Sorghum drought and heat stress patterns across the Argentinean temperate central region

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ABSTRACT

Argentinean current sorghum management is similar across the entire temperate region, and no environmental characterization is assisting breeding and management decisions. Crop growth and development simulation models are a valuable tool for generating this characterization. Our study calibrated and validated APSIM-sorghum for our genetics and production environments, and used it to characterize the main water and heat stress patterns at our temperate central region. The calibration and validation provided accurate phenology, biomass, and yield estimations. Long-term weather records (44–61 years per site) and soil data were used to simulate the seasonal drought patterns at seven representative sites across the region. Clustering analysis identified three major drought environmental types (ENVT): (i) a pre-flowering drought stress, showing large occurrence frequency (39%), (ii) a low terminal drought stress, showing similar frequency (38%), and (iii) a grain-filling drought stress, showing lower frequency (23%). The most frequent ENVT at individual sites agrees with the spatial distribution of annual rainfall. However, most sites evidenced variable frequency of all ENVT. Flowering heat stress (> 33 °C) showed an intermediate occurrence frequency (20–50%) only at lower latitudes, and was independent of drought ENVT. Defined ENVT helped explain observed genotype x environment (GxE) interactions for yield in an independent data set, showing they have practical implications for optimizing breeding and management strategies across the region of interest. Grouping sites of similar frequency can help to handle the spatial variability when defining these strategies, but dealing with seasonal variability will be challenging in the context of no predominant ENVT.

1. Introduction

Argentina is an historic sorghum producer, alternating the second place in exports with Australia during the last years (SSMA, 2016). The area sown with sorghum in Argentina is relatively constant when compared to other crops like soybean or maize. During the last twenty-five years, around one million hectares are sown with sorghum each year, being the fifth crop after soybean, maize, wheat, and sunflower. Historically, sorghum area used to be higher, exceeding two million hectares around 1970-1980. The expansion of soybean and maize crops has contributed to sorghum area reductions.

Agricultural production environments in Argentina cover an extensive area of around 65 million hectares, from latitude 24 to 40 °S, involving the Llanura Pampeana, or central region, and the Llanura Chaco Pampeana, or NEA (Alvarez and Lavado, 1998). Main soil taxonomy orders are Molisols in Llanura Pampeana, Alfisols in Chaco, and Entisols and Aridisols in the western area of both regions. This shows important variation in soil depth and clay content (Alvarez and Lavado, 1998). Annual average temperature range from 14 °C in the south to 23 °C in the north, and annual precipitation varies from 200 mm in the west to 1200 mm in the east. This diversity in climate and soils determines an important variation in sorghum yield across the entire region, from more than 10 t ha^{-1} in the more productive areas to less than 3 t ha^{-1} in the southwest of the central region (Ministerio de Agroindustria, 2018).

Sorghum crops are highly valued by farmers because it has relatively low production costs, has a particular ability to resist different types of abiotic stress including water deficit or excess, and produces a

high remaining biomass that improves physical and chemical soils properties (Doggett, 1988). For these reasons, sorghum is usually cropped in poor soils. Moreover, this has intensified during the last decades with the advancement of more profitable crops like maize and soybean. In agreement to this, applied technology (including N or P fertilization, weed and pest control) around the entire region is low, especially when compared to other crops (Brihet, 2017). The proportion of farmers applying low technology to their sorghum fields has increased in the last decade (Brihet and Gayo, 2016). Agronomic practices used by current sorghum farmers are not based on a clear understanding of GxExM (genotype by environment by management) interactions, which is in accordance to the current estimated yield gap (Gambin, 2015).

A clear definition of the target populations of sorghum environments in Argentina is currently lacking. For this reason, which genotypic traits or management practices are needed at different growing environments is not clear. Sorghum production environments are variable in soil type, soil depth, and water retention. This, combined with seasonal and annual variation in rainfall and temperature, determines different patterns of water stress during the crop cycle. It is well known that the timing, intensity, and duration of a water stress causes different effects on crop growth and development (Passioura, 1983), and we are lacking a measure of the frequency of occurrence of different types of stress.

The same applies with temperature stresses, which are predicted to be more frequent in the near future (Lobell and Field, 2007). The direct effect of heat stress on sorghum flower development and grain set has been demonstrated (Prasad et al., 2008, 2015; Singh et al., 2016), but the frequency of occurrence of extreme temperatures affecting sorghum in our region is not described. Because drought usually occurs when heat stress are also experienced, exploring the frequency of occurrence of both water and temperature stress is relevant. This type of information in sorghum is currently limited (Rötter et al., 2018).

Simulation models are a valuable tool to simulate crop growth and development (Passioura, 1996). They play a fundamental role in crop breeding when used (i) for environmental characterizations, in order to identify the nature and frequency of stress events in the target population of environments, and (ii) for predicting the outcome of GxM combinations in target environments (Hammer and Jordan, 2007). There are evidences of the use of simulation models for these purposes in several species, including sorghum, and regions (Chapman et al., 2000a; Chenu et al., 2011; Hammer et al., 2014; Sadras et al., 2012; Seyoum et al., 2017; Singh et al., 2017). This information for important sorghum production systems around the world is relevant for sharing management or breeding strategies, including candidate germplams tested, screening conditions, off-season trials, and selection criteria.

The common sorghum sowing date in the region (late October to mid-November) sets the end of the vegetative stage around January, with high temperatures and high water environmental demand. We hypothesize pre-flowering drought and heat stresses are frequent for crops planted at this timing. In order to test this hypothesis we needed to validate APSIM-sorghum for our temperate environments using representative genotypes. The objectives of our study were (i) to define the main drought ENVT based on water deficit patterns in the Argentinean central region, and to determine their occurrence frequency, (ii) to determine the probability of heat stress around anthesis and its association with previously determined ENVT, and (iii) to explore if defined drought ENVT can help explain observed GxE interactions for yield.

2. Materials and method

2.1. Model parameterization and testing

The Agricultural Production Systems Simulator (APSIM, McCown et al., 1995) is a modular modeling framework. The plant modules

simulate physiological processes and the management module allows specifying management rules that characterize the scenario being simulated. It operates on a daily time step in response to input daily weather data and soil characteristics (Keating et al., 2003).

The APSIM-sorghum module was described in detail by Hammer et al. (2010). The model contains processes that simulate phenology, canopy development, crop growth, and nitrogen dynamics. Phenology is simulated through a number of development stages, using thermal time targets for each stage (Muchow and Carberry, 1990; Muchow and Sinclair, 1994). Dry mass accumulation on a daily basis is only limited by radiation when conditions are optimum. It is calculated as the product of intercepted radiation and radiation use efficiency (Hammer et al., 2010). On the other hand, dry mass accumulation is limited by water when the crop is under drought stress, and calculated as the product of transpiration and transpiration efficiency (Hammer et al., 2010). The biomass partitioning is directly linked to thermal time through partitioning coefficients. This is the main difference with DSSAT (another commonly used sorghum model), which is distributed to stem, leaf, root, and grain with priorities to the different organs according to developmental stages (Akinseye et al., 2017).

2.1.1. Experimental details

Data for model parameterization was collected from field trials conducted during 2014 and 2016 growing seasons at the Campo Experimental Villarino, Facultad de Ciencias Agrarias, Universidad Nacional de Rosario, at Zavalla (33° 1′ S, 60° 53′ W, 130 m altitude), Santa Fe province, Argentina. The soil type was a silty clay loam Vertic Argiudoll (Soil Taxonomy, Soil Survey Staff, 2014) (Table 1). Model testing was done using independent field experiments conducted from 2011 to 2016 growing seasons at Zavalla, and during 2016 at Laguna Larga (31° 48′ S; 63° 46′ W) Córdoba province (soil type silty loam Entyc Haplustol), Venado Tuerto (33° 40′ S; 61° 58′ W) Santa Fe province (soil type silty loam Typic argiudol), and Gálvez (31° 59′ S; 61° 15′ W) Santa Fe province (silty clay loam Tipyc Argiudol), Argentina.

Experiments for model parameterization were done under non-limiting water and nitrogen (N) conditions (Mercau et al., 2007), while model testing included experiments under variable water and N availability (Table 1). Overall, three commercial genotypes from ADVANTA SAIC were used: ADV114 (short maturity), VDH314 (intermediate maturity), and VDH422 (late maturity), being these materials representative for each maturity in the central region. Data collected provided a sound basis for parameterizing aspects of the model associated with genotypic differences, and for comprehensive model testing.

In all experiments a randomized block design with three replicates was used. Plots were four rows 5.5 m long with 0.52 m row spacing. Soil samples until 60 cm depth were taken before sowing for determining initial soil proprieties. Soil test included P amount (ppm, 0–20 cm) and N-NO$_3$ (0–60 cm) determinations by spectrophotometry. Soil available water content was determined at each experiment until 2 m depth. Soil water content was determined by the gravimetric method (Black and Power, 1965).

Nitrogen (UREA) was applied at V4–V5 stage (Vanderlip and Reeves, 1972) and monoammonium phosphate (MAP) was applied at sowing to reach different N fertilization levels depending on the particular experiment (Table S1). Plots were over-sown and thinned after emergence to the target stand density (Table 1). In all experiments weeds and pests were controlled as required.

2.1.2. Phenotypic measurements

Experiments were sampled for development and growth regularly in a similar manner that described in van Oosterom et al. (2010). This included experiments done for model parameterization and several of the experiments done for testing (Table 1). The rest of experiments included some variations in phenotypic information that was available for testing.

Table 1

Detailed field experiments on sorghum conducted for model parameterization and testing. Experiments involved three sorghum genotypes under a range of N and water regimes over a period of five years in Argentina. Nitrogen availability represents soil nitrates at sowing (0–60 cm) plus N applied with fertilizers.

Exp	Location	Year	Sowing date	Genotype	Rainfall from sowing to April (mm)	Plant density (pl m^{-2})	SAWC[a] at sowing (mm)	N availability (kg ha^{-1})	Phenology / Leaf area / Biomass / Yield[b]
Model parameterization									
1	Zavalla	2014	Nov 13	ADV114, VDH314, VDH422	879[c]	18	264	162	+ / + / + / +
2	Zavalla	2016	Nov 3	ADV114, VDH314, VDH422	816	20	264	178	+ / + / + / +
Model testing									
3	Zavalla	2011	Nov 1	ADV114, VDH314, VDH422	581	20	70	27	r / - / r / +
4	Zavalla	2012	Nov 3	ADV114, VDH314, VDH422	763	20	264	118	r / - / r / +
5	Zavalla	2012	Dec 13	ADV114, VDH314	630	24	264	118	r / - / - / +
				ADV114, VDH314	630	17	264	118	r / - / - / +
6	Zavalla	2012	Nov 3	ADV114, VDH314, VDH422	763	20	264	118	r / - / r / +
7	Zavalla	2013	Nov 13	ADV114, VDH314, VDH422	451[c]	18	264	229	r / - / r / +
8	Zavalla	2013	Nov 12	ADV114, VDH314, VDH422	366	18	264	16	r / - / r / +
				ADV114, VDH314, VDH422	366	28	264	16	r / - / r / +
9	Zavalla	2014	Nov 13	ADV114, VDH314, VDH422	779	28	134	162	r / - / r / +
				ADV114, VDH314, VDH422	779	20	134	18	r / - / r / +
				ADV114, VDH314, VDH422	779	18	134	162	+ / + / + / +
10	Zavalla	2014	Nov 3	VDH314	779	8	134	12	r / - / r / +
				VDH314	779	18	134	12	r / - / r / +
				VDH314	779	28	134	12	r / - / r / +
11	Zavalla	2016	Nov 3	ADV114, VDH314, VDH422	816	20	264	109	+ / + / + / +
12	Zavalla	2016	Dec 16	ADV114, VDH314, VDH422	763	20	239	184	+ / + / + / +
				ADV114, VDH314, VDH422	763	20	239	253	+ / + / + / +
13	Galvez	2016	Oct 30	ADV114, VDH314, VDH422	559	20	240	115	r / - / r / +
14	Laguna Larga	2016	Dec 10	ADV114, VDH314, VDH422	387	20	217	227	r / - / r / +
15	Venado Tuerto	2016	Nov 11	ADV114, VDH314, VDH422	477	20	265	206	r / - / r / +

[a] SAWC, soil available water content until 200 cm depth.

[b] symbols "+" and "-" indicated that phenotypic measurements were done or not, respectively. + in phenology included time to panicle initiation, anthesis and physiological maturity; + in leaf area indicated leaf appearance, leaf area development and senescence during the crop cycle. "r" indicated regular samples during the crop cycle; + in biomass indicated that phenology and biomass samples were done at specific stages.

[c] Values include additional irrigation around anthesis.

2.1.2.1. Phenological development. The timing of panicle initiation, anthesis, and physiological maturity were observed for each plot. Panicle initiation was estimated by dissecting the growing point of one plant per plot every 2–3 days around the anticipated date, and recorded when visual recognition of the change of the growing point was seen. Anthesis was recorded as the day 50% of the plants of the two central rows had open anthers. Physiological maturity was recorded after visual observations of black layer in five of ten random consecutive plants at basal panicle positions (van Oosterom and Hammer, 2008).

Duration of the phases was converted to thermal time (TT, °Cd) using a broken linear function of temperature (T) using a base (Tb, 11 °C, before anthesis; 5.7 °C, after anthesis), optimum (Topt, 30 °C), and maximum (Tmax, 42 °C) temperatures (Hammer et al., 1993; Heiniger et al., 1993):

TT = 0 when T < Tb or T > Tmax

TT = T - Tb when Tb < T < Topt,

TT = (Topt - Tb) x [1 - (T - Topt) / (Tmax - Topt)] when Topt < T < Tmax

2.1.2.2. Leaf area measurements. Leaf area of fully expanded leaves was determined by measuring leaf length and breadth on main culm and tillers on five tagged consecutive plants at about weekly intervals in each plot. Numbers of fully expanded and senesced leaves were counted at weekly intervals on the same plants. A leaf was fully expanded when its ligule was visible above that of the previous leaf, and senesced if less than half its lamina area remained green. From the known dimensions of those leaves, total leaf area per plant was calculated following Muchow and Carberry (1990). To account for the area of expanding leaves, their area was assumed to equal the area of the next 1.6 leaves that appear (Muchow and Carberry, 1990) and the observed fully expanded leaf number was increased by 1.6 leaves.

2.1.2.3. Biomass samples and yield components. Above-ground biomass samples were obtained after cutting $0.5\,m^{-2}$ per plot at regular intervals coincident with V5, panicle initiation, ∼20 days before anthesis, 10 days after anthesis, and physiological maturity. Shoot biomass was always measured after drying plants in an air-forced oven at 65 °C for at least one week. Panicles (if present) were removed and weighted separately. Panicles were always cut one centimeter below the first primary branch (being fertile or not). Tillers were treated like main stems. Grain yield was determined harvesting the panicles of $2\,m^2$ per plot in center rows at physiological maturity. Above-ground biomass samples at physiological maturity were determining cutting $0.5\,m^{-2}$ within this area. Biomass and panicles were dried, and panicles threshed and weighted. Individual grain weight was estimated using a 200 grains sample per plot, and grain number was calculated as the ratio between grain yield and individual grain weight.

2.1.3. Model calibration

APSIM-sorghum model was calibrated manually for commercial sorghum hybrids from ADVANTA SAIC (ADV114, VDH314, VDH422) using empirical data on growth, development, and yield from experiments 1 and 2 (Table 1). Genotypic parameters relevant to simulate APSIM-sorghum were derived following the methodology described by Hammer et al. (2010). These included parameters quantifying genotypic effects on phenology, canopy development, growth, and grain set. Parameters for each particular genotype are described in Table 2. Genotypes were considered insensitive to photoperiod as observed from phenology data from experiments under different sowing dates (Cejas, unpublished data). Thermal time to emergence was set to 80 °Cd (Muchow and Carberry, 1990). For the calculation of maximum total leaf area per plant, fertile tiller number was considered zero, based on previous observed data from past experiments under the recommended densities in the region ($16–20\,pl\,m^{-2}$).

Table 2

Parameter values for relationships quantifying phenology, canopy development, growth and grain set in the sorghum crop model for genotypes used in this study.

Parameter	Genotype		
	ADV114	VDH314	VDH422
Thermal time to floral initiation (ºCd)	340	387	430
Thermal time A-PM[a] (ºCd)	795	810	799
γ (main stem coefficient)	3.2	3.2	3.23
α (total plant leaf area production coefficient; ºCd^{-1})	0.012	0.01	0.008
β (total leaf area inflection; ºCd)	540	583	609
κ (dry matter per seed; g grain^{-1})	0.000523	0.000604	0.00052

[a] A-PM is from anthesis to physiological maturity.

2.1.4. Model testing

Model testing was done comparing simulated versus observed data of phenology (days to anthesis and physiological maturity), leaf appearance, leaf area index (LAI), shoot biomass, and grain yield. Time-course of leaf appearance, LAI, and biomass were measured in experiments 9, 11, and 12 (Table 1). In most experiments, biomass was obtained at two timings (e.g., around anthesis and physiological maturity; Table 1).

Observed and simulated value agreement was tested using root mean square error (RMSE), D-index (Willmott, 1981), and model efficiency (ME) (Wallach, 2006).

2.2. Simulation of seasonal drought stress patterns and environmental type classification

A sorghum crop model (Hammer and Muchow, 1994) was used to simulate the seasonal drought stress patterns, in a similar manner than described in Chapman et al. (2000a).

The model was set to compute the daily value of relative transpiration (RT), time to anthesis, time to physiological maturity, and grain yield. The RT is calculated as the ratio of potential transpiration by the crop to the actual transpiration that can occur given the amount of soil water available that day. Several studies used RT as a measure of water stress (Chapman et al., 2000a; Chenu et al., 2011; Hammer et al., 2014; Sadras et al., 2012; Seyoum et al., 2017).

The simulations were run for seven sites representative of sorghum production, spread across the central region (Table 3, Fig. 1). For each site, a representative soil type was identified based on data provided by the Soil Institute of INTA (http://geointa.inta.gov.ar/, accessed 1 Jan. 2017). Functional soil properties required by APSIM to run crop simulation models were derived from soil series descriptions following the revisions made by Gijsman et al. (2002); Probert et al. (1998); Saxton et al. (1986) and the protocol for the development of APSOIL parameter (Dalgliesh et al., 2006) (Table 3).

Daily maximum and minimum temperature and precipitation data were derived from the INTA (National Institute for Agricultural Technology; http://siga2.inta.gov.ar/, accessed 1 Jan. 2017) and Facultad de Ciencias Agrarias weather stations (Table 3). Daily incident solar radiation data was used from NASA Prediction of Worldwide Energy Resource (POWER) – Climatology Resource for Agroclimatology (NASA, 2017). NASA-POWER solar radiation data is well correlated with measured solar radiation data in areas with flat topography (Van Wart et al., 2013; White et al., 2011).

The model was used to simulate the planting and growth of crops during each season of the record and estimate RT for each day. Other assumptions were that the crop was planted at 160.000 plants per hectare and that planting only took place when 15 mm of rain were received in a 6-day period within a planting window (15 Oct – 30 Nov). For these simulations we used the intermediate maturity cultivar (VDH314), it represents the most common management option used

Table 3
Soil and weather specifications for sorghum model simulations.

Site	Weather station location (Latitude, longitude)	Years	Mean rainfall (mm) (1/09-31/03)	Mean temperature (°C) (1/09 - 31/03)		Soil Taxonomy	Depth (cm)	SAWC [a] (mm)	Simulated yield (kg ha⁻¹)		
				Min.	Max.				Mean	Min.	Max.
Reconquista	−29.1, −59.7	1970–2017	956 ± 288	17.2	28.8	Vertic natracualf	148	168	9085	2572	13574
Rafaela	−31.1, −61.5	1956–2017	778 ± 217	14.9	28.2	Aquic argiudoll	148	206	10021	2437	16078
Manfredi	−31.8, −63.7	1970–2017	674 ± 145	13.2	27.1	Entic haplustoll	73	95	8303	2395	14843
Paraná	−31.8, −60.5	1956–2017	808 ± 234	15.9	27.2	Aquic argiudoll	155	201	9700	1833	12070
Zavalla	−33.0, −60.8	1973–2017	752 ± 173	14.0	26.6	Tipyc natracualf	152	199	10,368	2882	16,788
Anguil	−36.5, −63.9	1964–2017	584 ± 162	11.1	26.5	Entic haplustoll	95	112	5618	1076	12694
Tres Arroyos	−38.3, −60.2	1971–2017	539 ± 104	10.3	24.1	Petrocalcic argiudoll	85	99	3804	1339	8402

[a] SAWC is soil available water content.

across the region. We assumed that the soil water profile was filled to half of capacity prior to the sowing of each crop for simulation, which is an expected condition across the region. Nutrients (particularly nitrogen) were assumed non-limiting. Although this is not the typical situation for the entire region, this simplifies results interpretation (Muchow et al., 1996). We realize that this assumption might overestimate the stress level (i.e., lower RT values) in some sites (particularly northern sites) as N limitations reduce water demand by reducing LAI (Hammer et al., 2010). However, it should not affect water stress patterns significantly.

The classification of drought stress in ENVT was done following Chapman et al. (2000a). For each 100 °C d of thermal time the daily values of RT were averaged to form a matrix of RT for each season at a site. A hierarchical clustering method was used to cluster the seasons from all locations into groups (i.e., ENVT) according to how similar the RT pattern was across seasons. The classification method employed was a hierarchical agglomerative clustering procedure (Williams, 1976) based on dissimilarity measure squared Euclidean distance, and the grouping strategy was incremental sum of squares (Ward, 1963) and it was applied simultaneously over the entire dataset (329 seasons). An average pattern of RT was calculated for each of these ENVT. Frequency distributions of each ENVT were calculated for each location.

2.3. Heat stress frequency

The frequency of occurrence of extreme heat stress within each ENVT was explored. Maximum daily temperature thresholds were 33 °C, 36 °C and 38 °C, and were based on observed genotypic sensitivity differences to heat stress described in Singh et al. (2015; 2017). The period when maximum temperatures were evaluated was set to begin 50 °C d before anthesis, and to end 150 °C d after anthesis. The period around anthesis is considered by several authors as the moment at which high temperature stress has major consequences on reproductive development, and in particular on pollen germination and seed set (Prasad et al., 2008; Nguyen et al., 2013; Singh et al., 2015, 2016). It is considered the crop developmental timing when any stress causes large reductions in grain yield (Singh et al., 2017). The anthesis date at each location and for each sowing date was obtained as an output of the simulation used for the ENVT classification.

For each location we described the frequency of occurrence of 1, 2, 3, 4, or more than 4 days with maximum temperature above each threshold. In order to test the association between ENVT and heat stress, a Likelihood Ratio Test was done using the R package "vcd" (Meyer et al., 2017).

2.4. Drought environmental types and GxE interaction

The association between ENVT and observed GxE interaction for yield was explored using data from different experiments. Experiments are described in Table S1, and involved several experiments conducted for model testing already described in Table 1, and additional testing trials belonging to the ADVANTA SAIC sorghum program from Gálvez. Testing trials in Gálvez were conducted using a randomized block design with two replicates. Plots were four rows 5 m long with 0.52 m row spacing. Experiments were fertilized with nitrogen at a rate of 120 kg ha⁻¹ as UREA and MAP at a rate of 80 kg ha⁻¹. Plots were over-sown and thinned at V3 to the target stand density. Soil N and available water content at sowing were obtained through soil samples as described above (section 2.1.1.). This information was not available for experiments XIII to XX (Table S1), so they were estimated from near fields in the area.

Trials were simulated using climatic data from INTA weather stations (National Institute for Agricultural Technology; http://siga2.inta.gov.ar/). Soil data were obtained from the soil section of INTA (www.geointa.inta.gob.ar/). The RT index pattern for each trial was determined as described above (section 2.2). Trials were classified into
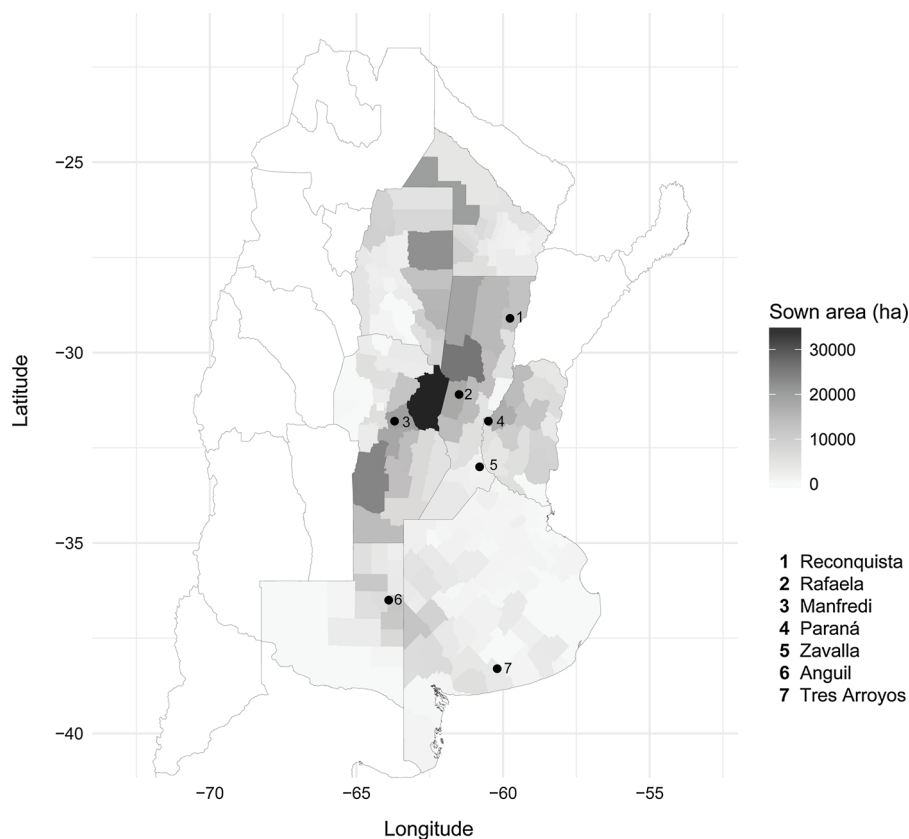
Fig. 1. Map of the region under study. Chosen sites for environmental characterization are identified with black dots. County boundaries are marked. The shading indicates sorghum average sown area observed between 2006 and 2016 for each county.

each ENVT based on the minimum sum of squared differences for the trial RT pattern compared with the RT pattern of the ENVT (Chenu et al., 2011). A principal component analysis was applied to the GxE matrix, with the environment standardized data transformation (Fox and Rosielle, 1982). The analysis and the resulting AMMI biplot were produced using R statistical software (R Core Team, 2018, version 3.4.4, agricolae package, de Mendiburu, 2014). An AMMI biplot analysis was done to enhance the visualization of the GxE interactions by integrating additive and multiplicative components into an integrated least-squares analysis (Zobel et al., 1988).

3. Results

3.1. Model validation

We first validated APSIM sorghum model for representative genotypes and growing conditions. The model accurately simulated crop phenology, biomass, and yield, as shown when contrasting observed versus predicted values for different genotypes and growing conditions were tested. These conditions included variations in genotype, water, and N availability. The values for RMSE, D-index, and ME confirm the robustness of the models (Table 4). The RMSE was 4 days for time to anthesis (Table 4, Fig. 2A), 5 days for time to physiological maturity (Table 4, Fig. 2 B), 1640 kg ha^{-1} for crop biomass at physiological

maturity (Table 4, Fig. 2 C), and 536 kg ha^{-1} for grain yield (Table 4, Fig. 2D). Model efficiency for biomass at physiological maturity was the lowest of tested traits (0.59, Table 4). Nevertheless, the model simulated satisfactorily the observed data (D-index > 0.85, Table 4). Time-courses of leaf number, leaf area index, and biomass during the crop cycle showed generally good correspondence with measured values for the three parameterized genotypes (Figs. S1 and S2).

3.2. Simulation of relative transpiration patterns

Once APSIM sorghum model was validated, we explored stress patterns for different sites around the region using historical weather records and a reference management. Given that simulations were constrained by a planting rain, the model planted a crop in all but 3 to 6 seasons at each location. Seven and three simulated seasons at Tres Arroyos and Anguil, respectively, were discarded due to an anticipated reduction of the crop cycle associated with low temperatures (data not shown). Average sowing date took place on late October in all sites. Time to anthesis and physiological maturity ranged from 83 to 118 days, and from 132 to 169 days respectively, across sites. Simulated values for phenology are in agreement to an intermediate maturity genotype.

Relative transpiration index patterns greatly varied across sites and seasons. Mean RT across all seasons and sites decreased from pre-

Table 4
Measures of agreement between model and measured data. RMSE stands for root mean square error, and ME for model efficiency.

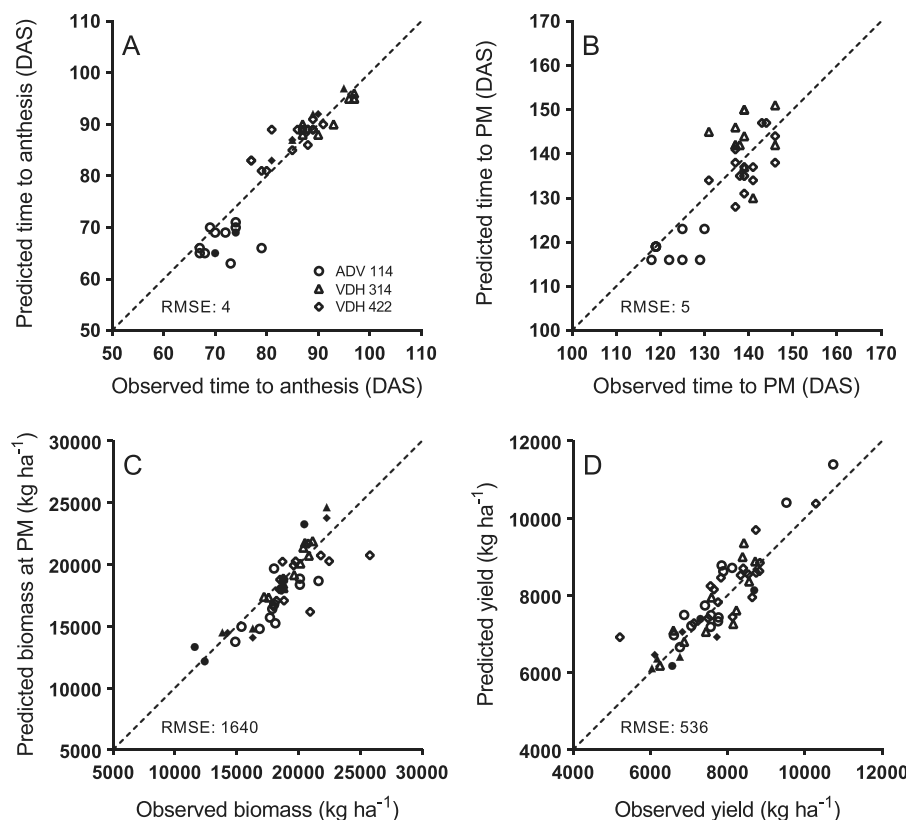| Accuracy estimator	Days to anthesis (d)	Days to physiological maturity (d)	Biomass at physiological maturity (kg ha^{-1})	Grain yield (kg ha^{-1})
RMSE	4	5	1640	536
D-index	0.99	0.98	0.89	0.93
ME	0.81	0.72	0.59	0.74

Fig. 2. Predicted versus observed relationships for (A) time to anthesis, (B) time to physiological maturity, (C) above-ground biomass at physiological maturity and (D) grain yield. Empty symbols correspond to the experiments conducted at Zavalla and closed symbols correspond to experiments at Laguna Larga, Galvez and Venado Tuerto. Details of experiments in Table 1. In each panel, the dashed line is the 1:1 line. RMSE is the root mean square error.
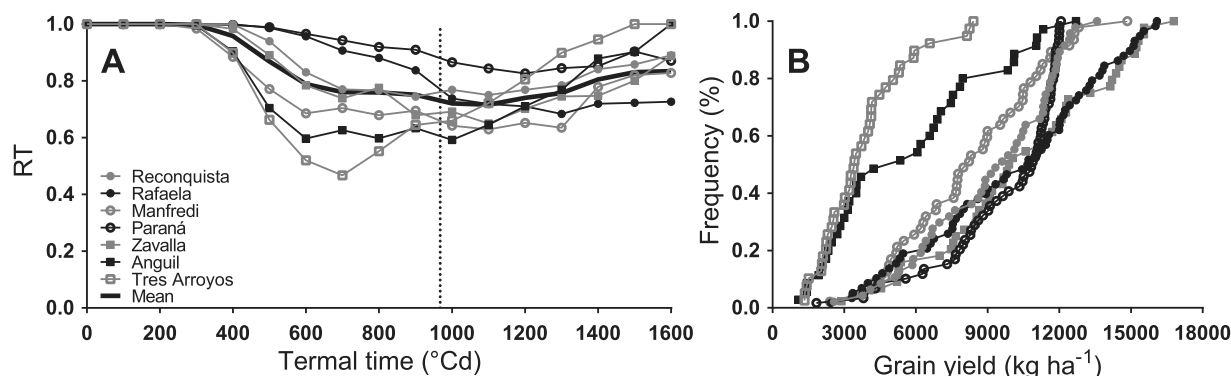

Fig. 3. (A) Mean RT index throughout the crop life cycle across seasons for individual sites. The dashed line indicates the mean flowering date. The RT index throughout the crop life cycle for all the seasons for each site is shown in Fig. S3. (B) Cumulative simulated grain yields frequencies for all seasons in each site.

flowering stages (about V4 stage) and was about 0.75 around flowering and most part of grain-filling period (Fig. 3A). Timing and intensity of stress differed with site, ranging from low stress levels (RT = 0.80) during grain filling at Paraná, to intermediate levels of stress (RT = 0.45) particularly during pre-flowering stages at Tres Arroyos (Fig. 3A).

Mean simulated grain yield ranged from 3804 to 10,368 kg ha^{-1} across sites (Table 3). The lowest values corresponded to western and southern sites (Manfredi, Anguil, and Tres Arroyos), showing lower precipitation levels and soils depth when compared to the rest of the sites (Table 3, Fig. 1). This is also in agreement to the lower RT index values (Fig. 3A, Fig. S3). Maximum yield ranged from 8402 to 16,788 kg ha^{-1} across sites (Table 3, Fig. 3B), indicating the high potential under no water and N limitations. Minimum yield varied from 1076 to 2882 kg ha^{-1} across sites (Table 3, Fig. 3B).

3.3. Classification of environmental types

Clustering of 329 RT trajectories indicated three major groups or ENVT, explaining 74% of the total sum of squares (dendrogram not shown). Defined ENVT varied mainly in timing and intensity of stress, and were identified as (i) a pre-anthesis stress that was relieved during grain filling, showing a frequency of occurrence of 39%, (ii) a low terminal stress, showing 38% of frequency, and (iii) a stress during grain filling, which was evidenced in 23% of the years (Fig. 4A, Fig. S4). Both pre-anthesis and grain filling stresses evidenced moderate stress levels around anthesis (RT ~ 0.6; Fig. 4A).

Fig. 4B describes the frequency of yield distribution for each ENVT. The low stress ENVT evidenced the higher yield levels, while the lowest yields were observed at the pre-flowering stress ENVT (Fig. 4B). Grain yield at low stress ENVT was always higher than 6000 kg ha^{-1}, while this level of yield was observed in 55% of the seasons showing pre-flowering stress ENVT. This frequency was less than 40% when the stress was during grain filling (Fig. 4B).
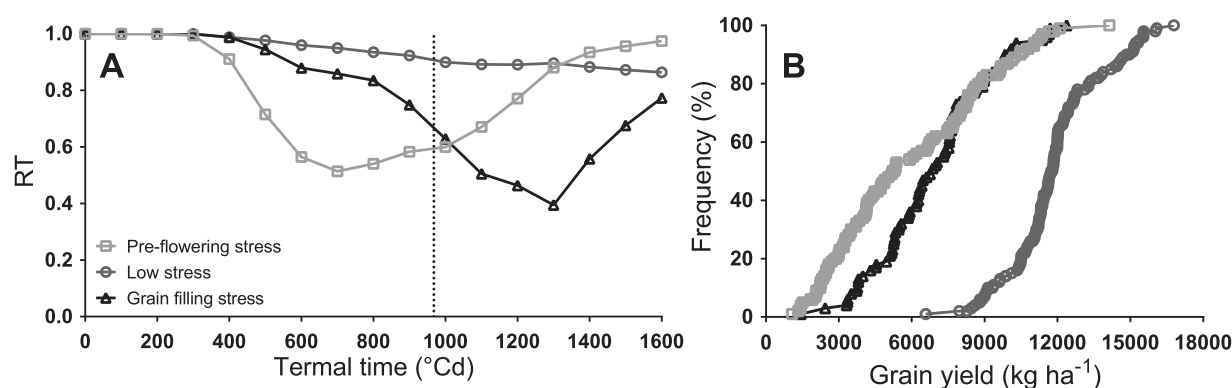
Fig. 4. (A) Mean RT index throughout the crop life for the clustered seasons. The dashed line indicates the mean flowering date. The RT index throughout the crop life cycle for all the seasons for each cluster is shown in Fig. S4. (B) Cumulative simulated grain yields frequencies for all seasons in each ENVT.
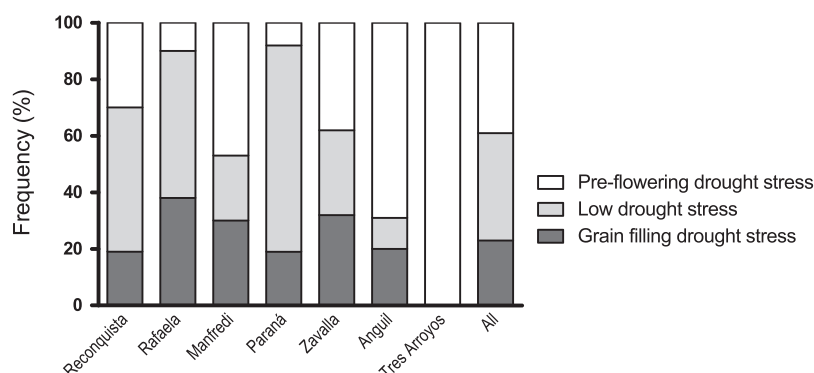

Fig. 5. Frequency distributions of the three ENVT within and across the 7 sites.

The frequency of occurrence of each ENVT varied considerably among sites (Fig. 5). For the southern sites (Anguil and Tres Arroyos), the pre-flowering stress ENVT was the most common (69% and 100% of frequency, respectively). Northeastern sites (Reconquista, Rafaela and Paraná) presented a high frequency of low stress ENVT (51%; 52% and 73%, respectively). Zavalla shows ENVT frequencies similar to the across-sites ENVT distribution, followed by Manfredi (Fig. 5). The grain filling stress ENVT showed a frequency from 0 to 38% across different sites, evidencing less variation compared to pre-flowering and low stress ENVT.

3.4. Heat stress frequency and its association with drought stress ENVT

The frequency of occurrence of extreme temperatures decreases from northern to southern sites (Table 5). Northeastern sites (Reconquista, Rafaela, and Paraná) showed intermediate frequency (~30 to 50%) of temperatures above 33 °C for more than 4 days during the critical window, while the probability of less days with temperatures above this threshold was lower (~10-20%). Zavalla and Manfredi showed an intermediate frequency (~30%) of experiencing one day with temperatures above 33 °C, while the frequency of more days with temperatures higher than 33 °C was low (less than 16%). Southern sites (Anguil and Tres Arroyos) evidence similar probability (and less than 14%) of having any number of days with temperatures above 33 °C (Table 5).

The frequency of years experiencing more than 4 days with maximum temperatures above 33 °C was not clearly associated with any ENVT (Table S2), although it tended to be more frequent during grain filling drought stress (Fig. 6A). This was particularly true for northeastern sites (Reconquista, Rafaela, and Paraná; Fig. 6A).

Most sites with the exception of southern sites showed some frequency of one day with temperatures above 36 °C, albeit this probability was low (15–20%). The probability of experiencing more than 2

Table 5
Probability of years experiencing different number of days with temperature above different thresholds (33, 36 and 38 °C) during 150 °C d, starting 50 °C d before anthesis, for different sites across the Argentinian central region.

Location	Temperature threshold (°C)	Days				
		1	2	3	4	> 4
Reconquista	33	9	19	9	13	49
	36	15	19	11	6	6
	38	19	2	4	2	0
Rafaela	33	10	9	17	9	45
	36	14	7	3	12	10
	38	5	10	5	0	2
Paraná	33	14	8	22	8	31
	36	14	7	2	3	2
	38	8	0	0	0	0
Manfredi	33	28	11	9	2	6
	36	6	2	0	0	2
	38	4	0	0	0	2
Zavalla	33	30	14	16	14	2
	36	20	2	2	0	0
	38	7	0	0	0	0
Anguil	33	13	14	7	3	13
	36	13	6	0	6	3
	38	4	3	0	0	0
Tres Arroyos	33	8	5	8	3	5
	36	0	3	0	0	0
	38	0	0	0	0	0

days with temperatures above this threshold was low for most sites, ranging from no probability in southern sites to some frequency when moving to lower latitudes (Table 5). The frequency of years with more than 4 days with temperatures above 36 °C was very low but mostly associated with pre-flowering and grain filling drought stresses (Fig. 6B).
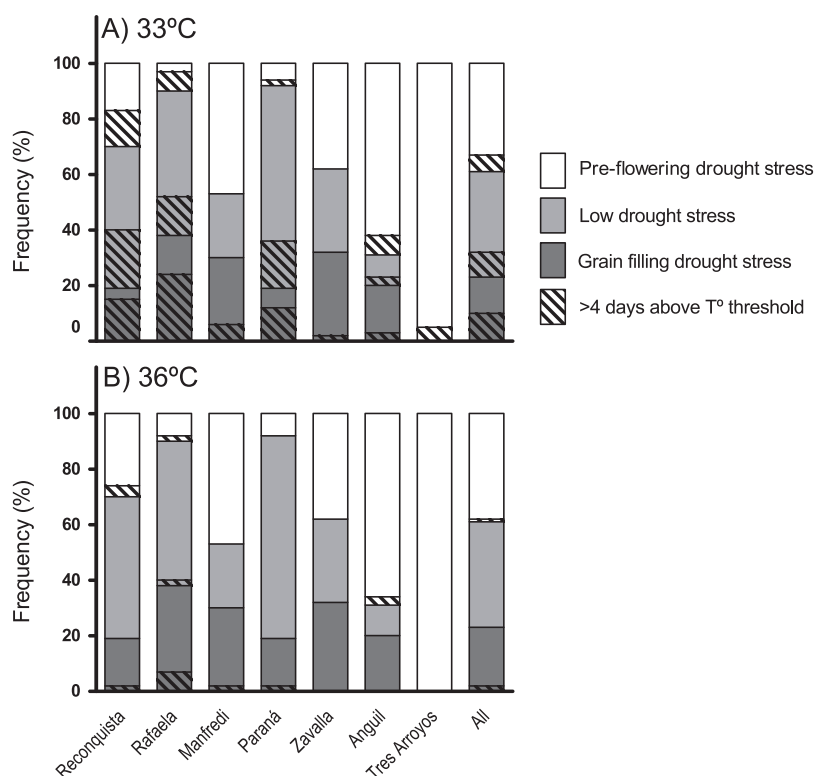
Fig. 6. Frequency distributions of the three ENVT within and across the 7 sites. In each bar, the proportion of years having days with maximum temperature above the threshold (A, 33 °C; B, 36 °C) around flowering is shown for each ENVT.

Only at Reconquista the probability of experiencing one day with temperatures above 38 °C showed low frequency (~20%), while this frequency was less than 10% or null for the rest of the sites (Table 5). In general, the frequency of undergoing two or more days with temperatures above 38 °C was less than 10% in most sites, being null in most cases when moving to higher latitudes (Table 5). For these reason, the frequency of years experiencing more than 4 days with temperatures above 38 °C was not clearly related to any ENVT (not shown).

3.5. Drought environmental types and GxE interaction

The frequency of occurrence of each ENVT in observed experiments ranked similarly to simulated values across the different combinations of sites and seasons, being 52% of the experiments classified as pre-flowering stress, 40% as low stress, and 8% as grain filling stress. Average yield was 7657 kg ha^{-1} for the low stress ENVT, 7560 kg ha^{-1} for pre-flowering stress ENVT, and 6600 kg ha^{-1} for grain filling stress ENVT.

Classified ENVT explained part of the GxE interaction for yield (Fig. 7). The late maturity genotype VDH422 performed relatively better at seasons classified as pre-flowering stress ENVT (Fig. 7). This genotype reached anthesis once the pre-flowering stress was relieved (Fig. S5). The short maturity genotype ADV114 performed well at seasons classified as low stress ENVT (Fig. 7). The relative low performance of this material under pre-flowering stress ENVT is associated with the coincidence of the water stress with the critical flowering period of yield definition (Fig. S5). In agreement to this, mean RT values during the critical flowering period was 0.63 for VDH422 and 0.56 for ADV114 under seasons classified as pre-flowering ENVT. The intermediate maturity VDH314 showed good performance in most ENVT.

4. Discussion

Argentinean area with sorghum has decreased during the last years

(FAOSTAT, 2018). The presence of more profitable crops like maize and soybean, the low genetic gain of sorghum when compared to other crops (Gizzi and Gambin, 2016; Luque et al., 2006; de Felipe et al., 2016), and the absence of transgenic technology - which provides easy solutions for weeds and pests management - are among the main reasons behind the reduction in sorghum adoption by farmers. In this context, we provided a characterization of the water and temperature stress patterns for the Argentinean central region. This characterization is new in the region and offers valuable information to assist crop breeding, through better defining the target population of environments or ENVT (Chapman et al., 2000a). The information will also assist crop management, finding the best combination of GxM for particular ENVT (Hammer et al., 2014).

The Argentinean sorghum central region is characterized by three major drought stress patterns or ENVT, differing mainly in the timing of stress: (i) a pre-flowering stress showing 39% of occurrence, (ii) a terminal low stress showing 38% of occurrence, and (iii) a less frequent grain filling stress (23%). Both pre-flowering and grain filling stress ENVT showed moderate intensity (averaging minimum RT values of 0.4; Fig. 4A). The intensity of stress ranging from low to moderate values was expected under these temperate environments, characterized by higher rainfall levels and deeper soils compared with other regions of the world like Australia (Chapman et al., 2000a; Hammer et al., 2014). Based on shorter maturity genotypes, the Australian sorghum belt is characterized by post-flowering water stress with higher stress intensities (RT values less than 0.25) (Chapman et al., 2000a). As reported by Chapman et al. (2000a), defined ENVT discriminated water stress patterns and yield levels more clearly than when these traits were analyzed by site (Fig. 4 versus Fig. 3), demonstrating the importance of an environmental characterization.

The contrasting defined ENVT are in accordance with the high observed GxE interaction for yield (Carcedo et al., 2017; Fig. 7). For this region, seed companies usually recommend intermediate maturity genotypes at normal sowing dates, which is in agreement with the
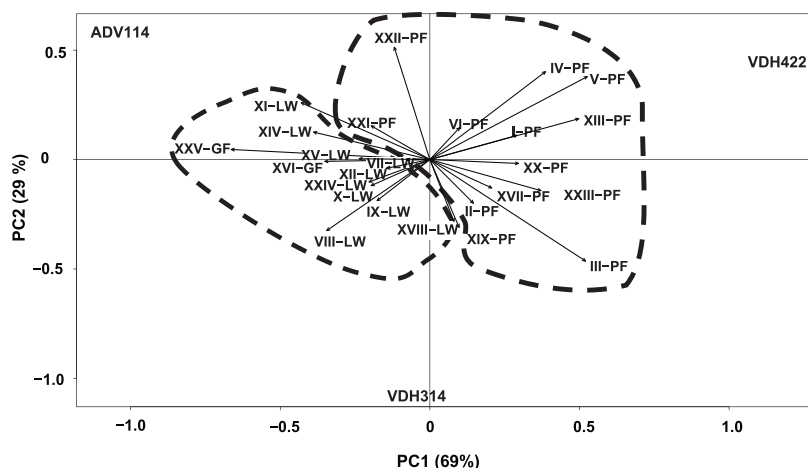
Fig. 7. AMMI biplot of the first and second principal components for grain yield of three genotypes (ADV114, short maturity; VDH314, intermediate maturity; VDH422, late maturity) grown in 25 environments (details of experiments in Table S1). Genotypes are represented by bold letters and environments by vectors. Environments belonging to pre-flowering stress ENVT and low terminal stress ENVT are enclosed in dashed lines. PF is pre-flowering stress, LW is low terminal stress, GF is grain filling stress.

relative better performance of this maturity across different ENVT (Fig. 7). Short and late maturity genotypes are also available options in this region, and we showed that each type of maturity is ideal for particular ENVT. Late flowering allows a drought escape of the critical flowering window under a pre-flowering stress ENVT, while a short maturity genotype would match water stress with the critical flowering period of yield definition. This means that maturity is a relevant genotypic trait that can be adjusted accordingly to the particular ENVT. Sowing date will also be a relevant management trait. Delaying the sowing date, for example, could help to escape a pre-flowering stress.

In general, the most frequent ENVT at individual sites was in agreement with the spatial distribution of annual rainfall. Sites with high frequency of pre-flowering stress ENVT (more than 60%, like Anguil and Tres Arroyos) were located under the 750 mm isohyet (below the 36° latitude; Telesca et al., 2012). Sites with high frequency of low stress ENVT (more than 50%, like Reconquista, Rafaela, and Paraná) were above the 1000 mm isohyet. These sites also evidence more favorable soil water-holding capacity. Despite this, and with the exception of Tres Arroyos, all the ENVT were represented at all sites (Fig. 5). This certainly complicates any breeding process, as testing trials at particular sites or seasons might not be representing the target population of environments. It has been shown that this could decrease or even reverse genetic gains (Cooper et al., 1996). In this particular case, it could partially explain the low national genetic gain of this species (Gizzi and Gambin, 2016). The weighting strategy of selection trials would be relevant to improve selection efficiency (Chapman et al., 2000b).

Defining the frequency of occurrence of seasonal drought stress patterns provides relevant information to breeding programs when defining target locations for broad or specific adaptation (Chapman et al., 2000a; Chenu et al., 2011). Sites as Zavalla or Manfredi showed ENVT frequencies similar to the across sites-seasons frequency, indicating that these sites are suitable to be used in a broad selection program. Tres Arroyos or Anguil are ideal locations for breeding for pre-flowering stress, while Paraná is not an ideal site for this purpose. An additional benefit of the analysis includes grouping sites of similar frequencies, reducing costs and increasing the efficiency of a breeding program (Chapman et al., 2000a).

Heat stresss around flowering in sorghum could significantly decrease yield through reducing seed set (Prasad et al., 2006, 2015, Singh et al., 2015, 2016). In our study, different maximum critical temperatures were explored, as temperature threshold affecting grain set has been shown to be genotypic-dependent (Singh et al., 2015). We showed that a heat stress duration of significant magnitude (more than 4 days; Prasad et al., 2015) with temperatures above 33 °C around the flowering period is relatively low (ca. three out of ten years), and that this probability is importantly reduced for temperatures above 36 °C

(Fig. 6), being particularly null for temperature above 38 °C. We concluded that heat stress is currently not a major constraint for the region, although heat stress is expected to become more frequent under future climate scenarios (i.e., average temperatures are likely to rise by 0.5–2.5 °C by 2100; IPPC, 2007). Critical threshold temperatures for our materials are unknown, but this information would be relevant for genotypes frequently used at lower latitudes, where the frequency of heat stress is higher.

The frequency of more than four days with maximum temperatures above a particular threshold was not consistently associated with any drought ENVT. The lack of association is probably linked to the fact that we explored direct effects of heat stress, not indirect effects through increasing vapor pressure deficit and water stress (Lobell et al., 2015). Although heat and drought stress often occur together, it is possible and relatively common to get one without the other (e.g., Sadras et al., 2012). Distinguishing between yield risks associated with drought and heat become useful when defining breeding and management strategies (Lobell et al., 2015). Sites showing very low or null heat stress, as Zavalla, become of interest for breeding particularly for drought stress. By contrast, the frequency of more than 4 days with temperature above 33 °C was higher during seasons showing grain filling drought stress at northern sites (Reconquista, Rafaela, and Paraná) (Fig. 6). This means that breeders will be probably selecting for both water and heat stress under seasons showing grain filling stress at the northern part of the region.

Finally, APSIM-sorghum model has been tested for particular genotypes and growing conditions, offering the opportunity for exploring in silico GxExM combinations of interest. The model could be used for defining ideal genotype x management combinations in target environments (Hammer and Jordan, 2007). In our context, genotype maturity in combination with sowing date appear to be relevant management variables under defined ENVT. Nevertheless, all in silico data are predictions and are subject to error. One evident weakness of the analysis is that the model was not tested for relative transpiration.

5. Conclusions

Under the typical sowing window, the temperate Argentinean central region is characterized by intermediate to low water stress levels, differing mainly in the timing of stress. Heat stress around flowering showed intermediate frequency at the lower latitudes, and no clear association with ENVT was found. Moreover, described ENVT helped explain observed GxE interactions for yield, providing relevant information for defining target population of environments, sites for testing trials, and future target genotype traits or crop managements in accordance to ENVT probabilities.

Grouping sites of similar ENVT frequency can help to handle the

spatial variability. Due to the large variability in the frequencies of ENVT shown by the studied sites, large yield improvements can be reached when seeking specific GxM combinations. Optimum plant type and management combinations for each scenario will need additional research. Nevertheless, dealing with seasonal variability will be challenging in the context of no predominant ENVT.

Acknowledgments

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fcr.2019.06.009.

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