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Adapting sorghum sowing date and genotype maturity to seasonal rainfall variation in a temperate region

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ABSTRACT

Reducing sorghum yield gaps depends on the capacity to identify combinations of genetics and management that best suit region and seasonal conditions. Using simulated and empirical data, we explored how the combination of different sowing dates and genotype maturity respond to specific water stress patterns common across a temperate region (Argentina Pampas). This region was recently characterized by three water stress patterns (or environmental types, ENVTs). These ENVTs are: pre-flowering stress, low terminal stress and grain-filling stress. In the north and central regions, significant ENVT × sowing date interaction for yield ($P < 0.05$) indicated that sowing date should be chosen depending on the prevailing seasonal ENVT. This drought escape strategy increased yields by 4068–5049 kg ha^{-1}. In the southern region, early sowings had the highest yields independently of the ENVT. Genotype maturity effect was less important, although early materials increased yield by 438–923 kg ha^{-1} (5–25 %) relative to the intermediate genotype, depending on the region. Under low terminal or grain-filling stress, early sowings gave the highest yields via increased accumulated biomass and/or harvest index. Under pre-flowering stress, delaying the sowing dates increased final yields via improved harvest index. Later sowings provided a conservative strategy for reducing risk in the north and central east regions, while for the central west and southern regions the sowing date should be as early as possible. We provided information to improve sorghum management decisions and guide breeding in temperate regions.

KEYWORDS: APSIM; grain yield; maturity; relative transpiration index; simulation model; sowing date.

1. INTRODUCTION

Sorghum is the fifth cereal in importance after wheat, maize, rice and barley, with a global production of around 45 million (millons of tons [MT]) (FAO 2018). Sorghum is a versatile crop grown for different purposes in tropical, subtropical and temperate environments. It has relatively low production costs, a particular ability to resist water stress when compared to other cereals (Muchow 1989) and produces large residue biomass that improves soil physical and chemical properties (Amaducci *et al.* 2000). These attributes are relevant in the context of sustainable agriculture (Foley *et al.* 2011).

Rainfed agriculture covers ~80 % of the current world cultivated area, and supplies about 60 % of the world's food (FAO 2011). Increasing the productivity under rainfed agriculture would have a significant impact on global food production. For that purpose, matching water use to rainfall patterns is clearly important due to the relationship between timing of water use and attainable harvest index (HI; Sadras and Connor 1991). In this sense, sowing date and crop phenology became critical management practices (Hammer *et al.* 2014; Rodriguez *et al.* 2018).

Chapman *et al.* (2000) presented a method to characterize water use with a crop simulation model, which allows determining the timing of drought stress relative to crop phenology, and the final impact on grain yield. Using this approach, sorghum growing environments in the Argentinean temperate region were classified into three possible seasonal patterns of water stress or environmental type (ENVT) that differs mainly in the timing of stress (pre- or post-flowering; Carcedo and Gambin 2019). This provides an interesting opportunity to explore the impact of sowing date and genotype maturity combinations on water use, biomass production and yield.

Sorghum management knowledge is limited when compared to other crops (Fischer *et al.* 2014; Brihet 2017). Under adequate soil moisture conditions the main constraint to sow sorghum in temperate regions relates to soil temperature. Germination and emergence are impaired with temperatures below 10 °C (Anda and Pinter 1994; Yu *et al.* 2004). Consequently, sowing dates are commonly advised when soil temperatures are above 15–18 °C, guaranteeing plant stand and uniformity. Combinations of recommended sowing dates and genotype maturities also seek to avoid flowering under high heat and drought stress probability (Prasad *et al.* 2008; Lobell *et al.* 2015), and frost damage during grain filling.

Even though Argentina is a relevant sorghum producer and the third world exporter (FAO 2018), reliable information on optimum sowing date and maturity for the main productive areas is not available. Currently, the most widespread materials are of intermediate maturity. Sowing date takes places during October to early January depending on the latitude, but without a clear understanding of the impact of different sowing dates on crop water status during critical crop stages. A proper exploration of the impact of these management variables in a range of temperate production environments can help define management strategies to increase crop productivity, or to identify potential traits for breeding improvement (Whitbread *et al.* 2010; Hammer *et al.* 2014; Clarke *et al.* 2019).

We hypothesize that the impact of sowing date and maturity will depend on the specific ENVT. Under low terminal water stress, early sowing dates combined with late maturity genotypes would produce higher yields by increasing total biomass at maturity (Hammer and Broad 2003). The same could be expected under the grain-filling stress ENVT, although in this case by increasing HI. Under pre-flowering stress, delaying the sowing date in combination with shorter duration materials would avoid the coincidence of water stress with critical stages (van Oosterom and Hammer 2008; Carcedo *et al.* 2017). Similar strategies have been successful in other important crops in the region, such as maize (Vitantonio-Mazzini *et al.* 2020) and soybean (Di Mauro *et al.* 2018).

Crop simulation models are a valuable tool to evaluate the impact of different management and genotype traits across environments (Baumhardt et al. 2005; Hammer *et al.* 2014; Flohr *et al.* 2017; Teixeira et al. 2017). This study uses a robust sorghum predictive model (Hammer *et al.* 2010) to explore management strategies for specific water stress patterns. The objectives were (i) to explore the impact of different sowing date and maturity across an important range of latitudinal gradient of a temperate region subjected to different seasonal water stress patterns, and (ii) to define management strategies that best suit region and seasonal conditions. Defined strategies were later verified with observed field data.

2. MATERIALS AND METHODS

The sorghum (*Sorghum bicolor*) model (Hammer and Muchow 1994; Hammer *et al.* 2010) operated within the cropping systems model Agricultural Production Systems SIMulator (APSIM), version 7.8 (McCown *et al.* 1995; Keating *et al.* 2003) was used to conduct simulations at four sites. Sites were selected based on availability of soil and weather data, and for a wide latitudinal range (from 29° to 37°S). In addition, these sites were previously identified as representative of regions inside the Argentinean sorghum production area (Carcedo and Gambin 2019). Sites are hereafter refereed as north (Reconquista), central west (Manfredi), central east (Zavalla) and south (Anguil) regions (Table 1).

2.1 Crop management set-up

Agricultural Production Systems SIMulator was set to sow sorghum on five to six fixed dates every 15 days from 15 October. The last explored sowing date was based on the probability of frost causing an early crop end, and was set on 1 January in the north and central east regions, and on 15 December in the central west and south regions.

Except for sowing date, management practices were the same in all simulated years and regions, reflecting the common management options in the region. Stand density was set at 16 plants per m^2 (at a depth of 30 mm) with a row spacing of 52 cm. Initial soil available water content was fixed to 50 %, and nutrients were assumed non-limiting. Although the latter do not reflect real production conditions (i.e. fertilization is not a common practice, and, when done, applied N rates are low; Brihet 2017), this decision was done to simplify interpretation of and to help focus on the main effects of interest.

Three commercial representative hybrids of different maturity were tested, including short (ADV114), medium (VDH314) and late (VDH422) growth maturities. Genotypic parameters for APSIM simulations are described in Table 2. These genotypes are characterized with day-neutral photoperiod response (photoperiod_slope = 0). The general model performance using these genotypes was recently tested

Table 1. Soil and weather specifications for sorghum model simulations. SAWC is soil available water content.

Region	Weather station location (latitude, longitude)	Years	Mean rainfall (mm) (1 September to 31 March)	Soil Taxonomy	Depth (cm)	SAWC (mm)
North (Reconquista)	−29.1, −59.7	1970–2018	956 ± 288	Vertic natracualf	148	168
Central west (Manfredi)	−31.8, −63.7	1970–2018	674 ± 145	Entic haplustoll	73	95
Central east (Zavalla)	−33.0, −60.8	1973–2018	752 ± 173	Typic natracualf	152	199
South (Anguil)	−36.5, −63.9	1964–2018	584 ± 162	Entic haplustoll	95	112

Table 2. Parameter values set in APSIM sorghum for genotypes used in this study.

Genotype	Thermal time to floral initiation (°Cd)	Thermal time A-PM[a] (°Cd)	γ (main stem coefficient)	α (TPLA[b]; °Cd^{-1})	β (total leaf area inflection; °Cd)	κ (dry matter per seed; g per grain)
ADV114	340	795	3.20	0.012	540	0.000523
VDH314	387	810	3.20	0.010	583	0.000604
VDH422	430	799	3.23	0.008	609	0.000520

[a] A-PM: anthesis to physiological maturity.

[b] TPLA, Total plant leaf area.

by Carcedo and Gambin (2019). Using independent data from different sites across the region and covering variation in water and N conditions, the model accurately simulated crop phenology, biomass and yield, as shown by the root-mean-squared error, D-index and model efficiency values [**see Supporting Information—Table S1**].

2.2 Simulated variables

Simulated variables were days to anthesis, days to physiological maturity, relative transpiration index, total above-ground biomass at maturity, HI and grain yield.

Relative transpiration, or daily water deficit index, is the relationship between potential crop transpiration and the actual transpiration that can occur given the amount of soil water available. Several studies used relative transpiration as a measure of water stress (Chapman *et al.* 2000; Chenu *et al.* 2011; Sadras *et al.* 2012; Hammer *et al.* 2014). When there is no soil available water the index is 0 (complete stress condition), and if the soil provides the crop with the necessary water to reach the potential production the index is 1 (absence of stress). For each 100 degree-days of thermal time, the daily values of relative transpiration were averaged. Relative transpiration during the crop cycle was used to define the seasonal drought stress patterns or ENVT.

For each simulation, final yield was that achieved on the last day of the crop cycle according to the model, even if the crop did not reach the physiological maturity stage (code 10 in APSIM phenology module).

2.3 Analysis of simulated data

Each seasonal simulated water stress pattern was classified into previously defined ENVT (Carcedo and Gambin 2019) based on their similarity. This was done through the minimum sum of square difference (Chenu *et al.* 2011). Defined drought ENVTs were: (i) pre-flowering water stress, (ii) low terminal water stress and (iii) grain-filling stress (Fig. 1; Carcedo and Gambin 2019).

Mixed-effects models (lme4 package, lmer function; Bates *et al.* 2015) were used to fit data in R (R Development Core Team 2016). Regions were analysed separately due to significant region × ENVT × sowing date interaction for yield [**see Supporting Information—Table S2**]. The effect of the ENVT, sowing date, genotype and all interactions were considered fixed effects, while year was treated as experimental observations and was assumed as random (Baumhardt *et al.* 2005). For the analysis of variance, days to anthesis was analysed excluding simulations where the crop did not reach this stage (i.e. ~20 % of simulations in the south and ~5 % of simulations in central west). For the rest of the variables, all simulated data were considered. Means were compared with a Fisher least significant difference (LSD) test at the 0.05 probability level. Pearson correlation test was used to analyze the association between yield and biomass.

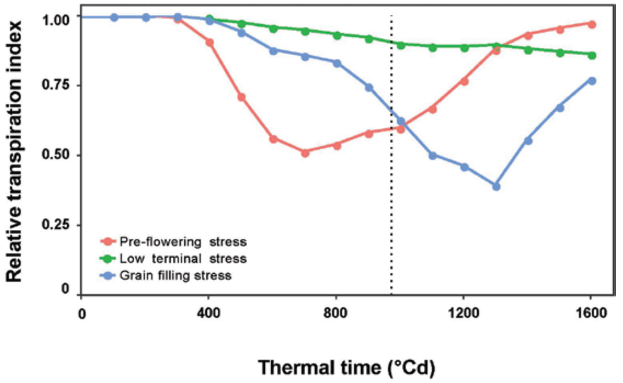

Figure 1. Mean RT index throughout the crop life for the clustered seasons. The dashed line indicates the mean flowering date. Adapted from Carcedo and Gambin (2019).

2.4 Contrasting observed versus simulated data

An available data set from 32 field experiments with different genotypes and sowing dates was analysed to check the agreement with simulated data. Experiments were conducted in the central east region [**see Supporting Information—Table S3**]. Experiments at Venado Tuerto (n = 20) (33°40′S; 61°58′W), Santa Fe province (soil type silty loam Typic Argiudol; Soil Taxonomy, Soil Survey Staff 2014) involved testing trials conducted at the Advanta Semillas SAIC sorghum programme from 2007 to 2018. Experiments at Zavalla (n = 6) (33°1′S; 60°53′W), Santa Fe province (soil type was a silty clay loam Vertic Argiudoll; Soil Taxonomy, Soil Survey Staff 2014) were conducted at the Campo Experimental Villarino, Facultad de Ciencias Agrarias, Universidad Nacional de Rosario in 2012, 2016 and 2017. Experiments at Pergamino (n = 6) (33°54′S; 60°27′W), Buenos Aires province (soil type silty loam Typic Argiudol; Soil Taxonomy, Soil Survey Staff 2014) were conducted at the Estación Experimental Fontezuela (Bayer Crop Science) in 2015 and 2016.

Experiments were conducted using a randomized block design with three (Zavalla and Pergamino) and two replicates (Venado Tuerto). Sowing date ranged from 1 November to 16 December in Venado Tuerto, from 1 November to 27 December in Zavalla and from 17 October to 20 December in Pergamino. Genotype ADV114 (short), VDH314 (medium) and VDH422 (late) were sown in each experiment, excepting for one or two experiments in Zavalla where genotype VDH422 or ADV114 and VDH422 were not tested, respectively.

Plots were four rows 5–6 m long with 0.52 m row spacing. Experiments were fertilized with nitrogen at a rate of 120–150 kg ha^{-1} as UREA and Monoammonium phosphate at a rate of 80 kg ha^{-1}, following regional recommendations to avoid nutrient deficiencies (Fontanetto 2008). Plots were over-sown and thinned at V3 to the target stand density (16–18 plants per m^2).

Because the lack of detailed information on initial conditions, years were classified into each ENVT based on previous classification at the central east region (Zavalla) from Carcedo and Gambin (2019). This classification considers the water stress pattern of a medium maturity genotype sown during late October, crop with a plant density of 16 plants per m^2 and with no N restrictions. Sowing dates were classified as early (from October to mid-November), intermediate (from mid-November to mid-December) and late (from mid-December). Classified ENVTs were not associated with any particular sowing date ($P > 0.05$).

Data were analysed using mixed-effects models in R. Environmental type, sowing date, genotype and all possible interactions were set as fixed effects while region, year and block were treated as random. We checked the Gaussian and homoscedasticity assumptions (Zuur *et al.* 2009) for the standardized residuals of the models with graphical analysis and these assumptions were valid in all cases.

3. RESULTS

3.1 Patterns of water stress across regions

Frequency of occurrence of each ENVT varied across regions (Fig. 2). Pre-flowering stress was the most frequent ENVT in all regions, averaging almost 50 %, and increased in preponderance in the south (75 %; Fig. 2). Low terminal stress and grain-filling stress showed similar frequencies across all regions, being ca. 25 % in the north and both central regions, and ca. 12.5 % in the south (Fig. 2).

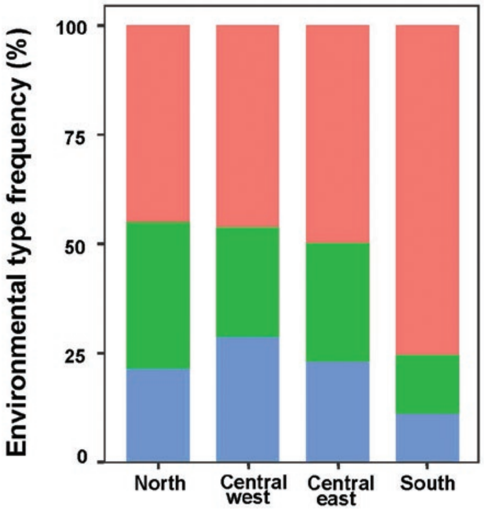

Figure 2. Frequency distributions of the three ENVTs (pre-flowering stress, red; low terminal stress, green; grain-filling stress, blue) for each region.

3.2 Phenology

Sowing date and genotype significantly affected the number of days to anthesis in all regions, explaining 80–95 % of the total variance when combined (Table 3). Delaying the sowing date reduced the days to anthesis by 14–20 days depending on the region (Table 3). The shortest duration genotype (ADV114) reached anthesis from 74 to 103 days from sowing, the medium genotype (VDH314) from 82 to 113 days and the longest genotype (VDH422) from 87 to 121 days (Table 3).

Sowing date × genotype interaction for days to anthesis was only significant in the central east, where a wider range of sowing dates was explored (Table 3). Delaying the sowing date from mid-October to mid-December reduced the days to anthesis similarly in all genotypes, and later sowing dates increased time to anthesis (by 4, 5 and 20 days compared to the sowing date of mid-December in the short, intermediate and late maturity, respectively; **see Supporting Information—Fig. S1**).

Sowing date and genotype significantly affected the grain-filling duration in all regions, explaining from 37 to 97 % of the total variance when combined (Table 3). Delaying the sowing date increased or reduced the grain-filling duration depending on the region. Grain-filling duration increased with delayed sowings in the north region. The same trend was observed in central regions, excepting for later sowings where the grain-filling duration was reduced (Table 3). In the south, delaying the sowing date always shortened the grain-filling duration. The grain-filling duration was higher (53 days) for genotypes ADV114 and VDH314, compared to VDH422 (48 days; Table 3).

Sowing date × genotype interaction for grain-filling duration was significant in the north and central regions (Table 3), and was associated with the relative change in the duration of grain filling at delayed sowing dates. In the north, the duration of grain filling increased in the 15 December and 1 January sowings, with this increment being more important in the intermediate and late genotypes (from 5 to 11 days, respectively). In contrast, the interaction in central regions was associated with a significant reduction in grain-filling duration for the last sowing date, depending on the genotype.

Frost events prior to physiological maturity in central and south regions increased under later sowing dates, explaining observed changes in grain-filling duration (Fig. 3).

Environmental type showed no significant effect on days to anthesis nor the duration of grain filling (Table 3).

3.3 Grain yield and relative transpiration index

Environmental type explained a large proportion of the total grain yield variability in all regions (Table 4). Yield was higher under low terminal stress, and was reduced depending on the region by 25–45 % and 30–42 % under pre-flowering and grain-filling stress, respectively. Sowing date significantly affected grain yield, except for the north region (Table 4). Genotypic differences also contributed to yield variations to a lesser extent, being higher in the short genotype ADV114, intermediate for VDH314 and lower for the late maturity VDH422 (Table 4).

Table 3. Days from sowing to anthesis (anthesis) and duration of grain filling (grain filling) for each region and ENVT, sowing date and genotype. Variance components are expressed as percentage of the total variance explained by the effects. **, *** indicate significance differences at $P < 0.01$ and < 0.001, respectively. Values within different letters are significantly different at $P < 0.05$.

Effect	North		Central west		Central east		South	
	Anthesis	Grain filling	Anthesis	Grain filling	Anthesis	Grain filling	Anthesis	Grain filling
				Days				
ENVT								
Pre-flowering stress	84a	51a	99a	54a	98a	55a	113a	44a
Low terminal stress	79a	49a	98a	55a	93a	55a	109a	45a
Grain-filling stress	81a	50a	95a	53a	97a	55a	106a	48a
Sowing date								
15 October	90d	47a	104c	53b	106d	52b	123d	49c
1 November	85c	47a	99b	54bc	99c	54bc	115c	49c
15 November	81b	48ab	95a	56cb	94b	56c	109b	47c
1 December	77a	49b	94a	57d	91a	60d	104a	42b
15 December	76a	52c	95a	50a	91a	61d	103a	32a
1 January	77a	58d			98c	46a		
Genotype								
ADV114	74a	50b	89a	56b	87a	57b	103a	48c
VDH314	82b	52c	98b	56b	97b	57b	113b	45b
VDH422	87c	48a	105c	50a	106c	51a	121c	41a
Variance components								
ENVT	7	2	2	0	2	0	7	3
Sowing date (SD)	33***	78***	17***	29***	12***	21***	41***	79***
Genotype (G)	55***	18***	78***	41***	68***	16***	53***	18***
ENVT × SD	5	1	2	0	10	11	0	0
ENVT × G	0	0	0	0	1	0	0	0
SD × G	0	1**	0	30***	7***	52***	0	0
ENVT × SD × G	0	0	0	0	0	0	0	0

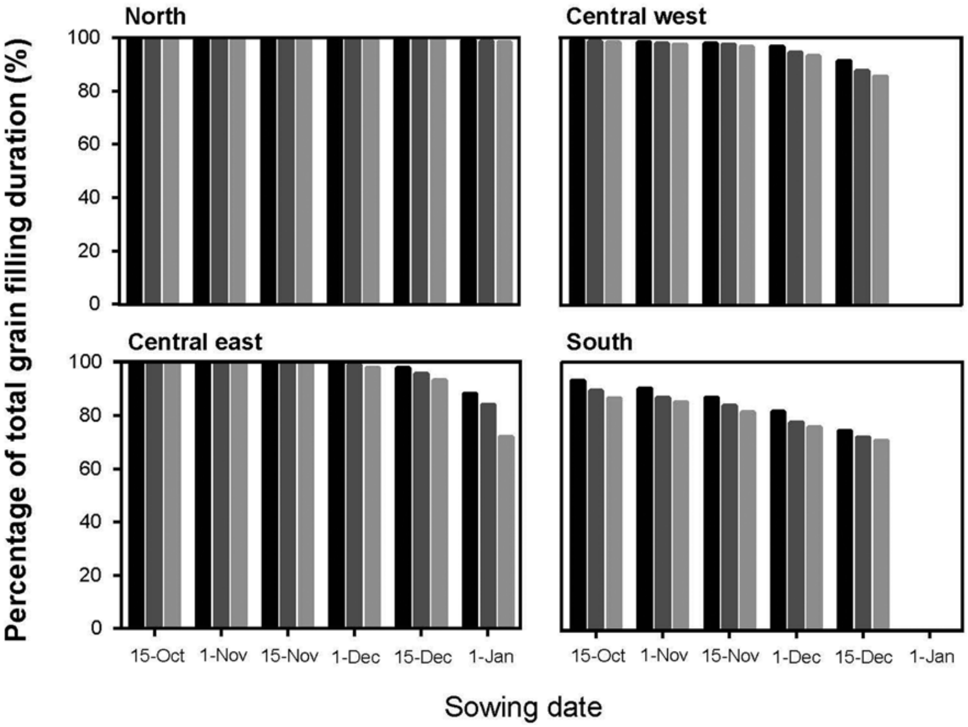

Figure 3. Percentage of total grain-filling duration achieved for each genotype (short: ADV114, dark grey; medium: VDH314, intermediate grey; late: VDH422, light grey) and region. This percentage was calculated from the amount of the thermal time actually accumulated at the end of the crop relative to the time requirement for each genotype (100 %).

Sowing date × genotype interaction was significant in central regions (Table 4), where delaying the sowing date reduced yield more for the intermediate and late maturity genotypes compared to the short maturity genotype.

The effect of sowing date depended on the water stress pattern, except for the south region where no significant ENVT × sowing date interaction was evident (Table 4). For the rest of the regions, delaying the sowing date promoted an accelerated yield reduction under low terminal stress (Fig. 4). In contrast, delaying the sowing date resulted in a yield increment under pre-flowering stress (Fig. 4). Finally, delaying the sowing date reduced grain yield under grain-filling stress linearly, except for the north region that had a yield recovery with later sowings (Fig. 4).

Grain yield response under different sowing dates and ENVT was in agreement with changes in relative transpiration index around anthesis (Table 5). High yields under low terminal drought stress are in agreement with high relative transpiration values (>0.74; Table 5). Under pre-flowering stress, delaying the sowing dates increased relative transpiration index around flowering in all regions ($P < 0.05$). Under grain-filling stress, delaying the sowing date implied a reduction in the relative transpiration index around flowering, which is only reversed at sowing dates of January in the north and central east regions (Table 5).

Relative transpiration index increases did not result into higher yields when delaying the sowing date shifted the flowering or the grain-filling period to decreasing solar radiation or temperature conditions [**see Supporting Information—Fig. S1**]. In the southern region, for example, delaying the sowing date always improved relative transpiration index for pre-flowering and low terminal stress situations (Table 5). However, yield consistently decreased under delayed sowings (Fig. 4).

Finally, ENVT × genotype interaction was only significant in central west region (Table 4), where yield under pre-flowering stress was similar for the late and intermediate maturity.

3.4 Biomass and HI

Yield variations were associated with variations in both biomass and HI (Fig. 5). Accumulated biomass at maturity and HI were higher under lower terminal stress ($P < 0.05$). Under this ENVT, both traits were higher in early sowings, and decreased with the delay in the sowing date ($P < 0.05$; Fig. 5). This reduction was higher in central and southern regions.

Biomass was lower ($P < 0.05$) and showed comparable values under pre-flowering and grain-filling stress. Yield differences due to sowing date were mostly explained by differences in HI (Fig. 5). Under pre-flowering stress, later sowings increased HI. Under grain-filling stress, both biomass and HI were higher in early sowings, and decreased with delay in the sowing date.

3.5 Contrasting estimated versus observed data

Observed data from experiments in the central east were in agreement with simulated data, showing significant ENVT × sowing date interaction for grain yield (Table 6). Under low terminal stress or grain-filling

Table 4. Grain yield (kg ha^{-1}) for each region and ENVT, sowing date and genotype. Variance components are expressed as percentage of the total variance explained by the effects. **, * indicate significance differences at $P < 0.01$ and < 0.001, respectively. Values within different letters are significantly different at $P < 0.05$.**

Effect	North	Cenwtral west	Central east	South
		kg ha^{-1}		
ENVT				
Pre-flowering stress	9159b	7029b	8350b	3445a
Low terminal stress	12 323a	9525a	11 133a	6220a
Grain-filling stress	8530b	5564b	6685b	3909a
Sowing date				
15 October	9663a	8048a	9764a	4954a
1 November	9905a	7936b	9854a	4600b
15 November	10 118a	7783c	10 042a	4136c
1 December	10 441a	7084cd	9949a	3321cd
15 December	10 539a	5257d	8664b	2003d
1 January	9897a		4110c	
Genotype				
ADV114	10 217a	7746a	9532a	4635a
VDH314	10 344a	7308b	9002b	3712b
VDH422	9723b	6611c	7657c	3061c
Variance components				
ENVT	68***	59***	34***	53
Sowing date (SD)	0	22***	28***	33***
Genotype (G)	1***	4***	5***	15***
ENVT × SD	30***	13***	22***	0
ENVT × G	0	<1**	0	0
SD × G	0	1***	10***	0
ENVT × SD × G	0	0	0	0

stress, yield was higher at sowing dates from October to mid-December (identified as early or intermediate in Fig. 6). In contrast, yield was higher from sowings from mid-November to mid-December under pre-flowering stress, and was significantly reduced at earlier sowings (Fig. 6). Yield was significantly reduced in late sowings (from mid-December) independently of the ENVT.

Similarly to simulated data, no ENVT × genotype interaction nor ENVT × sowing date × genotype interaction for yield was detected.

4. DISCUSSION

Genotype × environment interactions are often ubiquitous, and explain a large proportion of yield variability (Chapman *et al.* 2000; Carcedo *et al.* 2017). In this context, crop simulation models are a valuable tool to explore the impact of different genotype × management combinations across a target population of environments, and help define potential strategies for yield improvement (Whitbread *et al.* 2010; Chenu *et al.* 2011; Hammer *et al.* 2014; Clarke *et al.* 2019). In this study, we explored two relevant management practices in sorghum (sowing date and genotype maturity) across a temperate region commonly affected by different water stress patterns (Carcedo and Gambin 2019).

We showed that the sowing date that favours high yields depends on the specific seasonal ENVT (Fig. 4). Delaying the sowing date in years with pre-flowering stress restricts water stress to vegetative stages, avoiding the coincidence of water deficit with critical crop stages, and thus increasing HI via increasing water use around flowering. Delaying the sowing date in years with grain-filling stress places the timing of water stress at more critical stages and, for this reason, early sowings produced higher yields (Fig. 4). Success in adapting a crop to an area of seasonal drought usually has been achieved by shortening the crop growth cycle so that the plants mature before soil water limits yield (Begg and Turner 1976; Ludlow and Muchow 1990). Adjusting the sowing dates according to the prevailing ENVT follows this drought escape strategy (Begg and Turner 1976).

For southern regions, earlier sowing dates provided the higher yields independently of the explored ENVT (Fig. 4). This occurs even when earlier sowing dates imply locating the seed number determination period under lower relative transpiration index values in 3 out of 4 years, based on the simulated frequency of pre-flowering stress. Early sowing dates in the south produced more biomass due to increased crop duration, and also resulted in higher HI than later sowing. Delaying the sowing date reduced HI due to an anticipated reduction in grain-filling duration caused by frosts (Fig. 3). This provides new information in the area, where sowing dates usually take place from late November (Bolsa de Cereales 2020). Results from the present simulation suggest that farmers are currently losing yield as a consequence of low temperatures during grain filling.

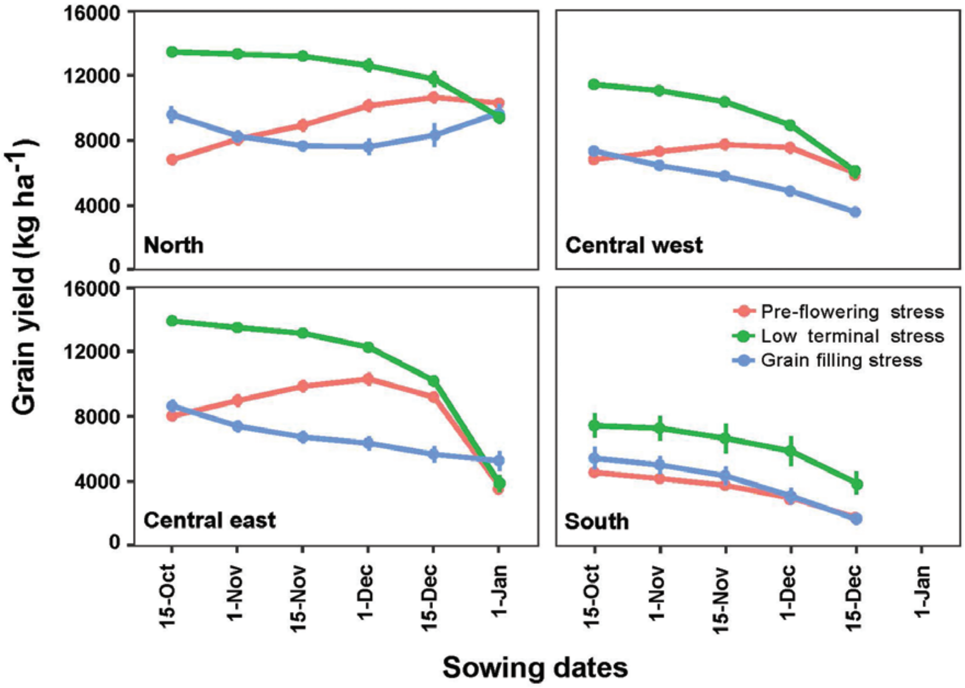

Figure 4. Mean simulated grain yield for years classified under each ENVT (pre-flowering stress, red; low terminal stress, green; grain-filling stress, blue) on 5–6 sowing dates starting on 15 October and every 15 days, for each region. Vertical lines are the standard error.

Table 5. Mean relative transpiration index around flowering for each planting date and ENVT for the four regions.

ENVT	Planting date	North	Central west	Central east	South
Pre-flowering stress	15 October	0.51	0.59	0.53	0.57
	1 November	0.61	0.61	0.63	0.67
	15 November	0.66	0.63	0.69	0.70
	1 December	0.75	0.69	0.83	0.80
	15 December	0.84	0.81	0.88	0.84
	1 January	0.90		0.92	
Low terminal stress	15 October	0.87	0.76	0.81	0.74
	1 November	0.85	0.78	0.84	0.75
	15 November	0.87	0.81	0.86	0.75
	1 December	0.89	0.89	0.90	0.86
	15 December	0.96	0.92	0.95	0.92
	1 January	0.88		0.95	
Grain-filling stress	15 October	0.71	0.61	0.65	0.76
	1 November	0.65	0.58	0.59	0.67
	15 November	0.57	0.59	0.59	0.62
	1 December	0.50	0.54	0.62	0.59
	15 December	0.66	0.52	0.69	0.51
	1 January	0.88		0.95	

Currently, sorghum farmers at high latitudes are constrained by low soil temperatures at sowing. Results from the present study demonstrate that cold-tolerant genotypes should be a prioritized breeding goal for sorghum production at high latitudes. Promising candidate genes conferring seedling cold tolerance have been recently identified (Parra-Londono *et al.* 2018; Moghimi *et al.* 2019). Similarly, the

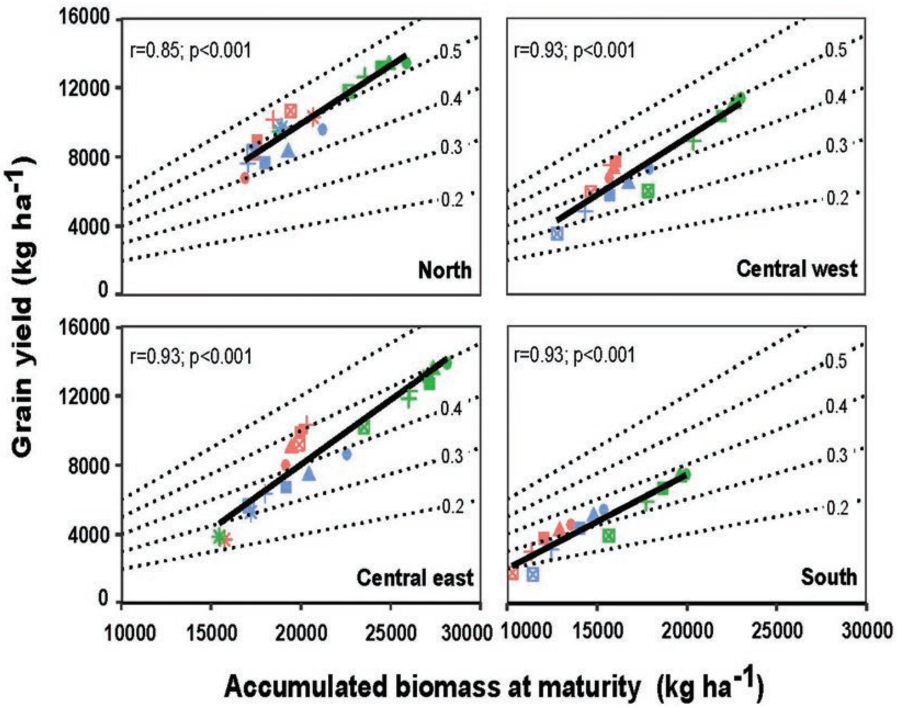

Figure 5. Relation between mean simulated grain yield and accumulated biomass at maturity for years classified under each ENVT (pre-flowering stress, red; low terminal stress, green; grain-filling stress, blue) on 5–6 sowing dates (●15 October, ▲ 1 November, ■ 15 November, + 1 December, ⊠ 15 December, ✻ 1 January) across the studied regions. Dotted lines indicate HI isolines.

Table 6. Variance components for observed grain yield in field experiments, expressed as percentage of the total variance explained by each effect. *, ** indicate significance differences at $P < 0.05$ and < 0.01, respectively.

Effect	Percentage of variance (%)
ENVT	35**
Sowing date (SD)	5*
Genotype (G)	18**
ENVT × SD	18**
ENVT × G	3
SD × G	19**
ENVT × SD × G	2

identification of genotypic variability for pre-anthesis base temperature found in Ethiopian genotypes has great value for breeding in temperate regions (Tirfessa *et al.* 2020).

Farmers need to define genotype and management combinations in advance of the season and face the risk on the production environment (Hammer *et al.* 2020). The yield–risk trade-off is a major factor confronting farmers in both developed and subsistence cropping systems (Hammer *et al.* 2014; Clarke *et al.* 2019). High-input or intensity genotype × management options favour high yield potential but come with increased risk of failure in poor seasons. Conservative genotype × management options reduce risk but cannot achieve the yield potential possible in favourable seasons (Hammer *et al.* 2020). In our region, a conservative strategy could be the best option in the north and central east as the yield lost for delaying the sowing dates to mid-November/early December under low terminal stress or grain-filling stress is lower (1464–1947 kg ha^{-1} averaging both ENVTs) than the yield that is gained for delaying sowings under a pre-flowering stress (3833–2287 kg ha^{-1}; Fig. 4). This strategy does not apply in central west, and consequently early sowing dates imply lower risk.

Late sowings as a strategy to provide yield stability in this region has been increasingly adopted by maize farmers during the last 10 years (Gambin *et al.* 2016; Bolsa de Cereales 2020). For sorghum, this same strategy would have important local consequences. Later sowing implies exposing the crop to high weed and insect pressures, something that has been overcome with genetically modified materials in maize (Bt, Williams *et al.* 1997; glyphosate-resistant, Johnson *et al.* 2000; Dirección de Biotenología 2020), but it is not an option in sorghum. Additionally, technology use in sorghum is usually low, weed control is one of the major production problems and pesticides are usually not applied (Brihet and Gayo 2016; Brihet 2017). This implies several challenges for sorghum breeding and management in the region.

Pre-flowering drought delays anthesis in sorghum (Wright *et al.* 1983; Ludlow and Muchow 1990; Craufurd et al. 1993). Although APSIM simulates the impact of water stress on delayed phenology (Hammer *et al.* 2010), this is done similarly for all genotypes. Local

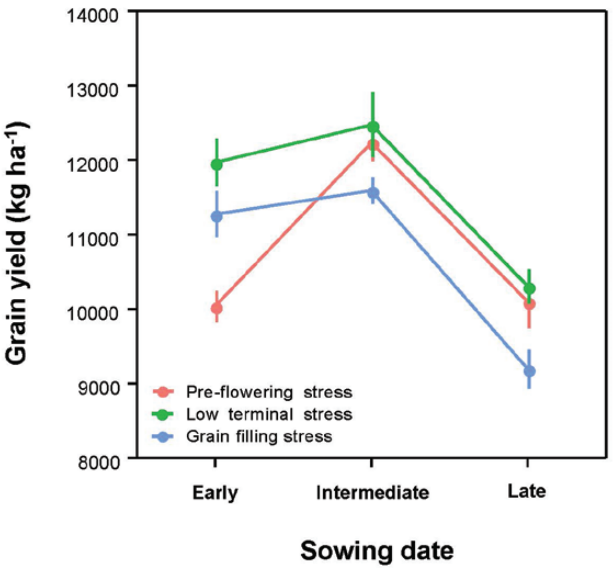

Figure 6. Observed grain yield from field experiments for years classified under each ENVT (pre-flowering stress, red; low terminal stress, green; grain-filling stress, blue) across different sowing dates (early, intermediate, late). Vertical lines are the standard error. Experimental details are provided in Supporting Information—Table S3, and involved three sorghum genotypes under a wide range of water regimes over a period of 12 years in central east region.

evidence indicated important genotypic differences in the delay in flowering time (up to 25 days) in response to pre-flowering water stress, which is largely independent of genotype maturity (Pardo and Gambin 2014). Consequently, the impact of genotype maturity might be higher than simulated in the present study, particularly for very late sowings in central and southern regions. Agricultural Production Systems SIMulator evaluation in this sense would be clearly important for using this tool in temperate regions.

5. CONCLUSIONS

Results showed that optimizing sowing date provides a drought escape strategy to reduce the impact of the different water stress patterns that usually affect the entire region. Genotype maturity showed negligible effects.

Later sowings (from mid-November to early December) provide a conservative management strategy for reducing risk in the north and central east regions, while in central west and south regions the sowing date should be as early as possible (October).

The study has important consequences for sorghum breeding and management, describing the relevance of optimizing sowing date in temperate regions.

SUPPORTING INFORMATION

The following additional information is available in the online version of this article—

Figure S1. Mean simulated dates of flowering and maturity for three sorghum genotypes sown at 5 to 6 sowing dates starting on the 15 of October and every 15 days.

Table S1. Measures of agreement between simulated and observed experiential data, adapted from Carcedo and Gambin, 2019.

Table S2. Variance components for observed grain yield from field experiments.

Table S3. Details of field experiments on sorghum. Experiments involved 3 sorghum genotypes under a range of N and water regimes over a period of 12 years in Argentina.

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CONTRIBUTIONS BY THE AUTHORS

A. J. P. C. contributed to the conception and design of the work, data collection, data analysis and interpretation, and drafting the article. E. C. contributed to data collection. B. L. G. contributed to conception and design of the work, data analysis and interpretation, and critical revision of the article.

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