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Drought stress characterization of post-rainy season (*rabi*) sorghum in India

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ABSTRACT

During the post-rainy (*rabi*) season in India around 3 million tonnes of sorghum grain is produced from 5.7 million ha of cropping. This underpins the livelihood of about 5 million households. Severe drought is common as the crop grown in these areas relies largely on soil moisture stored during the preceding rainy season. Improvement of *rabi* sorghum cultivars through breeding has been slow but could be accelerated if drought scenarios in the production regions were better understood. The sorghum crop model within the APSIM (Agricultural Production Systems sIMulator) platform was used to simulate crop growth and yield and the pattern of crop water status through each season using available historical weather data. The current model reproduced credibly the observed yield variation across the production region ($R^2 = 0.73$). The simulated trajectories of drought stress through each crop season were clustered into five different drought stress patterns. A majority of trajectories indicated terminal drought (43%) with various timings of onset during the crop cycle. The most severe droughts (25% of seasons) were when stress began before flowering and resulted in failure of grain production in most cases, although biomass production was not affected so severely. The frequencies of drought stress types were analyzed for selected locations throughout the *rabi* tract and showed different zones had different predominating stress patterns. This knowledge can help better focus the search for adaptive traits and management practices to specific stress situations and thus accelerate improvement of *rabi* sorghum via targeted specific adaptation. The case study presented here is applicable to other sorghum growing environments.

1. Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is the fifth most important cereal crop world-wide (http://apps.fao.org/default.jsp) as well as an important source of feed, fibre, and biofuel (Doggett, 1988). Sorghum is well adapted to drought environments compared to other cereals (e.g. see reviews by Doggett, 1988; Ludlow and Muchow, 1990; Mullet et al., 2001; Sanchez et al., 2002; Borrell et al., 2006), making it suitable for semi-arid tropical (SAT) agricultural production systems. Sorghum is considered a staple food grain for some of the world's poorest and most food-insecure people across developing countries of Asia and Africa (Murty et al., 2007).

Across India, around 3 million tonnes of sorghum grain is produced from 5.7 million ha during the post-rainy (*rabi*) season (Project Directorate for Farming Systems Research database (www.pdfsr.ernet.in), www.indiastat.com, Murty et al., 2007). The stover is also highly valued as a livestock feed (Blümmel and Rao, 2006). The majority of *rabi* sorghum stover and grain production is concentrated in districts across the states of Maharashtra, Karnataka and Andhra Pradesh (Trivedi, 2008; Rana et al., 1999; Hosmani and Chittapur, 1997; Murty et al., 2007; Pray and Nagarajan, 2009, see Fig. 1). The *rabi* cropping season follows the hot, wet rainy season (*kharif*) and is characterized by limited rainfall, cooler average temperature and shorter days, resulting in lower potential crop evapo-transpiration (Fig. 2). After the rainy season, the soil profile is fully charged with moisture to support the *rabi* crop. However, the frequent occurrence of shallow Entisol and Vertisol soils across the production area limits the antecedent moisture storage capacity often resulting in exhaustion of available moisture early in the crop cycle leading to limited grain and stover production (Murty et al., 2007; Kassahun et al., 2010). The nature of crop water stress in this region has been described as "terminal drought" with variable timing of onset during the crop cycle (e.g. Kassahun et al., 2010; Murty et al., 2007; Sajjanar et al., 2011). However, no attention has been paid to quantifying the detailed nature of these drought patterns across seasons. A better analysis of drought patterns would aid in focusing crop improvement efforts towards

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Abbreviations: S/D, supply demand ratio; APSIM, agricultural production systems simulator.

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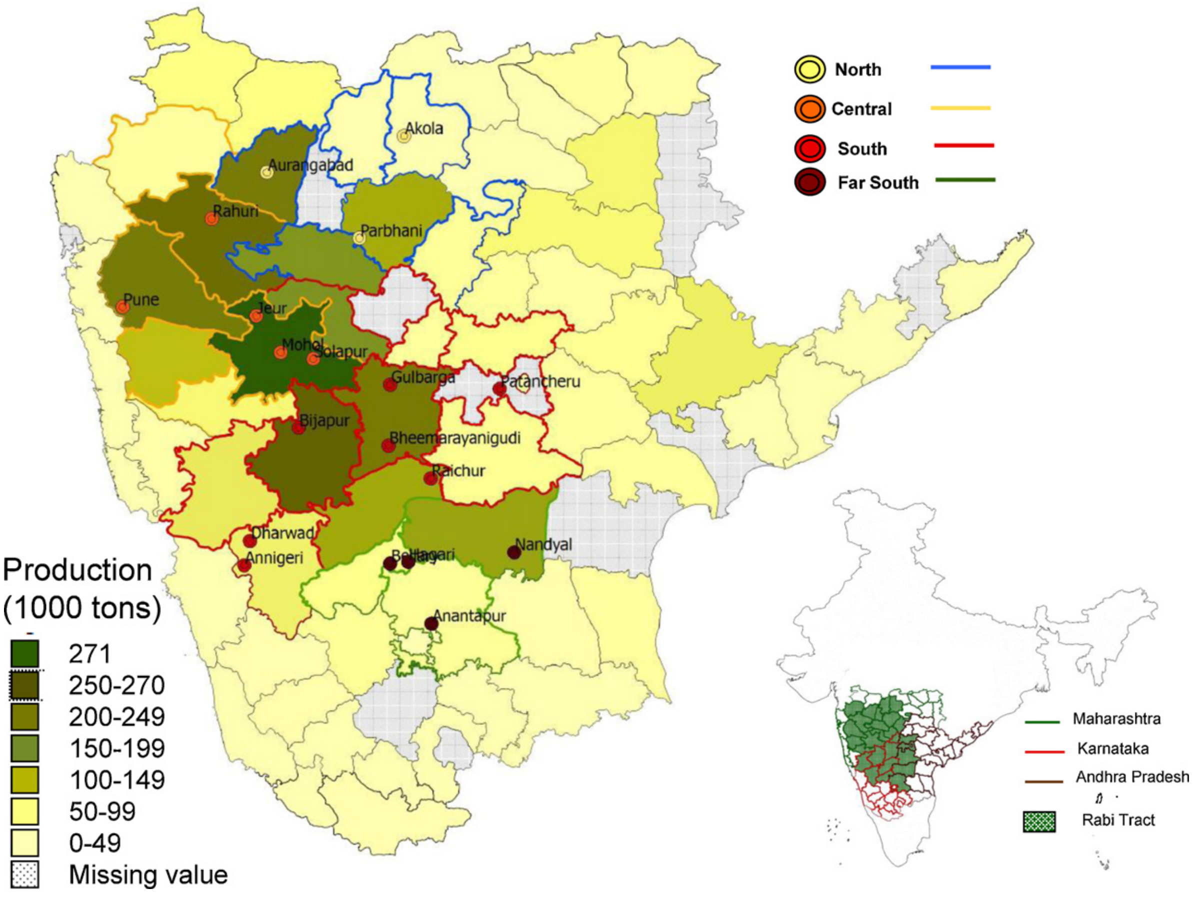

Fig. 1. Map of the sorghum *rabi* production tract in India with highlighted four major production zones – Central, Northern, Southern and Far South. The inset map shows the location of the Indian states (Maharashtra, Karnataka and Andhra Pradesh) and the major *rabi* tract. The main map shows the level of average total grain production in the *rabi* sorghum areas and the location of the 19 weather stations used in the simulation analysis.

combinations of genotype and management that are most suited to specific drought patterns. Improved knowledge on stress patterns may, in fact, prove crucial in the current situation where water availability is extremely limited while food and fodder demands rise (Blümmel and Rao, 2006; Balota et al., 2008; Chenu et al., 2011).

Lack of knowledge on drought stress scenarios is, at least partially, caused by the obvious difficulties in generating sufficient field experimental data to capture the dynamics of crop water status over a sufficient number of years to credibly classify stress categories. There is, however, an emerging capability for characterizing crop stress environments across broad regions, management practices, and crop cultivars via crop modelling. The modelling approach has been used previously to characterize water stress patterns in sorghum (Hammer and Jordan, 2007; Chapman, 2008) and wheat (Chenu et al., 2011) across Australia. In those studies the concept of a crop water status index based on the ratio (S/D) of potential soil water uptake (supply, S) to crop transpiration demand (D) was introduced as a pragmatic way to evaluate and classify the water stress environment experienced by the crop through its life cycle. However, the virtual crop model can be useful only if it sensibly reflects the real situation in farmers' fields and therefore requires knowledge on local management practices, good estimates of regional soil properties, and reliable weather records.

The aim of this study was to characterize the type of water stress patterns experienced by *rabi* sorghum crops across the major production area in India. We use the sorghum model (Hammer et al., 2010) and soil water balance within the cropping system simulation platform APSIM (Keating et al., 2003) to simulate patterns of crop water status through the crop cycle at representative sites using the soil characteristics and local field management practices for those areas.

2. Materials and methods

2.1. Overview

The cropping area contributing the majority (around 75%) of the Indian *rabi* sorghum grain production was identified using long term district production and yield averages from 1966 to 2007 (Project Directorate for Farming Systems Research database (www.pdfsr.ernet.in), www.indiastat.com). This included districts in the states of Maharashtra, Karnataka, and Andhra Pradesh (Fig. 1), in which on average 2.26 million tonnes of sorghum grain was produced from 4.43 million ha. This distribution was consistent with that noted previously by Rana et al. (1999), Hosmani and Chittapur (1997), and Murty et al. (2007). This "*rabi* sorghum belt" was divided into four production zones based on similarities in their geographical position, average yields, and similarity in broad environmental conditions (Table 1). Within these zones, historical weather records from 19 weather stations were collated from available databases (Indian Meteorological Department in Pune). The number of years of data available at each location ranged from 8 to 36. Soil properties for key production areas were collated from available databases (National Bureau of Soil Survey and Land Use Planning, International Soil Reference and Information Centre). Crop simulations were conducted for the key locations in each production zone, using the sorghum model in APSIM (version 7.3; Keating et al., 2003; Hammer et al., 2010) and local

Table 1
Characteristics of the four major production zones in the *rabi* sorghum belt. Within each zone, key locations with available weather records are listed along with the number of years of data available. The representative soil type, soil depth and plant available water content (PAWC) are given for each location.

Zone	Average production (in thousands tonnes)	Average area (in thousands of ha)	Average yield (kg ha^{-1})	Weather station (years)	Soil PAWC (mm)	Representative soil site/soil depth (cm)	Soil type
Central	826	1976	459	Jeur (25)	62.8	Solapur/50	Clayey Entisol, montimorillontic, isohyperthermic, Lithic ustorthents
				Mohol (23)	62.8	Solapur/50	
				Pune (36)	68.9	Solapur/55	
				Rahuri (20)	62.8	Solapur/50	
				Solapur (23)	62.8	Solapur/50	
South	659	1159	583	Bheemarayanigudi (8)	68.9	Solapur/55	
				Bijapur (12)	68.9	Solapur/55	
				Gulbarga (24)	68.9	Solapur/55	
				Patancheru (28)	98	Patancheru/70	Vertosol, mixed, Typic Rhodustalfs
				Annigeri (24)	73.1	Bellary/65	Vertosol, sodic haplustert, nontmorillonitic, isohyperthermic
				Dharwad (21)	73.1	Bellary/65	
				Raichur (10)	73.2	Raichur/60	Clayey skeletal Entisol, Typic haplustert
North	504	899	590	Akola (23)	85	Parbhani/75	Clay vertosol, montmorillonitic, isohyperthermis, calcareous, Typic chromusterts
				Aurangabad (25)	73.5	Parbhani/65	
				Parbhani (27)	85	Parbhani/75	
Far South	199	270	756	Anantapur (33)	91.4	Raichur/75	Clayey skeletal Entisol, Typic haplustert
				Nandyal (8)	97.4	Raichur/80	
				Hagari (23)	73.1	Bellary/65	Vertosol, sodic haplustert, nontmorillonitic, isohyperthermic
				Bellary (23)	73.1	Bellary/65	

management practices. The trajectory of the simulated crop water status index (water supply/demand ratio; S/D) through the crop cycle was captured in each instance and cluster analysis performed to identify the major drought patterns experienced. The incidence of particular stress types was quantified for each of the production zones and across the entire *rabi*-belt by weighting frequencies in each zone in relation to average production contributed from that zone. The associations between stress pattern and simulated grain and stover yields were examined. To evaluate the production potential of each zone simulations were also conducted assuming un-restricted water and N supply.

2.2. *Location, environmental data, and crop attributes*

Weather records for sites representative of each production zone were obtained from the Indian Meteorological Department in Pune. Nineteen weather stations across the Northern, Central, Southern and Far South zones were employed with a total of 404 years of historical records of daily minimum and maximum temperatures, rainfall, and radiation (Fig. 1 and Table 1). Information on soil characteristics was obtained from the National Bureau of Soil Survey and Land Use Planning (NBSS & LUP) in Bangalore, and the International Soil Reference and Information Centre (ISRIC). Five soil types were selected to represent the heterogeneity of geo-morphological units within the *rabi* production area. The soil depth used for simulations at each site was the estimated average soil depth across the district surrounding the particular weather station.

District level historical *rabi* sorghum production data were obtained from Project Directorate for Farming Systems Research database (www.pdfsr.ernet.in), and IndiaStat (www.indiastat.com). The districts' average yield records were used for initial separation of the main production area into 3 significantly different zones. Further the geographical position and soil type and qualities, were used to finalize the compartmentalization of the area of the *rabi*-belt into four production zones (Northern, Central, Southern and Far South; Northern and Southern regions had similar yield averages however geographical location and soil qualities differed).

Field management practices were assumed to reflect the generally accepted recommendation package for *rabi* sorghum cultivation (Trivedi, 2008; Rana et al., 1999; Hosmani and Chittapur, 1997). The most common sorghum cultivar grown is M35-1 (known locally as *maldandi*) due to its traditionally and culturally accepted grain and stover qualities. The crop is usually sown within a short planting window extending from the end of September through the first half of October. The actual sowing time in this period is determined by rainfall occurrence to facilitate successful emergence and early crop growth. Nearly all *rabi* sorghum is grown dryland and relies on stored moisture from the preceding rainy season and erratic precipitation, mainly early in the growing season (Fig. 2). As *rabi* sorghum stover is a valuable product as livestock fodder, the plant population recommended is high and ranges between 10 and 14 plants per m^2. To support effective crop growth and development, application of 20 kg urea ha^{-1} at sowing and 20 kg urea ha^{-1} at 27–30 days after sowing is recommended (Trivedi, 2008; Rana et al., 1999; Hosmani and Chittapur, 1997).

2.3. *Crop simulation*

Simulations were undertaken using the APSIM sorghum model at each location with the available historical weather data and relevant crop management practices. The *maldandi* sorghum type was represented by the M35-1 genotype, which had been previously extensively studied, parameterized and validated within the APSIM platform (Hammer et al., 2010; Ravi Kumar et al., 2009). Simulations were run at all sites assuming the *rabi* crop was planted following a fallow through the preceding monsoon season, which allowed accumulation of stored soil water. The sowing window was set as 25 September to 15 October and a minimum of 9 mm rain within 5 days was required to trigger sowing. If these requirements were met, the M35-1 genotype was sown at the density of 12 plants m^{-2} with an application of 20 kg urea ha^{-1} at sowing and further 20 kg urea ha^{-1} 30 days after sowing. For simulating production potential at each site, irrigation was added whenever the available soil moisture in the top 50 cm of the profile fell below 50% of that potentially available, and urea was applied at the rate

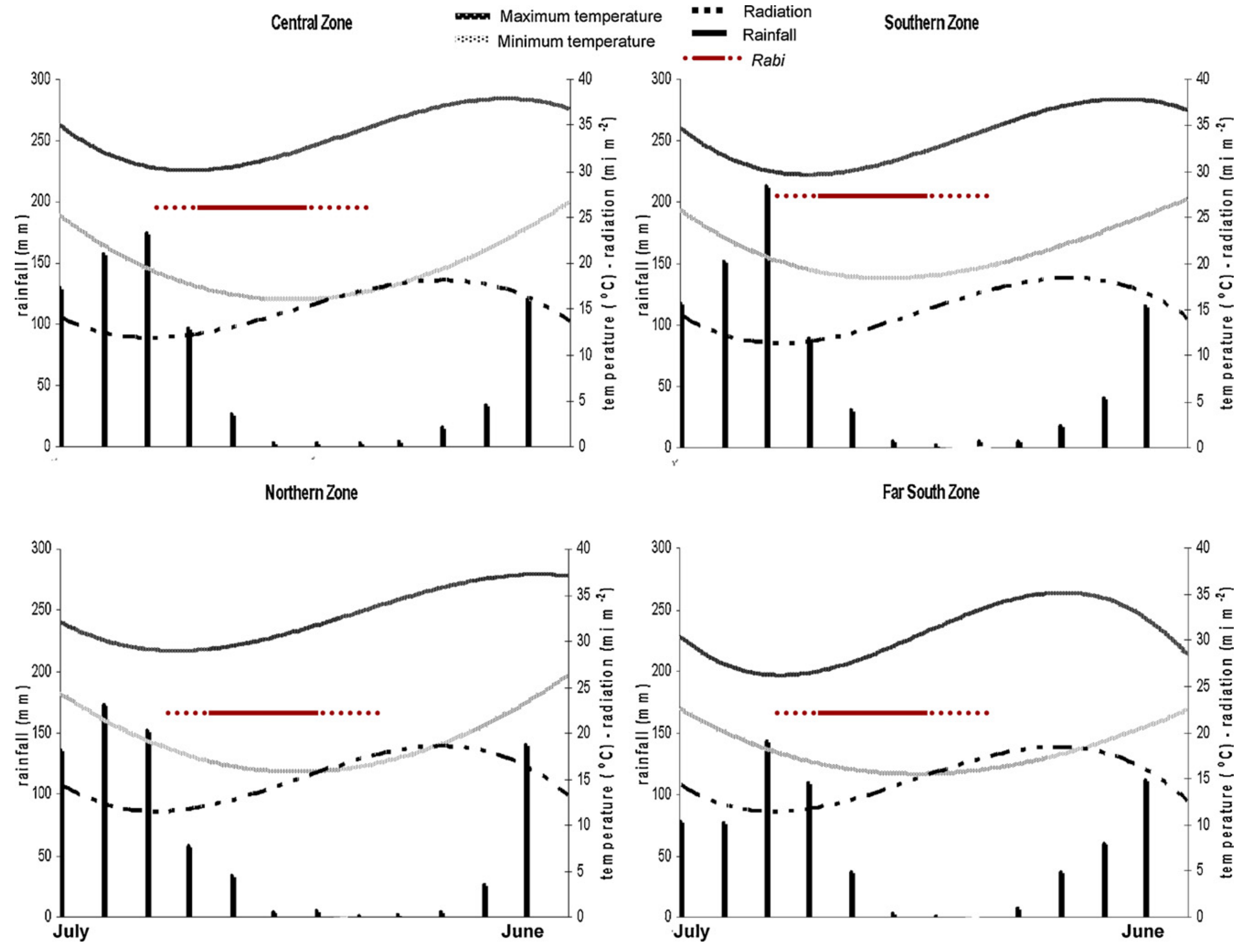

Fig. 2. Average monthly climatic conditions for four key sites representing the four production zones in the *rabi* sorghum tract; Sholapur – central zone, Gulbarga – southern zone, Aurangabad – northern zone and Anantapur – far south zone. The duration of the *rabi* season is indicated (dotted part of the line indicates the sowing/harvest window).

of 50 kg urea ha^{-1} at sowing and 100 kg urea ha^{-1} at 30 days after sowing.

For each crop simulated, the initial soil water status at sowing, the progression of crop water status through the growing season, grain and biomass yield, and other crop attributes (e.g. leaf area) were documented. To examine model fidelity, Albeit crudely gave the differences in spatial scale, the simulated average yield at a site was compared with the observed district yield average.

The nature of the water stress experienced by the crop was quantified by the simulated trajectory of the water supply/demand (S/D) ratio through the crop season (Chapman, 2008; Chenu et al., 2011). The water S/D ratio takes values between 0 and 1 reflecting the balance between potential soil water uptake by the crop (supply, S) and plant transpiration demand (demand, D) during its growth. Therefore, this ratio can be used as an indicator of crop water status, ranging from conditions of no limitation (S/D = 1; uptake from the soil fully meets transpiration demand) to complete limitation with no transpirable water available (S/D = 0). Investigated genotype M35-1, though photoperiod sensitive (Ravi Kumar et al., 2009), was planted during a narrow sowing window and showed conservative values of time to flowering (around 830 °C d (degree-day)) across environments. Therefore, simulated values of S/D ratio were averaged for each 100 °C d interval through the crop cycle from emergence to crop maturity. Thermal time was calculated using the temperature responses for crop development determined for sorghum (Hammer et al., 2010; Hammer and Muchow, 1994).

A set of simulated trajectories of crop water status through the life cycle was derived from the simulations across the *rabi* sorghum belt. The trajectories were subjected to cluster analysis in a manner similar to that of Chenu et al. (2011) using R software (R Development Core and Team, 2008) to identify the nature and prevalence of particular trajectories within the production zones. The frequency of each season type identified, and effects on simulated average grain and biomass yields, were examined for each production zone in the *rabi*-belt.

3. Results

3.1. Simulated site yields, district average yield, and simulated potential yield

Despite the fact that site yields were simulated using weather records from only a small number of locations within each zone, the average yields across years for the available sites correlated well ($R^2 = 0.73$) with the district average yield recorded across the same years of available data (Fig. 3 and Table 2). This indicated that the model captured the spatial variability in average productivity across districts well, i.e. the districts belonging to the central production zone were predicted to have the lowest average yield across seasons (617 kg ha^{-1}), whereas the yield of districts within North and South zones yielded comparably higher (917 and 945 kg ha^{-1}, respectively) and districts in the far south zone had the highest predicted yield (1190 kg ha^{-1}). Since similar field management

Table 2
The analysis of environment types in the *rabi* sorghum belt showing the frequency of each particular drought stress pattern in each production zone, along with average simulated total biomass and grain yield for each environment type in each zone. For each production zone, the average productivity across all environment types and the potential productivity with unrestricted water and N supply are also given. Values for the whole *rabi* tract were derived using weighted means across zones based on proportion of total production within each zone. Numbers in parentheses are the 1st and 3rd quartile values for the associated average value.

Production zone	Characteristic	Terminal droughts			Post-flowering relieved stress	Mild stress	Zone average	Zone potential
		Vegetative stress	Pre-flowering stress	Post-flowering stress				
Central	Pattern frequency (%)	15	16	15	18	37	–	–
	Biomass (kg ha^{-1})	2198 (1911, 2341)	2444 (2278, 2720)	3192 (2574, 3301)	3115 (2342, 3866)	2778 (1891, 3093)	2756 (2111, 3049)	8279 (6689, 9289)
	Yield (kg ha^{-1})	66 (0, 0)	174 (0, 376)	819 (538, 817)	883 (560, 1266)	860 (523, 1009)	617 (236, 867)	3014 (2608, 3350)
South	Pattern frequency (%)	9	15	16	26	34	–	–
	Biomass (kg ha^{-1})	3212 (2978, 3471)	3620 (3176, 4254)	4294 (3406, 4673)	4006 (3052, 5016)	3620 (2773, 5016)	3792 (2985, 4536)	8613 (10138, 7477)
	Yield (kg ha^{-1})	196 (0, 461)	445 (0, 786)	1110 (762, 1165)	1095 (779, 1336)	1173 (767, 1555)	945 (589, 1290)	3166 (2905, 3565)
North	Pattern frequency (%)	5	23	21	11	41	–	–
	Biomass (kg ha^{-1})	2594 (2519, 2709)	3198 (3051, 3458)	4269 (3623, 4833)	3748 (2766, 4361)	3408 (2686, 4255)	3545 (2786, 4224)	8714 (9650, 7430)
	Yield (kg ha^{-1})	0 (0, 0)	456 (153, 673)	1238 (988, 1636)	1205 (701, 1398)	1063 (605, 1512)	917 (515, 1307)	3213 (2906, 3496)
Far South	Pattern frequency (%)	4	13	16	16	52	–	–
	Biomass (kg ha^{-1})	3145 (2906, 3340)	3445 (3157, 3702)	4152 (3555, 4445)	3892 (3269, 4194)	3580 (3078, 4182)	3671 (3176, 4206)	6956 (8075, 4449)
	Yield (kg ha^{-1})	314 (230, 471)	570 (209, 886)	1405 (1165, 1543)	1286 (1078, 1506)	1324 (1096, 1414)	1190 (934, 1490)	2704 (1729, 3079)
Whole rabi-belt (weighted means)	Pattern frequency (%)	7	18	18	17	40	–	–
	Biomass (kg ha^{-1})	2614	3005	3831	3561	3216	3354	8334
	Yield (kg ha^{-1})	128	447	1190	1156	1128	847	3068

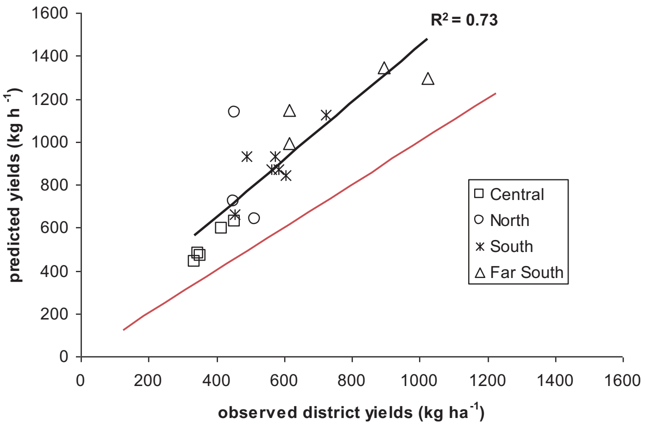

Fig. 3. Relationship between simulated average sorghum yield at specific sites and associated average district yield for sites within central, northern, southern and far-south production zones, respectively.

practices were used, this variability was caused by differences in soil qualities and rainfall patterns among the zones. Correlation analysis suggested that regional yield was highly responsive to soil water holding properties (data not shown). The tight correlation between predicted and observed yield indicates that the model was appropriately sensitive to these effects and was thus suitable for use to characterize stress patterns. The higher absolute values found for site average yield compared to district level observations (Fig. 3) reflect the comparison of point simulation to data averaged across a broad area. A 1:1 fit would not be expected across these differing scales due to inability of the point simulations to capture the spatial heterogeneity in soil and management practice.

3.2. Drought stress patterns

The trajectories of S/D ratio through the crop cycle were extracted from each simulated season as shown for the example of Solapur in Fig. 4. The cluster analysis across all such trajectories revealed five distinct environment type groups for the *rabi* sorghum tract (Fig. 5). Despite the finding that the soil profile held more than 90% of total water holding capacity at the beginning of the *rabi* season (data not shown), a majority of the seasons showed water limitations on crop growth. The dominant stress environments of the *rabi*-belt had the character of terminal drought and comprised either “vegetative” terminal stress with early onset during the vegetative stage of plant growth (500–600 °C day after emergence), “pre-flowering” terminal drought starting in a tight period before anthesis (700–800 °C day after emergence) and a “post-flowering” onset cluster of terminal drought patterns with a steep decline in S/D after 800 °C day after emergence. The other two environment types were a post-flowering type of stress that was relieved during grain filling, and a generally low stress environment throughout the crop cycle (Fig. 5). In some instances, and especially in the low stress environment seasons, the standard nitrogen management practice used in the simulations generated growth restrictions as N became limiting prior to a thesis.

3.3. Frequencies of environment types and their effects on sorghum production

The frequencies and effects of the drought stress patterns were examined across the *rabi*-belt.

3.3.1. Analysis within production zones

The major production zone – *central* zone – includes the districts of Maharashtra that produces more than 40% of the annual

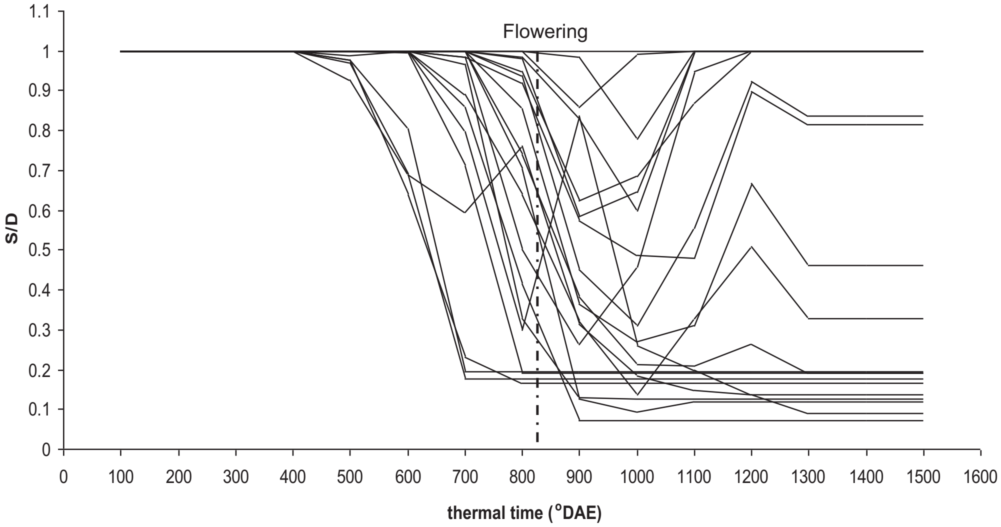

Fig. 4. Time course trajectories of the crop water status index (S/D ratio) through the crop cycle for each year simulated at Sholapur (central production zone). The water status index (S/D ratio) was averaged over each 100 degree-day interval after emergence up to plant maturity within each season. The vertical line indicates the thermal time to flowering (830 °C d) for cultivar M35-1.

rabi-belt sorghum grain production (0.83 million tonnes from 2 million ha, Fig. 1 and Table 1). This zone is characterized by the lowest long term yield average (around 460 kg ha^{-1}) corresponding to the harshest environments in the *rabi*-belt. The analysis of simulated stress patterns showed the highest proportion of severe stress types in this region (Table 2); vegetative terminal drought (15%) and pre-flowering terminal drought (16%). A similar proportion of seasons were classified as post-flowering terminal type (15%) or post-flowering relieved (18%). Only 37% of seasons in this region were classified in the low stress type. As expected, the vegetative and pre-flowering stress were associated with severe effects on crop production, resulting in 92% and 78% yield reduction relative to the low stress environments, respectively. The simulated yields for the other environment types were comparable with that in the mild stress environment (860 kg ha^{-1}), although this was lower than the yield in the other zones (Table 2). Total biomass production was also decreased in the vegetative and pre-flowering stress environment types, but not to the same extent as grain yield, with reductions of 21% and 12% respectively (Table 2). The other environment types showed similar total biomass production to that in the mild stress situation (Table 2).

The *Southern* production zone was the second ranked in *rabi* sorghum production (0.66 million tonnes, 30% of total) and area (1.20 million ha) and included districts located south and south-east from the central zone (Fig. 1). The average recorded yield in this area (580 kg ha^{-1}, Table 1) was comparably higher than that of the central zone. As in the Central zone, a significant proportion of environment types were either vegetative (9%) or pre-flowering (15%) terminal droughts. In these environment types simulated yield was reduced by 83% and 62% respectively, relative to the mild stress situation (Table 2). Both post-flowering stress types (terminal (16%), relieved (26%)) did not result in any major yield limitation compared to yield in mild stress environments, which were higher than in central zone. Stover yield was only affected in the vegetative stress environment type (11% decline, Table 2).

The *Northern* zone produces around 20% of *rabi* sorghum grain (0.51 million tonnes from 0.90 million ha (Fig. 1 and Table 1)) and includes districts from the northern and north-east areas

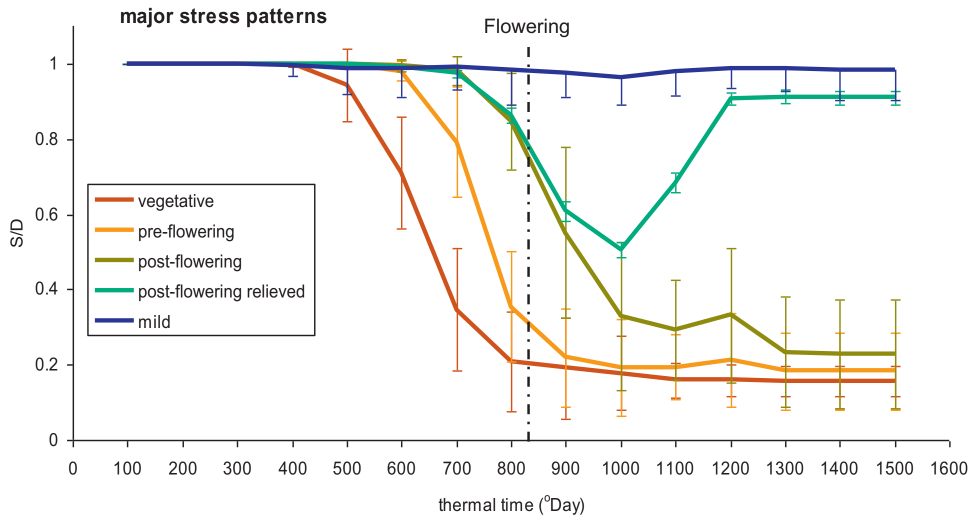

Fig. 5. The five trajectories of average crop water status (S/D index) through the crop cycle identified by cluster analysis of simulated trajectories for the entire *rabi* sorghum tract. Vertical bars show the standard errors for trajectories within each cluster. The vertical line indicates the thermal time to flowering for cultivar M35-1 (830 °C d).

of the *rabi* sorghum belt. Average yield reported for this zone was similar to that in the southern zone (average 590 kg ha^{-1}). Here the frequency of occurrence of the most severe drought pattern – vegetative stress (5%; Table 2) – was reduced but the proportion of seasons belonging to pre-flowering terminal stress cluster was elevated (23%). Also, all crops exposed to the vegetative stress pattern in this region completely failed to yield and the pre-flowering stress pattern resulted in 57% grain yield reduction compared to the mild stress environment type. In both of these stress types biomass production was also reduced although not to the same extent as for grain (24% and 6% respectively). As in the central and southern zones, there was little difference in stover and grain yield among the other three environment types.

The *Far South* zone is the most Southern part of *rabi* sorghum belt encompassing central districts of Karnataka and parts of central-west Andhra Pradesh districts. Although the average yield records from this region were the highest (around 760 kg ha^{-1}; Table 1) the amount of *rabi* production originating from this area and area sown to *rabi* sorghum is the lowest of the four zones (around 10% of *rabi*-belt; i.e. 0.24 million tonnes from 0.34 million ha, Fig. 1 and Table 1). According to the simulation, the far south zone had the lowest proportion of severe stress environment types. Vegetative and pre-flowering stress types occurred in only 4% and 13% of the cases, respectively. Nevertheless, these forms of stress had similar effects on sorghum production as in other zones and lowered average yield by 76 and 57%, respectively (Table 2). Similarly, biomass production was affected only by vegetative drought environment types but to a much lesser extent than grain yield (12% reduction relative to mild stress environment type). The simulation confirmed that this region is dominated by mild stress environments (52%) and the two forms of post-flowering drought, which accounted for 16% of years each, had minimal impact on grain and biomass yield (Table 2).

3.3.2. Analysis across the whole rabi-belt

For the analysis across the entire *rabi*-belt, the outcomes for each zone in relation to stress pattern frequencies and grain and stover yields were weighted according to the contribution of each zone to total grain production. This weighted analysis indicated that overall the *rabi* sorghum crop faced water limitation in 60% of occasions (Table 2). Out of these the more severe vegetative terminal drought types occurred 7% of the time, pre-flowering terminal drought 18% of the time, post-flowering terminal drought 18% of the time, and post-flowering relieved stress 17% of the time. The *rabi* sorghum crop faced only mild drought limitation within the season 44% of the time.

The weighted grain yield across the *rabi* tract for both severe types of drought stress environments (i.e. the vegetative and pre-flowering terminal droughts) were 128 and 447 kg ha^{-1} respectively, which was a 89% and 60% yield reduction compared to the mild stress environment. Both post-flowering stress types, terminal and relieved, which occurred on 35% of occasions, did not notably affect the overall average grain yields, compared to that under the mild stress conditions. Stover yields were not so drastically affected by environment type across the full region of the sorghum *rabi*-belt. For stover, the vegetative and pre-flowering terminal drought environment types induced only 18% and 1% average biomass loss compared to the mild environment type and both post-flowering stress environment types did not result in any biomass reduction (Table 2).

3.4. Sorghum production potential

In general, the total biomass and grain yield production potential of the zones was 2–3 times greater than that realized under normal dryland and recommended N input conditions. However, the three major zones differed in simulated production potential (Table 2). The greatest average grain yield (above 3 t ha^{-1}) and biomass production (above 8.5 t ha^{-1}) occurred in the north and south zones. Slightly lower average biomass (around 8.3 t ha^{-1}) and grain yield (around 3 t ha^{-1}) could be expected under optimal water and N conditions in the central production zone. The far south production zone showed lower total biomass (around 7 t ha^{-1}) and grain yield (around 2.7 t ha^{-1}) potential under non-limiting water and N conditions. Although the regions appeared to receive similar average radiation (Fig. 1), closer investigation revealed that three of the four sites used in the simulations for the far south zone had comparatively lower in-crop radiation averages along with lower temperature conditions (Fig. 1).

4. Discussion

4.1. Nature of environments in the major rabi-production zone

The point simulations credibly reflected district yield variations across the *rabi*-belt (Fig. 3). More than 400 site-season combinations across the *rabi* sorghum belt were simulated to quantify the environment types experienced. The approach was similar to that used for evaluation of drought patterns across Australia (Chenu et al., 2011; Chapman, 2008; Hammer and Jordan, 2007). Using the trajectory of the crop water stress index (supply/demand ratio (S/D)) through the crop life cycle five major patterns of drought environment were found across the whole region. The majority of the trajectories demonstrated a terminal stress character, but with differing time of onset during the crop cycle. This is consistent with previous reports (Kassahun et al., 2010; Murty et al., 2007; Sajjanar et al., 2011) but, in addition, here we were able to quantify the nature and frequency of the particular environment types occurring. The terminal stress types could be differentiated into those with early onset during the vegetative stage (onset from 500 to 600 °C day after emergence), or onset just before anthesis (700–800 °C day after emergence), or onset during post-flowering (after 800 °C day after emergence). In some cases, the post-flowering stress was relieved during the grain filling stage, giving rise to the post-flowering relieved drought environment type. In addition, in about one third of cases only mild stress was experienced at any stage in the crop cycle. These reflected situations with abundant mid-season precipitation, which re-filled the soil profile enough to sustain the crop water demand till the end of the season.

4.2. Frequencies and effects of drought types

The main area of the *rabi* sorghum belt was partitioned into four "production zones" that grouped neighbouring districts with similar yield averages across seasons, geographical position and comparable pedology, i.e. central, southern, northern and far south production zones (Fig. 1 and Table 1). This approach was similar to that of Murty et al. (2007) although their zones accounted only for similarities in-crop yield. The frequency of severe stress environments was the greatest in the central production zone, which concurs with Murty et al. (2007). This zone had the lowest average yield (around 460 kg ha^{-1}), but also had the largest production and area (around 0.83 million tonnes from 2 million ha; i.e. 40% of *rabi*-belt). In this zone 31% of the simulated site-season combinations had terminal water stress environments with onset either early in the vegetative stage (15%) or just pre-flowering (16%). These environment types were associated with greatest effects on grain yield (66 and 174 kg ha^{-1} respectively) with almost complete crop failure. These two severe stress types also had negative effects on total stover production (Table 2). This outcome was linked to the poor soils (very shallow Entisols and Vertisols with low plant available water content (PAWC)) combined with slightly lower average in-crop precipitation within this zone. Further the distance from the production "core", more favourable environmental conditions occurred (greater PAWC and slightly more in crop rainfall) and linked well with higher yields in northern, southern and far south zones (around 580–590 kg ha^{-1} in northern and southern zone and 756 kg ha^{-1} in far south zone). The predicted yield responded similarly to these conditions and showed higher simulated yields than in central zone. As simulations further clarified, the greater yields of these zones were associated with lower frequencies of severe drought environments and their diminishing effect on crop production (Table 2).

The area considered for this study encompassed highly heterogeneous locations covering around 75% of total *rabi* grain production (2.26 million tonnes, 4.43 million ha, Fig. 1). Across the whole *rabi*-belt, severe water limitation occurred with a frequency of 25% of seasons (7% vegetative and 18% pre-flowering onset droughts), leading to near crop failure and severe decrease in stover quantity (Table 2). Post-flowering droughts occurred on 35% of occasions (18% post-flowering onset terminal and 17% post-flowering relieved stress) but they had minimal effect on grain yield and stover quantity when compared to mild drought conditions, which occurred on 40% of occasions. Throughout the *rabi*-belt the environment types with stress onset after flowering did not result in significant decrease in total biomass and grain yield relative to the mild stress environment type. Each environment type cluster includes a heterogeneous set of stress trajectories, so that even the group classified as mild stress environments will include seasons with some episodes of drought. However, it was notable that the average in-crop radiation in seasons with mild stress environments was lower (data not shown), and likely associated with increased cloudiness and precipitation. This could limit crop growth and yield despite enhanced water availability late in the season. However, it is known that the traditional cultivar (M35-1) produces few, large grain with a very low potential harvest index (van Oosterom and Hammer, 2008; Hammer et al., 2010), which suggests that the grain sink is not sufficient to take advantage of additional water resource availability in mild stress seasons. These tall cultivar types are also more susceptible to early senescence associated with depletion of soil N supply as much N is sequestered in structural stem tissue (van Oosterom et al., 2010). So the inability to effectively utilize additional water in mild stress seasons may reflect restrictions on growth during grain-filling associated with the exhaustion of available N and early canopy senescence. This likelihood is reinforced by the differences in biomass and grain production between simulations for mild stress environments and production potential conditions given both high water and N supply (Table 2). While some water limitation remains in the mild stress environments, the low yield resulting in those instances most likely reflects early depletion of N reserves.

4.3. Prospects for yield improvement

Current scientific efforts emphasize the importance of droughts effects on sorghum production (e.g. Borrell et al., 2006; Kassahun et al., 2010; Srivastava et al., 2010; Vadez et al., 2011) and sorghum breeding efforts lean towards the development of drought tolerant sorghum *rabi* cultivars (e.g. Patil, 2007; Arun Kumar and Biradar, 2004; Biradar et al., 2008; Reddy et al., 2009). However, breeding progress has been slow mainly due to the confounding effects of genotype-by-environment interactions (Pray and Nagarajan, 2009; DeLacy et al., 2010; Sajjanar et al., 2011). As a result, the *rabi* cultivar M35-1, which was introduced in 1930s still dominates the area sown during the post-rainy season (Directorate of Sorghum Research, 2007 (DSR; www.sorghum.res.in); Reddy et al., 2009). Here, the identification of particular stress patterns and their frequencies of occurrence across the production zones opens the possibility to focus breeding on specific adaptation, while also considering specific management practices.

The most severe droughts occurred across the area producing the majority of the *rabi* sorghum and were predicted to devastate crop grain yield in about 25% of seasons. This situation is partly associated with the dual purpose of *rabi* sorghum for grain and stover. At current market values, good quality stover (3–4 Rs kg^{-1}) is around 40% the price of grain (10 Rs kg^{-1}) and is in high demand as livestock production rises (Blümmel and Rao, 2006). Farmers grow *rabi* sorghum at high density to ensure a good quantity and quality of stover is produced as this provides income even in these severe drought years that fail to realize grain (Murty et al., 2007; Pray and Nagarajan, 2009). This strategy, however, accelerates the early exhaustion of water available in these poor soils and generates stress trajectories not favouring grain production. Here, a possible strategy might be to reduce planting density in order to ensure more water is available to the crop during grain filling. Genetic strategies restricting early leaf area development (van Oosterom et al., 2011) or limiting maximum transpiration rate (Sinclair et al., 2005, 2010; Gholipoor et al., 2010; Vadez et al., 2011; Kholová et al., 2010a,b) would also be appropriate as a means to save water early in the season for use later.

In contrast, crops growing in the mild stress season type, which occurred around 40% of the time, often did not utilize the available water and occasionally exhausted soil N supplies. The grain sink limitation of M35-1 (Hammer et al., 2010) also limited yield in these environments. In such environment types removing these impediments by management (additional N) or breeding (grain sink, N use efficiency) would be appropriate crop improvement strategies. The significantly greater potential stover and grain yield levels (Table 2) are indicative of the productivity foregone in these more favourable seasons.

In the scenario with drought occurring after flowering (35% of seasons) there was limited impact on yield relative to the mild stress environments. However, this most likely reflected the restrictions on yield expression in the mild stress environments. Hence, any strategy resulting in delay of drought onset could improve yield, but would also require improved genotypic attributes and management (as for mild stress conditions) to be realized. The delay of drought onset could be obtained via the water-saving strategies outlined for the severe drought environments. While it is clear that the development of drought tolerance strategies for genetic and management manipulation would serve to improve productivity in the majority of environment (E) types in the *rabi* sorghum tract, there is a dilemma in that strategies to take most advantage of the mild stress season types would be opposing and exacerbate the level of effect in the environment types with terminal drought. As all environment types occur at all locations, albeit with different frequencies, and the ability to forecast the season type remains probabilistic (Meinke et al., 2001; Meinke and Stone, 2005; Jagtap et al., 2002), this dilemma generates substantial trade-offs between production/profit likelihood and risk in choosing genotype (G) and management (M) system combinations.

However, we are now well positioned to conduct a comprehensive G × M × E simulation analysis to explore these trade-offs. This analysis of E types and the insights it generates about plausible G and M strategies, along with the advanced modelling capability now available for sorghum in India to predict phenotypic consequences (Hammer et al., 2010), underpins that capability. Such an analysis would necessarily include consideration of stover and grain components in assessing profitability and risk profiles.

5. Conclusions

In this study we have comprehensively characterized the dynamics of the water limitation environment during the sorghum crop life cycle throughout the *rabi* tract of India. The simulated trajectories of drought stress through each crop season were clustered into five different drought stress patterns. Analysis of these patterns indicates potential opportunities for crop improvement by management and genetic manipulation. There are trade-offs between stover and grain production and profit and risk that will confound crop improvement strategies. However, we are now well positioned to conduct a comprehensive G × M × E simulation analysis to explore these trade-offs.

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