Euphytica (2008) 162:395–410
DOI 10.1007/s10681-007-9579-z

Characterization of drought stress environments for upland rice and maize in central Brazil

Alexandre Bryan Heinemann · Michael Dingkuhn · Delphine Luquet · Jean Claude Combres · Scott Chapman

Received: 13 August 2007 / Accepted: 19 September 2007 / Published online: 10 October 2007

Abstract Drought stresses arise when the combination of rainfall and soil water supply are insufficient to meet the transpiration needs of the crop. In the Cerrado region of Goiás state, Brazil, summer rainfall is typically greater than 1000 mm. However, drought stress can occur during rain-free periods of only 1–3 weeks, since roots are frequently restricted to shallow depths due to *Al*-induced acidity in deeper soil layers. If these droughts are frequent, then plant breeding programs need to consider how to develop suitable germplasm for the target population of environments (TPE). A crop simulation model was used to determine patterns of drought stress for 12 locations and >30 environments (6 years × 5–6 planting dates) for short and medium duration rice crops (planted in early summer), and for maize grown either as a 1st or 2nd crop in the summer cycle. Regression analysis of the simulations confirmed the greater yield impact in both crops of drought stress (quantified as the ratio of water-limited to potential transpiration) when it occurred around the time of flowering and early grain-filling. For rice, mild mid-season droughts occurred 40–60% of the time in virgin (0.4 m deep for rice or 0.5 m for maize) soils and improved (0.8 m for rice or 1.0 m for maize) soils, with a yield reduction of <30%. More severe reproductive and grain-filling stress (yield reductions of 50% for rice to 90% for maize) occurred less frequently in rice (<30% of time) and 1st maize crop (< 10% of time). The 2nd maize crop experienced the greatest proportion (75–90%) of drought stresses that reduced yield to <50% of potential, with most of these occasions associated with later planting. The rice breeding station (CNPAF) experiences the same pattern of different drought types as for the TPE, and is largely suitable for early-stage selection of adapted germplasm based on yield potential. However, selection for virgin soil types could be augmented by evaluation on some less-improved soils in the slightly drier parts of the TPE region. Similarly, the drought patterns at the maize research station (CNPMS) and the other maize screening locations are better suited to selection of lines for the improved soil types. Development of lines for the 2nd crop and on more virgin (acidic) soils would require more targeted selection at late planting dates in drier sites.

Keywords Crop modelling · Target population of environments · Cerrados · Breeding

A. B. Heinemann (✉)
Embrapa Rice & Beans, Rodovia GO 462, km 12, Santo Antônio de Goiás, GO 75375-000, Brazil
e-mail: alexbh@cnpaf.embrapa.br

M. Dingkuhn · D. Luquet · J. C. Combres
CIRAD BIOS – UPR 59, TA A59/01, Avenue Agropolis, Montpellier 34398, France

S. Chapman
CSIRO Plant Industry, Queensland Bioscience Precinct, 306 Carmody Rd, St. Lucia, QLD 4067, Australia

Introduction

In the Cerrado environments of central Brazil, breeding of rainfed upland rice and maize is based on early screens for agronomic traits such as crop duration, vigour, plant, panicle and grain type, commonly under irrigated conditions on research stations. Only once lines reach advanced testing stages are they evaluated under the bio-physical constraints that characterize farmers' fields.

The Cerrado is a complex and extensive biome undergoing rapid changes in land use. The rainfall averages about 1200 mm per year, falling mainly (ca. 1000 mm) from November to January (cropping season). Upland rice plays an important role in bringing cleared areas into cultivation because of its comparative tolerance to acid, aluminium-toxic soils (Pinheiro et al. 2006). After two or three years of rice cropping in combination with dolomite and phosphate amendments, cropping systems based on intensified pasture and cash crops such as soybean and maize are established. The rice crop is affected by restrictions to rooting depth as a result of acid subsoil, which in turn increases the effects of intermittent drought caused by variable rainfall. This limiting soil depth reduces plant available water, and therefore drought resistance is a major breeding objective for annual crops in the Cerrados, particularly upland rice.

Meaningful breeding for drought tolerance requires information on the inter and intra-annual probability of drought occurrence, as well as on the characteristics of prevalent drought types such as duration, intensity (which in turn depends on soil depth) and timing with respect to crop phenology. This information can be captured by defining the target population of environments (TPE) for the crop (rice and maize). The TPE is defined as the set of environments, including spatial and temporal variability, to which improved crop varieties developed by a breeding program need to be adapted (Nyquist 1991; Cooper et al. 1997). With information on the TPEs, a significant component of the genotype × environment interactions (G × E) for grain yield may be explained and predicted, enabling the optimization of environmental screens and breeding itineraries (e.g., Chapman et al. 2000a, b, c).

More recent efforts to characterize TPEs for drought have utilised crop models. For sorghum, Muchow et al. (1996) showed that a crop model was more effective to quantify the incidence of drought stress than simple water balance or budgeting models. Jongdee et al. (1997b) used the RLRice model to characterise the patterns of drought stress in various environments sampled in a multi-environment trial to examine attainable-yield variation in north and northeast Thailand. Chapman et al. (2000c) used the APSIM crop model to create a regional drought typology from information on soils and historical weather records for sorghum in Queensland, Australia.

For rice breeding for central Brazil, screening takes place on a research station (CNPAF—Embrapa Rice & Beans Centre) located within the geographical boundaries of the crop production area. For maize, the research station (CNPMS—Maize & Sorghum Centre at Sete Lagoas) is now located outside the major cropping area which has expanded to the west and north of this location. This paper explores possibilities to adjust regional breeding systems to optimally fit the range of environments they are targeting (TPE), using the example of upland rice and maize in Brazil's Cerrados. The specific objectives are to (a) determine the geographical and inter-annual variation of seasonal drought patterns for upland rice and maize (as first and second crop); (b) evaluate how well the current environmental screens for upland rice and maize fit the TPE for this crop; and (c) provide, as a case study, strategies that may help improving the efficiency of these breeding programs.

Materials and methods

Extent and characteristics of study zone

In this study the production area corresponds to the Goiás state, located in central Brazil, with a surface area of 340,086 km^2, a range in altitude of 400–1300 m and latitude and longitude from –12.8° to –19.5° (S) and –49.0 to –50.9 (W) (Fig. 1). In 2005, this region produced 374 600 t of rice (80% is upland rice) and 2,213 440 t of maize (78% as first crop and 22% as second safrinha crop in double cropping systems) (IBGE 2006).

The climate in Goiás State is tropical, warm and humid with mean annual precipitation of 1,000–1,500 mm (mono-modal summer rains; Prance 1987).

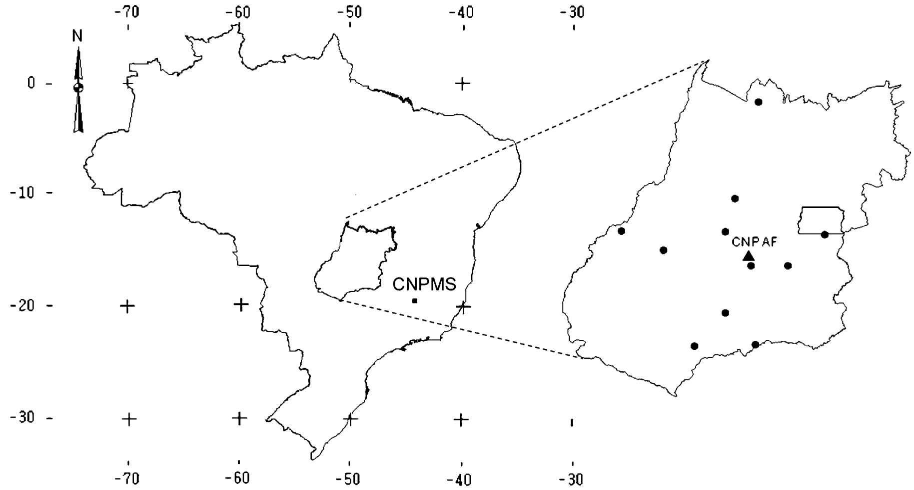

Fig. 1 The TPE location in Brazil and (●) selected sites used in this study. (▲) represents the upland screening site CNPAF and (■) maize screening site CNPMS

Establishment of the TPE, climatic and soil data base

For the establishment of the TPE, 12 locations were selected from the sites used for testing with the crop production area (Fig. 1). The climatic data base also came from these 12 sites. Seven climatic variables, e.g., precipitation, maximum and minimum temperatures, wind speed, maximum and minimum humidity and global radiation were used (Table 1).

All climate data sets were organized in a data base and submitted to verification and cleaning. For the process of filling missing data and null records the LADSS (2004) protocol was followed. Daily global radiation was not available for the CNPAF site, and was calculated from sunshine hours using the Angstrom equation (Allen et al. 1998). For all sites, missing values of global radiation were completed with the help of a regression model using a quadratic response surface. Partial least squares (PLS) regression method was used to solve the model. The input variables were daily rainfall, extra-terrestrial radiation, temperature amplitude and maximum temperature. Terms were made for

Table 1 Reference sites used in this study: Site, Brazilian State, geographic location, altitude, number of years with available agro-meteorological data and source of data

Site	State	Latitude	Longitude	Altitude (m)	No. of years	Source
Aragarças	Goiás	–16.00	–52.00	310	6	http://simego.sectec.go.gov.br
CNPAF	Goiás	–16.50	–49.30	741	22	http://www.cnpaf.embrapa.br
Ceres	Goiás	–15.33	–49.60	739	6	http://simego.sectec.go.gov.br
Goiânia	Goiás	–16.73	–49.25	749	6	http://simego.sectec.go.gov.br
Iporá	Goiás	–16.41	–51.11	688	6	http://simego.sectec.go.gov.br
Itaberai	Goiás	–16.01	–49.78	1001	6	http://simego.sectec.go.gov.br
Itumbiara	Goiás	–18.40	–49.18	449	6	http://simego.sectec.go.gov.br
Planaltina	Goiás	–16.08	–47.70	1007	6	http://simego.sectec.go.gov.br
Porangatu	Goiás	–13.30	–41.11	391	6	http://simego.sectec.go.gov.br
Quirinópolis	Goiás	–18.43	–50.40	633	6	http://simego.sectec.go.gov.br
Vianópolis	Goiás	–16.80	–48.48	1110	6	http://simego.sectec.go.gov.br
Vicentinópolis	Goiás	–17.70	–49.78	648	6	http://simego.sectec.go.gov.br
CNPMS	Minas Gerais	–19.46	–44.25	732	44	http://www.cnpms.embrapa.br

each variable as linear, quadratic, and the cross-products between variables according to Ball et al. (2004).

The most common soil types, covering 46% of the region, are Oxisols and Latosols (EMBRAPA 1999). They have excellent physical properties but are strongly weathered and thus have low cation exchange capacity, frequently causing nutrient deficiencies in crops. Soil water holding capacity is about 100 mm m^{-1} (Balbino et al. 2001; Schaffert et al. 2000). Rooting depth is generally limited by soil acidity increasing with depth, and may be as shallow as 0.3 m under low input management (Martinez 1977). This variability mainly affects rice as the initial crop in virgin soils. This was taken into account in the modeling study by setting maximum rooting depth to 0.4 m (low management or pioneer crop scenario) and 0.8 m (scenario for established, well managed cropping system). For maize, which roots more deeply than rice and is grown more often on somewhat improved soils, the scenarios were 0.5 m and 1.0 m.

Model description and parameterization

General approach

Two reference upland rice varietal types (short and medium cycle) and one reference maize type (short cycle), based on the characteristics of the most commonly planted genotypes in the Cerrado, were parameterized using the crop models RICE06 (for rice) and CEREAL06 (for maize), both derived from the generic model SARRA, and implemented on the ECOTROP modeling platform of Cirad (Dingkuhn et al. 2003; Sultan et al. 2005; Baron et al. 2005).

ECOTROP is a crop modelling platform developed from SARRA, the water balance model frequently used by agronomists and agro-meteorologists in West Africa (zoning and risk analyses: Affholder 1997; Baron et al. 1999; yield forecasting: Samba 1998). The platform serves to assemble simple crop models from a library of modules and to apply them with the help of various tools for sensitivity analysis, parameter optimisation, database management and graphic interfaces. Only details relevant to this particular version are described.

Soil water dynamics

The model simulates, at daily increments, water runoff and infiltration using an empirical threshold of 20 mm (Baron et al. 1996). The soil is divided into a user defined top layer (15 cm for this study), used to simulate evaporation, and a layer of variable thickness representing the wetted zone. Water holding capacity of the soil between wilting point (pF 4.2) and field capacity (pF3) of the soil was calibrated from available soil data, and was set to 100 mm m^{-1} for this study to represent an oxisol. The root front, which descends at genotype specific rates depending on the growth stage, follows the wetting front. It is limited by the soil depth parameter (set to different values according to crop type and presence of an impenetrable, acid horizon as described above) and the current depth of the wetting front. Water extraction from the soil consists of two additive components, surface evaporation and extraction from the root zone through transpiration. Fraction of ground cover is used to partition evaporative demand acting on the soil and the plant. Ground cover is computed from simulated leaf area index (LAI) and an extinction coefficient K_{df} according to Beer-Lamberts's law (Vose et al. 1995). The K_{df} was set to 0.43 for rice and 0.6 for maize.

Plant water use and drought simulation

Drought level is evaluated from Fraction of Transpirable Soil Water (FTSW) according to Sinclair and Ludlow (1986) calculated for the bulk root zone. The FTSW is the relative, volumetric soil water content between wilting point and field capacity normalized on a scale between 0 and 1. This state variable acts as a reducing factor on plant transpiration and carbon assimilation based on FAO guidelines, using a genotype-dependent depletion factor P (Allen et al. 1998). This coefficient was set to 0.55 for maize (Allen et al. 1998) and to 0.35 for rice (D. Luquet, CIRAD, Montpellier, 2006, unpublished data), which was thus considered more sensitive to drought than maize. Calculation of soil evaporation in the model is based on the same concept, but applied to the full range of soil moisture between dry and saturated state, in the surface layer of the soil. Maximum evapotranspiration of the soil and canopy, achieved at full ground cover, is set with a crop coefficient K_c

according to FAO guidelines for different crop species (Doorenbos and Pruitt 1977; Doorenbos and Kassam 1979). K_c was set to 1.2 for rice and 1.15 for maize. The physiological stress level of the plant is expressed by the state variable *cstr* (range 0–1), equal to the simulated ratio of water-limited to potential transpiration as calculated from current FTSW based on the FAO depletion factor.

Carbon assimilation and partitioning

Potential assimilation rates are obtained by multiplying intercepted photosynthetically active radiation, calculated with Beer-Lambert's law, by an empirical conversion coefficient. This coefficient is similar to the radiation use efficiency coefficient (RUE) term described by Sinclair and Muchow (1999), but larger because it is based on carbon assimilation before, and not after the subtraction of respiration losses. Water limited assimilation rates are then obtained by applying the drought related reduction coefficient *cstr*. After subtraction of a temperature and biomass dependent maintenance respiration term (Penning de Vries et al. 1989), biomass is partitioned during vegetative stage between roots, stems and leaves according to empirical, allometric rules (Samba et al. 2001). Grain filling, however, is simulated with somewhat more detail to allow for variable harvest index, by determining sink capacity during pre-floral stages and inducing leaf senescence after flowering when sink capacity exceeds current assimilation rate. Leaf biomass is converted to leaf area using specific leaf area (Penning de Vries et al. 1989; Asch et al. 1999) whose dynamics are simulated on the basis of a genetic minimum and maximum value. For both rice and maize, a drought (low FTSW) sensitive phase for grain sink capacity begins 10-days preceding anthesis. In rice, this corresponds to the period of pollen development (from meiosis to pollination) and in maize to silk elongation (determining the anthesis-silking interval, ASI), both of which are crucial for seed set and are highly stress sensitive, e.g., Bolanos and Edmeades (1993).

Phenology

Although the model is capable of simulating variable crop duration depending on day length, photoperiod response was suppressed by setting a fixed thermal time of 1 day for the photoperiod-sensitive phase for all crops. Crop duration was thus the sum of genotypic, thermal durations of the basic vegetative phase (BVP), reproductive phase and ripening phase. Thermal time was simulated by setting base temperature to 10°C for rice and 8°C for maize.

Model outputs used for TPE characterization

Among the many model output variables, only attainable (water and radiation limited) and potential (radiation limited) grain yield at maturity were used, as well as the seasonal dynamics of *cstr*, which served as an indicator of the current physiological drought level. The relative water stress impact on yield (RWSI) was evaluated by expressing attainable yield as a fraction of potential yield.

$$\mathrm{RWSI} = 100 - (\mathrm{GY_{att}}/\mathrm{GY_{pot}}) * 100 \qquad (1)$$

whereby:

RWSI—relative water stress impact (%);
GY_{att}—simulated attainable grain yield, kg/ha;
GY_{pot}—simulated potential grain yield, kg/ha.

Model testing

For validation and calibration of rice and maize reference genotypes, parameters for plant phenology, biomass and yield data were taken from Embrapa Rice & Beans and Embrapa Maize & Sorghum breeding program data bases. The calibrated model was validated with observed data from a fully irrigated maize experiment (BRS3003—hybrid triple, Romano 2005) and a non-irrigated rice experiment using the short-duration upland rice cultivar Guarani and the medium-duration cultivar Caiapo. The model performance for the three cases was quite suitable in terms of capturing patterns of LAI, biomass and yield in these relevant environments (Fig. 2).

Simulated scenarios

Simulations were undertaken for a range of sowing dates for each crop type, site and year, according to

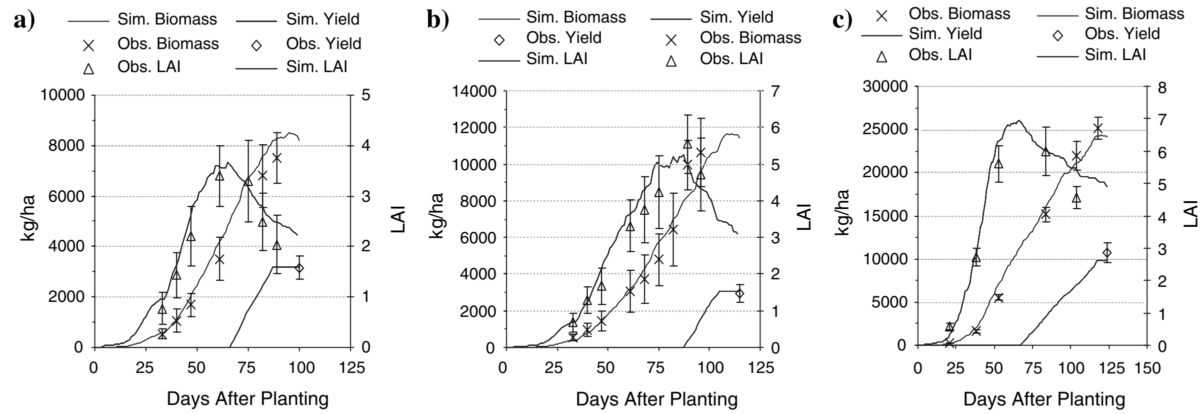

Fig. 2 Crop model performance for yield (kg/ha), biomass area (kg/ha) and LAI for (**a**) short rice cycle not irrigated, (**b**) medium rice cycle not irrigated and (**c**) maize fully irrigated experiments

recommended practices. Sowing dates were defined at 15-day intervals during the main planting season (rice or maize as first crop) and at 10-day intervals during the second season (maize as second crop). The planting seasons were defined as 01 November–31 December for short-cycle rice and 15 October–31 December for medium-cycle rice and maize as first crop (1st). For the rice medium-duration crop, earlier planting dates are recommended because it is considered less sensitive to the rainfall variation at the beginning of the cropping season. Specifically for the sites Planaltina and Vicentinópolis, the earliest sowing date for upland rice was shifted by one month, 01 November–01 December, due to the short rainy period at these locations. For maize as 2nd crop, possible sowing dates were considered between 20 January and 01 March. These choices of potential crop calendars were based on the climatic-risk zoning for the Goiás state developed by the Brazilian Government (http://www.agricultura.gov.br/).

Because sowing dates were fixed independently of rainfall occurrence, a provision was made that allowed germination only if FTSW in the top soil layer was 0.7 or higher. For any given year and sowing date, if soil moisture did not permit germination within 10 days of sowing, the crop was considered as failed. Simulation runs were generally initiated in July, regardless of sowing date, in order to allow the establishment of a realistic soil water profile on the basis of rainfall patterns occurring before sowing, with the starting water profile as zero due to completion of a previous crop.

Analysis of yield sensitivity to physiological stress level

The reference genotypes were used to simulate, for each scenario, the attainable yield, potential yield and the average level of cstr for each successive 100°C d period throughout the crop cycle (corresponding to about one week). For each TPE (ensemble of scenarios per crop type), a linear regression model was built relating relative (attainable over potential) grain yield to stress intensity patterns during crop development (mean *cstr* per 100°C d period), based on Eq. 2:

$$\hat{y} = GY_{att}/GY_{pot} = \beta_i X_i + \ldots + \beta_n X_n \quad (2)$$

where:

$\hat{y}$ = relative grain yield;
GY = grain yield (attainable, att; potential, pot);
β_i *to* β_n = regression coefficients;
X_i *to* X_n = mean *cstr* simulated for each successive 100°C d period during crop development.

The partial least square (PLS) regression method was used to determine the weighting of growth periods as a function of the mean *cstr* simulated for the 100°C d periods, according to their influence on relative grain yield.

Stress pattern typology using diagnostic output variables of the model

To develop a typology of drought patterns for each rice and maize TPE, a four-dimensional matrix consisting of location, sowing date, year and growth phase (100°C d period) was established for the mean *cstr* simulated for the 100°C d periods. This classification employed a hierarchical agglomerative clustering method (Williams 1976) with a squared Euclidian distance as the dissimilarity measure, and incremental sum of squares (Ward 1963) as the fusion criterion. For each TPE, the simulated drought stress scenarios were classified into three main groups based on the similarities in the phenological sequence patterns of *cstr*.

To avoid bias in the stress pattern analysis resulting from the strong variation in *cstr* during crop establishment, which is due to the initially shallow root system but has only small effects on subsequent growth, only the period from mid vegetative stage (400, 500 and 400°C d after sowing for short, medium rice and maize) to end of grain filling was considered. Similar drought classification procedures were described previously by Muchow et al. (1996) and Chapman et al. (2000b).

The statistical software used in this study was the freeware R v. 2.4.0 (R Development Core Team 2005). The R packages used were PLS and Cluster.

Results

Analysis of yield sensitivity to physiological stress level

The sensitivity analysis of relative yield ($\hat{y}$ as defined in Eq. 3) to the simulated water stress indices (*cstr*) for different growth phases, conducted for the entire TPEs (Fig. 3), revealed distinct periods during which *cstr* was influential. For the short-duration upland rice TPE (Fig. 3a), the most sensitive period was flowering (occurring at 64 ± 2.5 DAE), followed by the grain filling period (simulated for the 20 days following flowering). During the reproductive phase (from panicle initiation to flowering), sensitivity of relative yield to *cstr* increased gradually. The vegetative phase was the least sensitive. Similar patterns were simulated for the shallow (0.4 m) and deep (0.8 m) soil scenarios, which affected stress incidence but not the relative sensitivity of different growth stages to stress. These types of developmental-stage dependent effects of drought on rice yields have also been observed managed irrigation experiments in the field (e.g., Cruz and O'Toole 1984; Lilley and Fukai 1994). The yield response simulated by the model had several components, the most influential being spikelet sterility caused by drought between booting (about 10 d before flowering) and flowering. Figure 4 shows, as example, the variation of rice short cycle simulated spikelet sterility (%) due to drought stress among the TPE sites for soils deep 0.8 and 0.4 m. Drought sensitivity of yield simulated before that period influenced dry matter accumulation and with it, the reservoir of reserves accumulated in the plant that can be mobilized for grain filling. Drought after flowering reduced yield through limited current assimilate resources for grain filling. Hence, for the TPE studied here, these effects added up to constitute a broad peak of yield sensitivity centred at flowering.

Drought sensitivity patterns simulated for the medium-duration rice TPE (Fig. 3b) were similar as for short-duration rice, but *cstr* effects were spread over a longer period and showed a less pronounced peak at flowering (84 ± 3.5 DAE). The highest sensitivity was simulated for the grain filling period, given that the later maturation of this crop increased the occurrence of terminal drought.

In the TPE for maize as first crop (Fig. 3c), the most sensitive period was at about 52 DAE, 5–7 days before silking (57 ± 2.5 DAE). In terms of model mechanisms, the algorithms used were the same as for rice but parameterized differently. In maize, the observable effect of drought near flowering is a delay in silking. However, this is a symptom of reduced ear growth rate and reduced establishment of grain number per plant, and at the physiological level is similar in effect as the effect of male sterility as in rice. For TPE of maize as second crop (Fig. 3d), the most drought-sensitive, phenological period was also 7 days before anthesis (58 ± 2.5 DAE), but the peak was less pronounced. Instead, *cstr* had a greater influence on $\hat{y}$ during grain filling because in this TPE, drought mainly occurred during this period.

TPE characterization

Short-duration rice TPE

Based on cluster analysis, three predominant stress patterns were observed, denominated as low (L), mid-

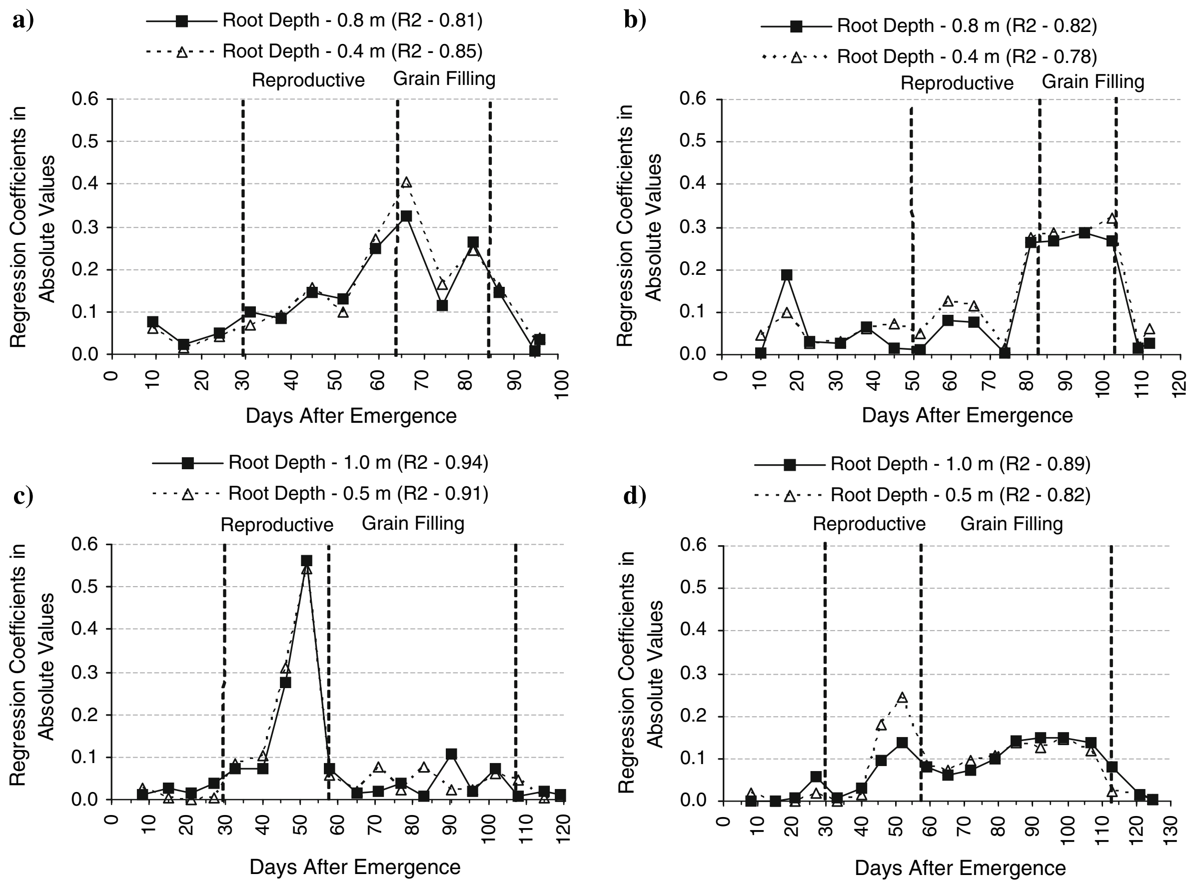

Fig. 3 Estimation along crop cycle in days after emergence of the most influential period of water stress (stress index averaged for each 100°CD: $CSTR_{100}$) on simulated yield reduction (computed as the ratio between actual and potential (no stress) yield) for (**a**) short rice TPE, (**b**) medium rice TPE, (**c**) Maize as first crop TPE and (**d**) Maize as second crop TPE and rooting depth limitations (0.4 and 0.8 m for rice; 0.5 and 1.0 m for maize)

season (M) and terminal (T) stress (Fig. 5a). The most severe but less frequent stress pattern, T (Table 2) began about 600°C d after emergence (38 DAE), at the beginning of reproductive phase and was most intense between 800 (52 DAE) and 900°C d (59 DAE), corresponding to a period of marked sensitivity of yield to *cstr* (Fig. 3a). The T stress pattern also affected the grain filling phase, particularly under conditions of shallow soil (0.4 m) and reduced potential yield by >50% in both soil types. The L pattern was most frequent for deep soil (46%) and the M pattern was most frequent for shallow soil (48%) with smaller relative effects on yield. The overall, weighted yield reduction confounding all stress patterns was 18% for deep soil and 36% for shallow soil (Table 2).

Apart from the fact that the frequency of T type stress was lowest at Nov 15 plantings, sowing date was not related to the occurrence of T type stress (Fig. 6a), i.e., in general, no reliable pattern of rainfall distribution occurred within the season that would enable escape from terminal drought by changing of sowing date.

Medium-duration rice TPE

As for the short-duration TPE, cluster analysis identified three predominant stress patterns for medium-duration rice, but they affected phenological phases differently (Fig. 5b). They were denominated as low stress (L), vegetative stage stress (V) and mid-

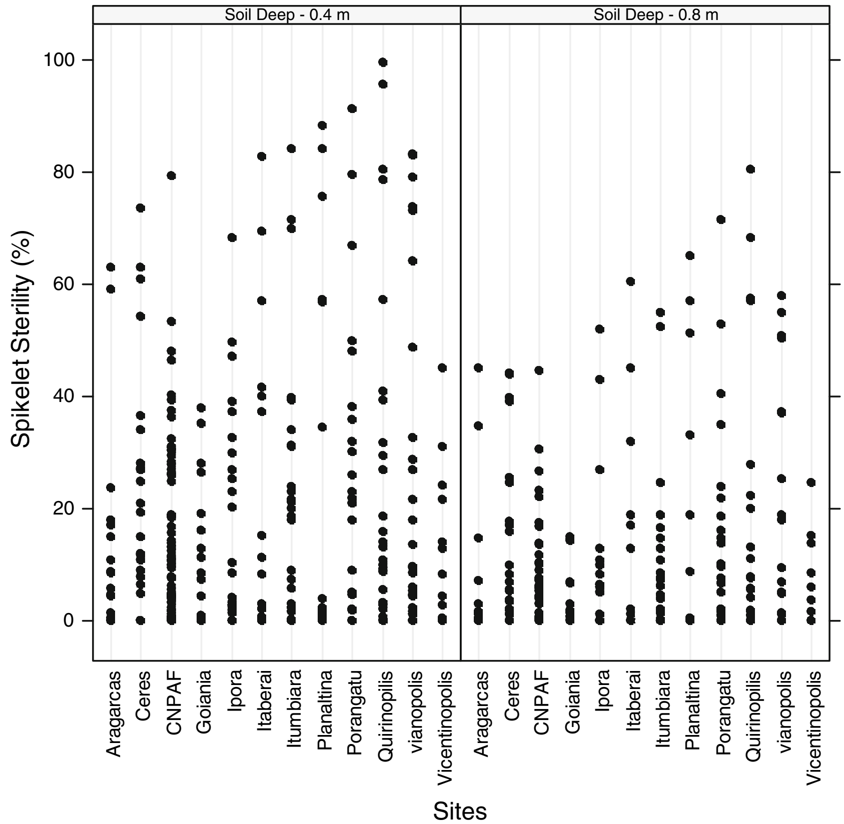

Fig. 4 Variation on the simulated spikelet sterility (%) due to the drought stress for short rice cycle among the TPE sites for both scenarios (soil deep 0.4 and 0.8 m)

season to terminal stress (MT). These stress patterns resembled those observed for short-duration rice but affected earlier stages of development due to the longer cycle of the crop. The relative frequency of occurrence of L, V and MT patterns was similar to that of the corresponding classes observed for short-duration rice (Table 2), and these stresses had similar relative effects on yield (>50% for the MT stress).

The overall, weighted yield reduction confounding all stress patterns was 12% for deep soil and 33% for shallow soil (Table 2).

TPE for maize as first crop

The three stress patterns determined by cluster analysis (Fig. 5c) included a nearly stress-free environment (L), a mild, mid-season stress pattern covering both the reproductive and early grain filling periods (M), and severe drought occurring during the late reproductive period (SR). Patterns were similar for deep (1 m) and shallow (0.5 m) soil. The most frequent patterns were L for deep soil (62% of cases), incurring only minimal yield reduction (RWSI = 1%), and M for shallow soil (71% of cases), incurring a mean yield reduction of 29% (Table 2). The SR stress pattern was rare (4% of cases for deep soil and 9% for shallow soil) but led to extreme yield reductions (RWSI = 81% for deep soil and 89% for shallow soil). This severe stress pattern occurred most frequently for the latest sowing date considered (31 December, Fig. 6c), particularly when associated with shallow soil.

The overall, weighted yield reduction confounding all stress patterns was 12% for deep soil and 29% for shallow soil, and thus was similar to % yield reductions in rice, but at a much higher overall yield level (Table 2).

TPE for maize as second crop

This TPE had different stress patterns as compared to the other TPEs described so far because the seasonal window for planting was situated at the end of the cropping season. Due to the high risk of terminal

Table 2 Potential yield (GY_{pot}, no water limitation), attainable yield (GY_{att}, with water limitation), relative water stress impact (RWSI) on yield and stress type frequency simulated by ECOTROP crop model for each TPE as a function of the stress types (sd: standard deviation)

Soil depth	Variable	Short rice TPE				Medium rice TPE				Maize first crop TPE				Maize second crop TPE			
		Stress type				Stress type				Stress type				Stress type			
		L	M	T	Average	L	V	MT	Average	L	M	SR	Average	L	T	RT	Average
Deep 0.8 m (rice) or 1.0 m (maize)	*GY_{pot} (kg ha^{-1})	3937	4120	4217	4051	2950	2885	2860	2911	7725	8117	8978	7908	8065	8342	8923	8317
	**sd (kg/ha)	718	622	542		483	485	498		1246	1211	1001		799	980	1205	
	***GY_{att} (kg/ha)	3718	3378	1982	3311	2853	2597	1402	2566	7638	6161	1739	6900	7141	3639	786	3850
	sd (kg/ha)	785	834	942		535	720	914		1219	1797	1642		1199	1582	906	
	****RWSI (%)	6	18	53	18	3	10	51	12	1	24	81	12	11	56	91	52
	Stress frequency (%)	46	38	16		44	44	12		62	34	4		25	52	22	
Shallow 0.4 m (rice) or 0.5 m (maize)	GY_{pot} (kg/ha)	3927	4027	4270	4074	2976	2873	2956	2935	7430	7964	8480	7904	7983	8244	8781	8398
	sd (kg/ha)	677	668	590		407	493	514		1272	1238	1023		966	918	1133	
	GY_{att} (kg/ha)	3516	2742	1634	2599	2683	2086	1018	1929	7271	5661	945	5559	5547	2630	463	2214
	sd (kg/ha)	728	869	944		560	773	737		1218	1754	781		1634	1574	575	
	RWSI (%)	10	32	62	36	10	27	66	33	2	29	89	29	31	68	95	73
	Stress frequency (%)	23	48	29		17	59	24		20	71	9		11	55	34	

Stress patterns are classified as low (L), mid-season (M), terminal (T), vegetative stage (V), mid-season to terminal (MT), severe reproductive stage (SR) and reproductive stage to terminal (RT)

*GY_{pot}—Simulated potential grain yield (no water stress), kg/ha;

**sd—standard deviation;

***GY_{att}—Simulated attainable grain yield, kg/ha;

****RWSI—Relative water stress impact on yield, %;

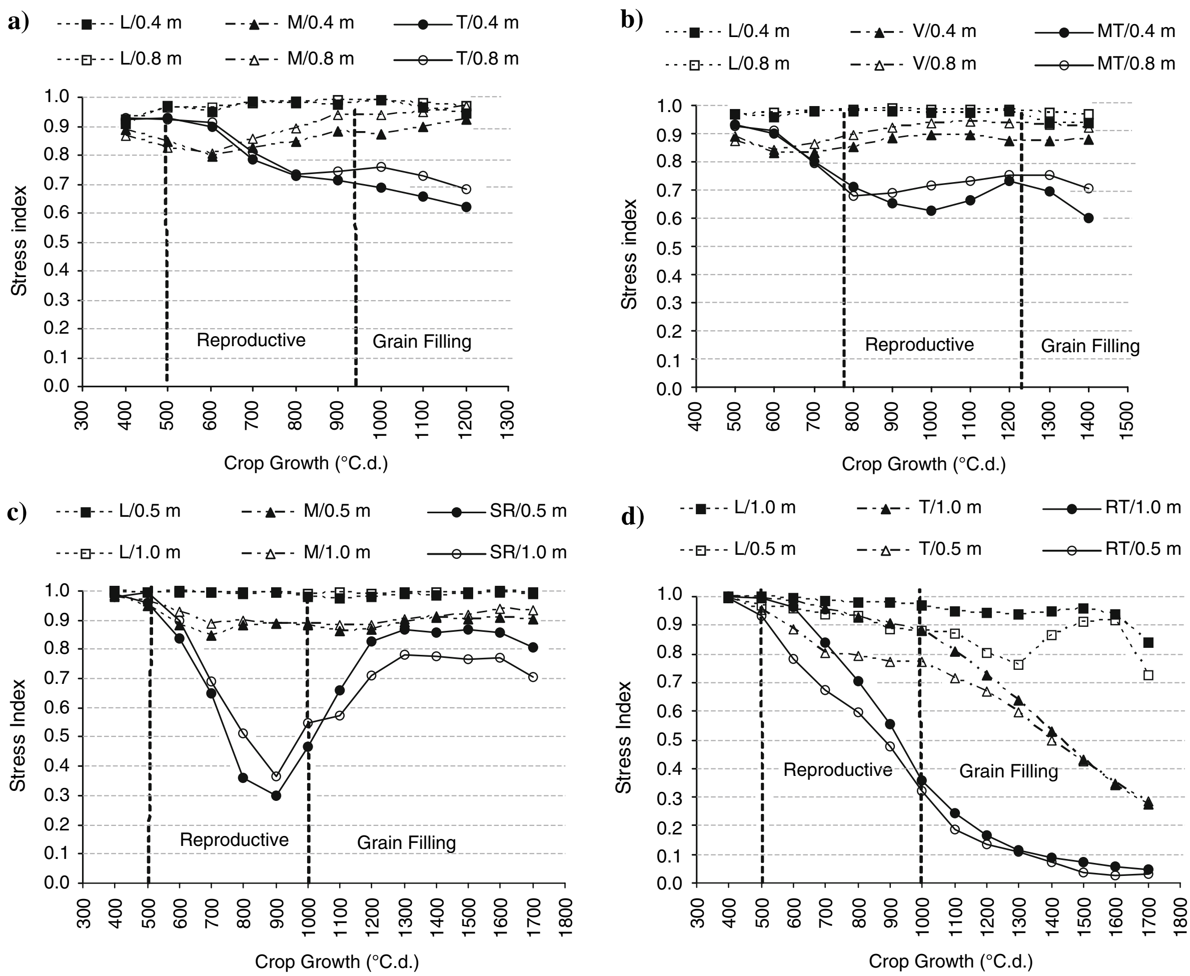

Fig. 5 Stress patterns from the cluster analysis of ECOTROP crop model simulations for (**a**) short cycle rice, (**b**) medium rice, (**c**) Maize first crop and (**d**) Maize second crop using Cerrado climatic data sets. The legends indicate to different stress types (low -L, mid-season-M, terminal-T, vegetative stage-V, mid-season to terminal-MT, severe reproductive stage-SR and reproductive stage to terminal-RT) and rooting depth limitations (0.4 and 0.8 m for rice; 0.5 and 1.0 m for maize)

drought, it is generally managed as a low-input system. For this reason, the shallow-soil scenario (0.5 m) deserved particular attention.

The three predominant stress patterns observed were low (L), terminal (T) and reproductive-terminal (RT) stress (Fig. 5d). The relatively favorable L pattern caused a yield reduction of less than 15% (Table 2) and was relatively infrequent (25% of cases on deep soil and 11% on shallow soil). The most frequent stress pattern was terminal (T), accounting for about half of the scenarios constituting the TPE, regardless of soil depth. It resulted in 56% yield reduction on deep soil and 68% on shallow soil, and can therefore be considered severe. Lastly, the RT stress pattern occurred in 22% of cases on deep soil and 34% on shallow soil, resulting in almost total yield loss according to the model. It is quite obvious that the risk of occurrence of the extreme RT stress pattern directly depended on sowing date (Fig. 6d), the risk being small on the earliest date (20 January).

Screening sites in the TPE

The cluster analysis also allows evaluation of the extent sites currently used for germplasm screening are representative of the TPEs. In Fig. 6a and b, the relative frequency of different stress patterns for short

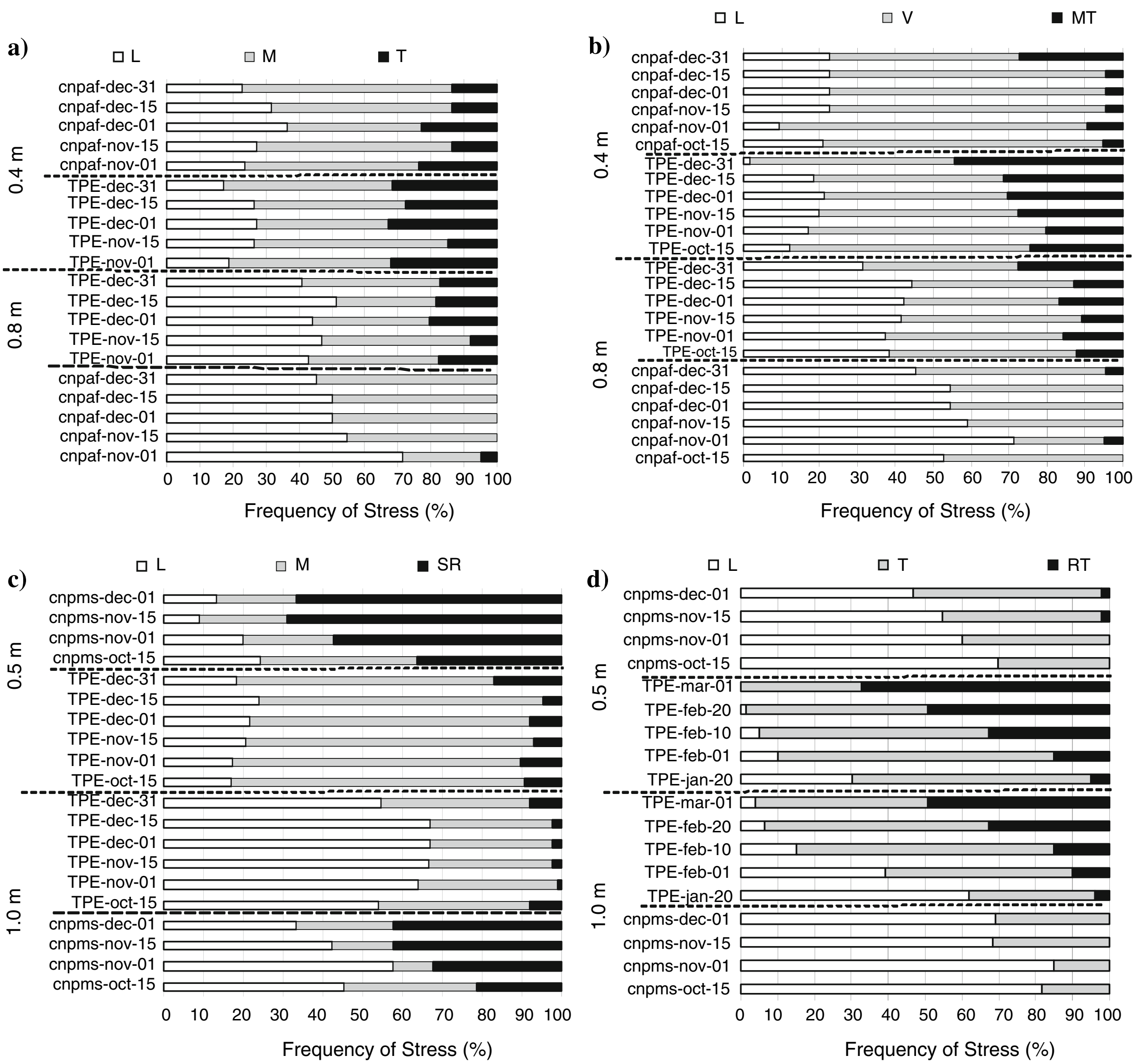

Fig. 6 Comparison of stress type occurrence as a function of planting date range for between (**a**) short rice TPE (Target Population Environmental) and CNPAF (screening site for rice), (**b**) medium rice and CNPAF, (**c**) maize as 1st crop and CNPMS (screening site for rice) and (**d**) maize as 2nd crop and CNPMS (screening site for maize) for the rooting depth limitations scenarios 0.8 and 0.4 m for rice and 1.0 and 0.5 m for maize. CNPAF (National Research Center for Rice and Been) and CNPMS (National Research Center for Maize and Sorghum)

and medium-duration rice are compared for the entire TPE and for the CNPAF, the principal germplasm screening site for the two crops in Central Brazil, which is located within the TPE. In Figs. 6c and d, the relative frequency of different stress patterns for 1st and 2nd season maize are compared for the entire TPE and for the CNPMS, the principal germplasm screening site for the maize crops in Central Brazil, which is not located within the TPE (Fig. 1).

Discussion

Upland rice TPE vs. breeding strategies

Breeding activities for upland rice in Brazil are based on direct selection for grain yield. Fukai and Cooper (2001) identified three broad mechanisms (yield potential, drought escape and drought tolerance) which summarized the complex processes and traits involved in rice drought tolerance and described their influence on yield depending on the drought severity and drought predictability. Under mild stress, yield potential is the most important determinant of yield of a genotype. Although raising the yield potential often leads to an increase in the yield gap (Manneh 2004), there tends to remain a positive yield gain even under moderate water limitation. Under severe drought that reduces yield by more than 50%, however, the positive correlation between yield under favorable and stress conditions is broken in crops like barley (Ceccarelli and Grando 1991). Thus, under severe drought stress, genotypes are incapable of expressing their genetic yield potential (Pantuwan et al. 2002). For such situations, a mechanism for drought escape and/or tolerance is required.

The results of the present study on rice TPEs indicated that yield reduction caused by drought (RWSI) is on average less than 50% for both soil depth scenarios (Table 2). On deep soils, the L (for both short and medium duration TPEs), plus the M (short-duration) or V (medium-duration) stress patterns represent 84% and 88% of all the stress pattern frequencies, i.e., the drought environment that causes yield reduction of >50% occurs at a frequency of <20% in deep soils. Hence, although any criteria of the effects of drought severity on yield are somewhat arbitrary, our simulation results support in principle CNPAF's strategy to base rice selection mainly on yield potential, especially when considering soils that have been managed to improve effective rooting depth. The positive development of upland rice yields in Brazil observed after 1990s (Pinheiro et al. 2006) further support these strategy choices. Consequently, for the deep soil scenario, water deficit is not the main constraint to be addressed by the upland rice breeding program, especially if it is largely avoided by 'optimal' planting at around Nov 15.

In practice, the frequency of more severe drought is likely to be much higher among small, family based holdings in Goiás State, associated with low inputs and effectively shallow soils (Buainain et al. 2003). The most frequent stress pattern for this scenario are M and V, with a probability of 48% for short-duration and 59% for medium-duration rice, associated with mild drought (RWSI 36% and 33%, respectively; Table 2). Comparing rice TPEs (short and medium cycle) for the shallow soil scenario (0.4 m), we observed that medium cycle rice genotype is less affected by mild drought (Figs. 3a, b and 5a, b), indicating a smaller influence of drought during the reproductive phase. When vegetative phase is longer, the highest levels of stress were shifted from the very sensitive reproductive phase to the less stress sensitive vegetative phase. On the other hand, the medium-duration type was more frequently affected by terminal drought (Fig. 5 a, b). Therefore, for the medium-duration type grown on shallow soil, the margin for stress escape was small.

EMBRAPA's upland rice screening site CNPAF was found to the less stress prone than the overall TPE, but as pointed out above, drought severity in this TPE is mostly low (Fig. 6a and b). Consequently, a breeding strategy focusing on yield potential may be appropriate and can thus make use of this favorable site. Depending on the importance attributed to shallow soil situations, however, an additional drought screen in a different environment (i.e., specific site, planting date combination) may be necessary to ensure the opportunity to select for germplasm that has suitable adaptation to the types of stresses experienced in shallow unimproved soils.

Maize as first and second crop TPEs vs. breeding strategies

The CNPMS is physically located outside the TPEs studied here, although this was the major production area at the time the center was established (Fig. 1). The breeding strategy for maize adopted by this center emphasizes yield potential, targeting primarily the favorable production environments, but also develops maize materials that can tolerate acid-soils and effectively increase the accessible rooting depth and water holding capacity. This is done through supplemental screening for Al toxicity tolerance in hydroponic culture (Parentoni et al. 1999). As for rice, breeding for maize is also based on direct selection for grain yield, as well as a suite of disease and quality related traits. As the initial screening site is not located within the TPE, the research Center CNPMS developed a "pre-trial" phase, in which the best entries from the screen at CNPMS are sent to CNPAF, located within the major TPE. After 1–2 years of testing at CNPAF, the best 50 entries undergo multi-environment trials in the TPE. This strategy aims at uniform trend gains in the selection for the TPE.

The simulation results of this study for maize as first crop TPE indicated that the RWSI for yield is less than 50% for both soil depth scenarios (Table 2). The L and M stress patterns represent over 90%. However, we observed that the TPE for first crop maize is more heterogeneous than that of rice due to the larger seasonal window for planting. This explains why the mean RWSI for maize 1st crop TPE are higher than that for rice (Table 2). As observed for rice, the currently practiced strategy for maize selection based on yield potential yield appears to be appropriate in view of the generally low severity of drought. Probably, the "pre-trial" phase could be substituted by an indirect selection method, where yields are 'weighted' (Cooper and DeLacy 1994). This procedure will take into account the variation over the TPE and probably give a uniform trend gains in the selection for the TPE. Therefore, the best entries selected from screening (CNPMS) could be distributed directly to sites in the TPE, reducing the time in the selection process.

EMBRAPA´s maize screening site CNPMS was found to be more stress prone than the overall TPE for maize as 1st crop (Fig. 6c). Using the best planting date, e.g. around 1 November, in the screening site, and with supplemental irrigation (semi-managed system), it should be possible to identify genotypes that maximize the potential yield for this 1st crop.

The second crop maize TPE, denominated in Brazil as "Safrinha", markedly differed from the 1st crop maize TPE. This crop is highly dependent on the sowing date and duration of the 1st crop. The 2nd crop maize system is not studied in detail and has no specific breeding program exists for it, as the system has only evolved recently. However, its importance is increasing in many areas although, all genotypes available for "Safrinha" come from selection for the traditional crop season (Tojo-Soler et al. 2001).

The 2nd crop maize TPE showed the highest mean RWSI among the TPEs studied (52% for deep soil and 73% for shallow soil). According to Fukai and Cooper (2001), severe drought conditions call for drought escape and/or tolerance mechanisms. Because stress simulated for the RT stress pattern (reproductive to terminal) was generally severe, the escape mechanism would theoretically be more promising. This mechanism is already being used by some farmers who prefer to grow "superprecoce" hybrids that flower earlier, at less than 830°C d from planting (Gadioli 2000). As terminal stress probability and intensity (Fig. 5d) are highly dependent on planting date, further research should be conducted into cropping calendars and the choice of cultivars that are grown in direct succession.

Selection for (early) phenology *per se* does not require drought environments. Specific selection for tolerance to silking stage and terminal stress, applied to ultra-short duration populations, would also be useful if sufficient genetic diversity exists. Genotypes could be developed by making use of the naturally occurring decrease in rainfall in this TPE, possibly with supplemental irrigation during vegetative growth to avoid cases of early onset of drought (semi-managed). As shown by Fig. 6d, it is difficult to "mimic" the environmental conditions of this TPE (high probability of terminal stress) in the Embrapa maize screening site CNPMS during the crop season.

Conclusion

The methodology shown in this study can be applied to environmental characterization. However, the success of this methodology is highly dependent on the amount and quality of climatic data available for the target environment. In many countries, such as the example in this study, it can be a restriction. Based on the climatic data available in this study, it could be concluded that:

– For upland rice, both short and medium-duration, the region can be characterized by three different stress patterns. For upland rice short cycle the stress patterns were low (L), mid-season (M) and terminal (T) stress and for medium cycle low stress (L), vegetative stage stress (V) and mid-season to terminal stress (MT). For the scenario with no physical restrictions on root development, the stress level does not limit breeding for potential yield;
– for maize as first crop the region also can be characterized by three different stress patterns, nearly environment free of stress (L), a mild, mid-season stress pattern covering both the reproductive and early grain filling periods (M), and severe

drought occurring during the late reproductive period (SR). For the scenario with no physical restrictions on root development, the stress level also does not limit breeding for potential yield;
- for these crops in shallow soils, there is a need to attempt to use two to three site × planting date combinations that are more likely to cause development of mid-season and terminal type droughts that could identify germplasm with improved adaptation at these greatly reduced yield levels;
- for maize as second crop, the breeding target should be "escape" (developing of earlier-season cultivars) and/or development of a drought breeding program specific for terminal stress;

Acknowledgements We would particularly like to thank Dr. Camilo de L. T. Andrade (Embrapa Maize and Sorghum), Sergio Lopes Jr., Msc Silvando C. da Silva (Embrapa Rice & Beans), Andre Amorim and Rosidalva Lopes da Paz (SECTEC/SIMEGO—Secretaria da Agricultura do Estado de Goiás) for providing us with the climate data and the Generation Challenge Programme (CGIAR) for financial support to the project.

References

Affholder F (1997) Empirically modelling the interaction between intensification and climatic risk in semiarid regions. Field Crops Res 52:79–93

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration—guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. FAO, Rome, Italy

Asch F, Sow A, Dingkuhn M (1999) Reserve mobilization, dry matter partitioning and specific leaf area in seedlings of African rice cultivars differing in early vigor. Field Crops Res 62:191–202

Balbino LC, Bruand A, Brossard M, Guimarães MF (2001) Comportement de la phase argileuse lors de la dessication dans des Ferralsols microagrégés du Brésil: rôle de la microstructure et de la matiére organique. C R Acad Sci Paris II A 332(11):673–680

Ball RA, Purcell LC, Carey SK (2004) Evaluation of solar prediction models in North America. Agron J 96:391–397

Baron C, Clopes A, Perez P, Muller B, Maraux F (1996) Manuels d'utilisation de SARRAMET 45 p, SARRABIL 35 p et SARRAZON 29 p., CIRAD, Montpellier, France

Baron C, Reyniers FN, Clopes A, Forest F (1999) Applications du logiciel SARRA à l'étude de risques climatiques. Agriculture et Développement 24:89–97

Baron C, Sultan B, Balme M, Sarr B, Traore S, Lebel T, Janicot S, Dingkuhn M (2005) From GCM grid cell to agricultural plot: scale issues affecting modelling of climate impact. Phil Trans R Soc B 360:2095–2108

Bolanos J, Edmeades GO (1993) Eight cycles of selection for drought tolerance in lowland tropical maize. II. Responses in reproductive behavior. Field Crop Res 31:253–268

Buainain AM, Romeiro AR, Guanziroli C (2003) Agricultura familiar e o novo mundo rural. Sociologias 10:312–347

Ceccarelli S, Grando S (1991) Environment of selection and type of germplasm in barley breeding for low-yielding conditions. Euphytica 57:207–219

Chapman S, Cooper M, Butler DG, Henzell RG (2000a) Genotype by environment interactions affecting grain sorghum. I. Characteristics that confound interpretation of hybrid yield. Aust J Agric Sci 51:197–207

Chapman S, Cooper M, Hammer GL, Butler DG (2000b) Genotype by environment interactions affecting grain sorghum. II. Frequencies of different seasonal patterns of drought stress are related to location effects on hybrid yields. Aust J Agric Sci 51:209–221

Chapman S, Hammer GL, Butler DG, Cooper M (2000c) Genotype by environment interactions affecting grain sorghum. III. Temporal sequences and spatial patterns in the target population of environments. Aust J Agric Sci 51:223–233

Cooper M, DeLacy IH (1994) Relationships among analytical methods used to study genotypic variation and genotype-by-environment interaction in plant breeding multi-environment experiments. TAG Theor Appl Genet 88:561–572

Cooper M, Stucker RE, DeLacy IH, Harch BD (1997) Wheat breeding nurseries, target environments, and indirect selection for grain yield. Crop Sci 37:1168–1176

Cruz RT, O'Toole JC (1984) Dry land rice response to an irrigation gradient at flowering stage. Agron J 76:178–183

Dingkuhn M, Baron C, Bonnal V, Maraux F, Sarr B, Sultan B, Clopes A, Forest F (2003) Decision support tools for rainfed crops in the Sahel at the plot and regional scales. In: Struif Bontkes TE, Wopereis MCS (eds) Decision support tools for smallholder agriculture in Sub-Saharan Africa—a practical guide. CTA Wageningen, The Netherlands, pp 127–139

Doorenbos J, Kassam AH (1979) Yield response to water. FAO Irrigation and Drainage Paper No 33. FAO, Rome, Italy, 193 pp

Doorenbos J, Pruitt WO (1977) Guidelines to predicting water requirements. FAO Irrigation and Drainage Paper No 24. FAO, Rome, Italy, 179 pp

EMBRAPA (1999) Centro Nacional de Pesquisa de Solos (Rio de Janeiro, RJ) Sistema Brasileiro de Classificação de Solos. Embrapa Produção de Informação, Embrapa Solos, Brasília

Fukai S, Cooper M (2001) Development of drought resistant cultivars for rainfed lowland rice experience from Northeast Thailand and surrounding areas, Proceedings of International Conference on the Impact of Agricultural Research for Development in Southeast Asia CARDI, Phnom Penh, Cambodia. 24–26 October 2000, pp 185–194

Gadioli JL, Dourado Neto D, Garcia y Garcia A, Basanta MV (2000) Air temperature, maize yield and phenological characterization associated to heat units. Scientia Agricola 57(3):377–383

IBGE (2006) Levantamento Sistemático da Produção Agrícola. IBGE. (http://www.sidra.ibge.gov.br/bda/)

Jongdee S, Mitchell JH, Fukai S (1997) Modelling approach for estimation of rice yield reduction due to drought in Thailand. In: Fukai S, Cooper M, Salisbury J (eds) Breeding strategies for rainfed lowland rice in drought-prone environments. Proceedings of an International Workshop, Ubon Ratchathani, Thailand, 5–8 November 1996, ACIAR Proceedings 77, Canberra, ACT, pp 65–73

LADSS (2004) LADSS Version 2.0—Climate Data "Cleaning" Process. http://www.macaulay.ac.uk/LADSS/reference.shtml

Lilley JM, Fukai S (1994) Effect of timing and severity of water deficit on four diverse rice cultivars. I. Rooting pattern and soil water extraction. Field Crops Res 37:205–213

Manneh B (2004) Genetic, physiological and modelling approaches towards tolerance to salinity and low nitrogen supply in rice (Oryza sativa L.). Wageningen University, Ph.D. Thesis 218 p

Martinez CP (1977) Aluminum toxicity studies in rice. Corvallis: Oregon State Univ PhD Thesis 113 p

Muchow RC, Cooper M, Hammer GL (1996) Characterizing environmental challenge using models. In: Cooper M, Hammer GL (eds) Plant adaptation and crop improvement. CABI, Wallingford, UK, pp 349–364

Nyquist WE (1991) Estimation of heritability and prediction of selection response in plant population. Crit Rev Plant Sci 10:235–322

Pantuwan G, Fukai1 S, Cooper M, Rajatasereekulc S, O'Tooled JC (2002) Yield response of rice (Oryza sativa L.) genotypes to drought under rainfed lowlands 2. Selection of drought resistant genotypes. Field Crop Res 73:169–180

Parentoni SN, Gama EEG, Santos MX, Lopes MA, Alves VMC, Bahia Filho AFC, Vasconcelos CA, Magnavaca R, Pacheco CAP, Meirelles WF, Guimarães PEO (1999) Adaptação de milho a solos ácidos: tolerância a toxidez de alumínio e eficiência no uso de nutrientes no Programa de Pesquisa da EMBRAPA-Milho e Sorgo. In: mémoria 18 Reunion Latinoameriaca del maiz, Sete Lagoas, 22–27/08/1999. EMBRAPA-CNPMS/México-CIMMYT, 684p., 179–202 p

Penning de Vries FWT, Jansen DM, Ten Berge HFM, Bakema A (1989) Simulation of ecophysiological processes of growth in several annual crops. PUDOC Wageningen, Wageningen, The Netherlands, p 291

Pinheiro B da S, Castro E da M de, Guimarães CM (2006) Sustainability and profitability of aerobic rice production in Brazil. Field Crops Res 97:34–42

Prance GT (1987) Vegetation. In: Whitmore TC, Prance GT (eds) Biogeography and quaternary history in tropical America. Oxford, NYC pp 28–45

R Development Core Team (2005) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org

Romano MR (2005) Physiological performance of the maize crop with different plants architecture: parameters for growth models. Thesis—Escola Superior de Agricultura Luiz de Queiroz, USP, São Paulo, Brazil. 100 pp

Samba A (1998) Les logiciels Dhc de diagnostic hydrique des cultures. Prévision des rendements du mil en zones soudano-sahéliennes de l'Afrique de l'Ouest. Sécheresse 9(4):281–288

Samba A, Sarr B, Baron C, Gozé E, Maraux F, Clerget B, Dingkuhn M (2001) La prévision agricole à l'échelle du Sahel. In: Malézieux E, Trébuil G, Jaeger M (eds) Modélisation des agro-écosystèmes et aide à la décision. Cirad and INRA, Montpellier, France, pp 243–262

Schaffert RE, Alves VMC, Parentoni SN, Raghthama KG (2000) Genetic control of phosphorus uptake and utilization efficiency in maize and sorghum under marginal soil conditions. In: Ribaut JM, Poland D (eds) Molecular approaches for the genetic improvement of cereals for stable production in water-limited environments. A strategic planning workshop held at CIMMYT El Batan, Mexico, 21–25 June 1999. Mexico DF: CIMMYT. Mexico DF

Sinclair TR, Ludlow MM (1986) Influence if soil water supply on the plant water balance of four tropical grain legumes. Aust J Plant Physiol 13:329–341

Sinclair TR, Muchow RC (1999) Radiation use efficiency. Adv Agron 65:215–265

Sultan B, Baron C, Dingkuhn M, Janicot S (2005) Agricultural impacts of large-scale variability of the West African monsoon. Agric For Meteorol 128:93–110

Tojo-Soler C, Folegatti MV, Faria RT (2001) Identification of the best genetic traits and agronomic practices for corn-sowed out of season using the CERES-Maize model. Revista Brasileira de Agrometeorologia Santa Maria 9(2):339–346

Vose JM, Sullivan NH, Clinton BD, Bolstad PV (1995) Vertical leaf area distribution, light transmittance, and application of the Beer-Lambert law in four mature hardwood stands in the southern Appalachians. Can J For Res 25:1036–1043

Ward JH (1963) Hierarchical grouping to optimise an objective function. J Amer Stat Assoc 58:236–244

Williams WT (1976) Pattern analysis in agricultural science. Elsivier Scientific Publishing Company, Amsterdam