} $year^{-1}$; and that that by linking APSIM-Sorghum and ACCESS-S1 could be used to inform the likelihood of favorable soil temperatures over the following few weeks crucial to achieve uniform crop stands in winter sown sorghum.

Key Words
Crop design, seasonal climate forecasting, profits and risks, winter sown sorghum, APSIM

Introduction
In dryland sorghum cropping, growing conditions are influenced by three major factors, namely soil conditions at the time of sowing (i.e. soil fertility and soil water availability), in-crop rainfall and distribution, and the occurrence of heat stresses around flowering. While soil conditions at sowing are usually known (or at least knowable), probabilistic information about future rainfall could be obtained using skillful seasonal climate forecasts (Hudson et al., 2013). While for the case of heat stresses around flowering an increasingly adopted practice involves sowing the crop in Winter, if soil temperatures can be expected to remain over 12°C for at least two weeks after sowing. This highlights the importance of farmers having access to accurate climate information at a range of temporal scales, from weeks to a few months. Information from seasonal climate forecasts have proven to be particularly useful when linked with crop simulation models (Meinke et al., 2009); this is because the capacity of dynamic crop models to capture climate – soil – crop interactions and their emerging dynamics on water supply and demand, stress patterns and interactions that determine the final yield. Particularly after the recent improvements in the capacity of APSIM-Sorghum (www.apsim.info) to simulate the physiology and genetics of complex adaptive traits, provides opportunity to inform optimum combinations of genetics (G) and managements (M), known as 'crop designs' (GxM) (Hammer et al., 2014; Rodriguez et al., 2018). Our present understanding of crop stress physiology indicates that in hindsight, these optimum crop designs (GxM) should be known, while the main problem is to predict relevant attributes of the environment (E), at the time of sowing, so that optimum GxM combinations could be informed. Similarly, information on the likelihood of soil temperatures to remain above minimum thresholds to warrant a uniform crop emergence, could be used to inform practices that are likely to reduce the impact of heat stresses around flowering.

Here we test our capacity to inform that "hindsight", by linking a tested crop model (APSIM-Sorghum) with outputs from two global circulation models (GCMs) the previous (POAMA-2) and present (ACCESS-S1) seasonal climate forecasting models from Australia's Bureau of Meteorology (BOM), to answer *"What is the value of informing optimum crop designs?*" and *"How early is too early to sow winter sorghum?"*

Methods

Climate data, seasonal climate forecasting tools and APSIM-Sorghum runs

Hindcasts from the previous (POAMA-2) and currently operational (ACCESS-S1) Australian seasonal climate forecasting systems were assembled for four sites in Australia's northern grains region i.e. Capella, Dalby and Goondiwindi in Queensland, and Moree in New South Wales, and used to run the APSIM-Sorghum model.

APSIM-Sorghum was used to run two *in silico* experiments, (i) a factorial combination of hybrids (G) and managements (M); and (ii) the time course of soil temperatures for the top soil layer (0-0.1m) during winter and spring sowing times. The seasonal climate forecasts were used to (i) assess the value of using APSIM to optimise crop designs (GxM) to the expected seasonal conditions forecasted at the time of sowing using POAMA-2; and (ii) the capacity of ACCESS-1 to predict soil temperatures during crop establishment so that winter sowing of sorghum could be recommended. The different GCMs were used to answer the different questions, POAMA-2 was used to produce seasonal yield forecast given its longer hindcast and higher skill, and ACCESS-1 was used to predict short term soil temperatures (30 days) because of its higher spatial resolution.

The GxM simulations included a factorial combination of physiological traits (G) i.e. maturity, tillering and stay green types; management (M) options i.e. planting time, plant density, and nitrogen fertilisation; and sites and site-soil conditions i.e. plant available water capacity of the soil, and plant available water at the time of sowing. The model was run over the 1981-2015 (34 years) for POAMA-2; and for 1995-2018 (23 years) for ACCESS-2, hindcast series, resulting in up to a total number of GxExM combinations of ca. 300,000,000 crop year simulations. The skill of both forecasting systems was calculated on simulated sorghum yields. Measures of skill included the Brier Skill Score (BSS) (Murphy, 1986), and percent consistent rates. Percent consistent compares how often the forecast favored a particular outcome and how often that outcome was realized.

The skill of the forecast

The skill of the forecasting systems was calculated on both 3-month 60km gridded rainfall and simulated sorghum yields. From the rainfall forecast distributions, probabilities of above median, tercile 1 and 3 rainfall, and a binary outcome i.e. correct or incorrect, for each forecast were calculated. Measures of skill included the reliability diagram, the Brier Skill Score (BSS), percent consistent rates, and measures of shift in the mean i.e. absolute mean deviation (AMD), and dispersion i.e. the variance ratio (VR) of the sample variances. For further details refer to Rodriguez et al., 2018.

The value of linking APSIM and a seasonal climate forecast to inform crop designs

The value of using a seasonal climate forecast to inform more profitable and less risky crop designs was derived for the subset of GxExM combinations producing positive BSS values for forecasts of above / below median sorghum yields. A search algorithm was developed that included the following steps (i) a matrix of average profits and down side risk for current farmers' practice and for a factorial combination of GxM (hybrid maturity and tillering type, plant density, row configuration and fertilization rate) was created; (ii) GxM combinations having values of BSS higher than zero (skill) for predicted profits were kept; (iii) For each year in the hindcast the GxM alternative showing the highest profit were then selected; (iv) Value was then calculated in terms of changes in average gross margins and down side risk i.e. likelihood of a profit lower than 600 AU$ ha^{-1}, between current farmers' practice, i.e. a static though locally common agronomic management, and the selected GxM combination predicted using the forecast for each year in the hindcast series, (ValueoptS); and relative to the simulated most frequent optimum static GxM strategy (ValueoptSCF). Then, ValueoptS represents both gains from improved crop design and the use of climate information, while ValueoptSCF represents just the value from the use of the new climate information. As a reference point, value was also calculated for the hypothetical situation that the future climate was known i.e. perfect knowledge (ValuePK). ValuePK was calculated as the difference in profit between common practice and the optimized crop design and farmers' practice using observed climatology. Profits were calculated for median sorghum prices over the last 10 years (2007 to 2016) i.e. 254 AU$ t^{-1}. Variable costs included insurance i.e. 1% of the gross income, while the fertilizer cost was 30 cents kg^{-1} urea (http://agmargins.net.au). Variable costs for failed crops were then 161 AU$ ha^{-1} (excluding harvest costs), and 211 AU$ ha^{-1} for harvested crops.

Results

Skill in the prediction of sorghum yield

Across all tested sites and tested crop designs, POAMA-2 showed skill (Brier Skill Score, BSS) for the predictions of sorghum yield (Shown in Fig 1 for Dalby and Moree). We therefore used the POAMA-2 ensemble seasonal forecast downscaled to station level for the period 1981-2015 to calculate the value (\$ ha^{-1} $year^{-1}$) to identify optimum crop designs in sorghum. An analysis of variance on the values of BSS for the locations and factors in the GxExM factorial combination showed that the factor 'Location' had a highly significant ($p<0.0001$) effect on the BSS (not shown). The influence of the different factors in the GxM factorial was then tested within each location. Results showed that with the exception of soil type and sowing density at Dalby, and row configuration and nitrogen fertilization at Goondiwindi and Moree, most factors significantly affected the value of BSS. Across all locations higher values of BSS (high skill) were observed when the GxExM factor combination resulted in crop designs that were highly dependent on in crop rainfall (see Rodriguez et al., 2018 for details).

Fig 1. Density of Brier Skill Scores for for a large GxM combination on sorghum yields in Dalby and Moree. Red shaded areas in each graph indicate no skill.

Value in the skill of the seasonal climate forecast (months)

Irrespective of the calculation method, the value of linking APSIM and POAMA-2 was different across locations and soil types. Within each location $Value_{optS}$ was largest for crops grown on deeper soils, both in terms of higher profits and reductions in down side risk. On average, $Value_{optS}$ showed increases in average profits from 10.2 to 26.1% i.e. 56 to 226 AU\$ ha^{-1}, and average reductions in down side risk of up to 100% i.e. no risk. At Dalby common practice is to sow sorghum in October, on at least 60% initial soil water (i.e. more than 100 mm of stored soil water), using medium maturities and medium tillering hybrids, sown at 5 plants m^{-2} and using medium levels of ca. 50kg N ha^{-1}. However, using APSIM combined with POAMA-2 we can devise a more profitable and less risky static GxM combination if the farmer is more risk neutral: the simulations show that on high PAWC soils, increasing plant populations and nitrogen supply would increase profits by up to 16% in 26% of the hindcast years (Table 1). On medium PAWC soils, gains in profit were 29% in 26% of the years; while on low PAWC soils, gains in profits were 21% in also 26% of the years (Table 1). When we calculated the value of skill in seasonal climate forecasting relative to an improved static management involving higher levels of investment in nitrogen fertilizers, the additional value of the new climate information was smaller, on average 17 AU\$ ha^{-1}, i.e. $Value_{optSCF}$. The value of perfect knowledge "Crystal ball" ($Value_{PK}$), this is, the difference between an optimized crop design and the static farmers' management, calculated using observed climatology we can conclude that present value in the skill of seasonal climate forecasting falls approximately mid-way between 'no skill' and perfect knowledge of the future climate.

	Soil type (PAWC)	Profit (\$ ha^{-1})	Risk neutral	Risk neutral	Climate info	Crystal ball
		Farmers	Optimized	$Value_{optS}$	$Value_{optSCF}$	$Value_{PK}$
Capella	High	1108	1260	152	3	335
	Medium	748	824	77	3	224
	Low	544	600	56	4	219
Dalby						
	High	1127	1337	210	13	353
	Medium	1048	1241	194	17	351
	Low	795	913	118	12	288
Goondiwindi						
	High	866	1092	226	16	432
	Medium	841	1011	170	63	345
	Low	678	793	115	6	312
Moree						
	High	1025	1226	202	23	406
	Medium	814	962	148	32	370
	Low	373	427	54	19	210

Table 1. Value of linking APSIM and a seasonal climate forecast to inform optimum crop designs. Profits (\$/ha) from current GxM (Farmers) and optimised GxM (Optimised) and their difference ($Value_{Opts}$); value of the additional climate information ($Value_{optSCF}$); and value of having perfect knowledge on the seasonal conditions ($Value_{PK}$), across four sites and three soil types.

Value of short-term forecasts of soil temperature (weeks)

A framework for assessing the value of linking APSIM and ACCESS-S1 to predict soil temperatures for the few weeks after the winter sowing of sorghum was developed. Initial results (Fig 2) show useful skill (values of percent consistent higher than 50%) for predicting above or below median crop emergence date across Australia's sorghum growing regions. The highest values of skill were observed particularly for August plantings. These results indicate the potential value for linking a crop simulation model (APSIM) and a seasonal climate forecast (ACCESS-S) to inform winter sorghum planting opportunities.

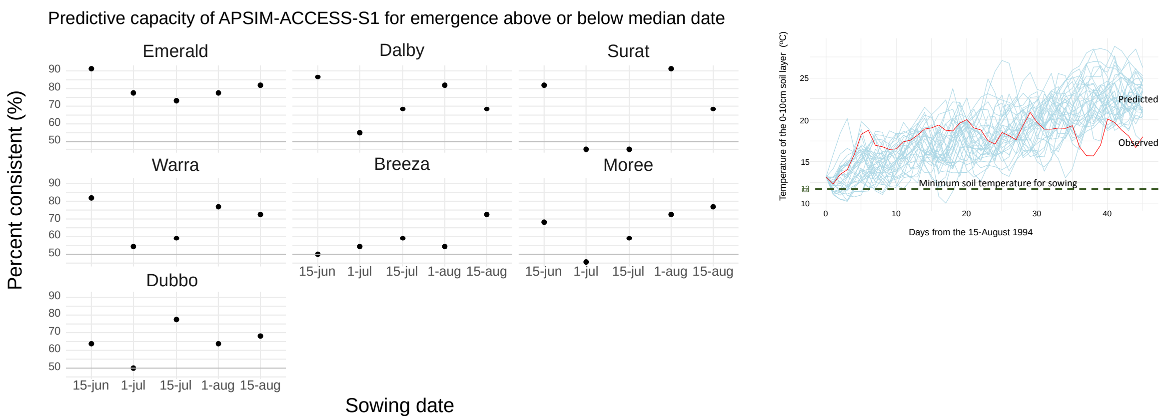

Fig 2. Predictive capacity of APSIM - ACCESS-S1 to predict above or below median crop emergence date as a function of sowing date winter sown sorghum across Australia's main sorghum growing regions. Values of 50% or lower indicate no skill. The inset shows the plumes of simulated sol temperatures and the observed soil temperatures for a single sowing date and simulated year.

Conclusion

We conclude that reliable and skilful dynamic GCM models, interfaced with validated crop simulation models, can now be used to inform optimum crop designs to increase farmers' profits and reduce risks. There is also useful skill in the use of GCMs to inform the likely occurrence of cold snaps in winter sown summer crops. Further research is being conducted to test the skill and value in the forecast of frosts and heat stresses during crop sensitive stages. Further, efforts will also continue to make such information available to decision makers in a form that is understandable and useable.

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