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Onset of the rainy season and crop yield in sub-Saharan Africa – tools and perspectives for Cameroon

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Abstract In dry sub-humid and semi-arid regions, where rainfall is limited to only a few months per year, rainfall is the most important factor affecting crop growth and yield. Every year, farmers are faced with the crucial question of when to start planting. Do the first rainfalls after the dry season resemble the onset of the rainy season (ORS) or not? A fuzzy logic-based algorithm for estimating the ORS and the optimal planting date was developed. It is based on rainfall data and accounts for agriculturally meaningful aspects. The ORS algorithm, which calculates the planting date for each year, was coupled to the physically-based crop model CropSyst. A Monte Carlo approach was applied to generate annual planting dates from 1979 to 2003. Therefore, the definition constraints, which are allowed to vary within reasonable parameter ranges, are generated randomly. The averaged crop yield served as a performance measure for each realization. The parameter range of the best realizations is retained. Various iterations are necessary to obtain a robust set of "optimal" definition parameters. The coupled ORS definition-crop modelling system was applied for two different crop species and five different observation stations across Cameroon for the period 1979–2003. It is shown that the derived "optimal" planting dates would allow for significantly increased crop yields compared to the existing planting rules in Cameroon.

Key words crop modelling; CropSyst; Monte Carlo approach; onset of the rainy season; planting date

INTRODUCTION

The spatial and temporal variations of crop yield may have a profound impact on the national economy of semi-arid sub-Saharan countries, which are primarily dependent on the agricultural sector. These variations result from changes in numerous factors, in particular, physical and chemical soil properties, climatic factors and human management. Of all climatic factors in semi-arid sub-Saharan Africa, rainfall variability is considered to be the most critical for rainfed agriculture. According to Sivakumar (1988), the variable nature of rainfall is often given as the main reason for frequent crop failures and food shortages, and the intra-seasonal distribution of rainfall is more important than the total seasonal rainfall amounts (e.g. Monteith, 1991). Wheeler *et al.* (2005) showed the simulated effect of evenly and unevenly distributed intra-seasonal rainfall on crop productivity for a station in India, independent of the seasonal rainfall amount.

The amount of water available to plants strongly depends on the onset, termination and length of the rainy season (Ati *et al.*, 2002). According to Stewart (1991), the onset of the rainy season (ORS) is the most agriculturally relevant variable to which all the other seasonal variables are related. The ORS determines the planting date, with planting too early possibly leading to crop failure, and planting too late leading to a reduced growing season and crop yield (Sarria-Dodd & Jolliffe, 2001). For sowing, it is important to know whether the rains are continuous and sufficient to ensure enough soil moisture during planting and whether this level will be maintained, or even increased, during the growing period in order to avoid crop failure (Walter, 1967).

There is increasing awareness that short-term climate events of only a few days duration can severely impact crop productivity if they coincide with a sensitive phase of the growing cycle, e.g. the occurrence of high temperatures near to the time of flowering (e.g. Wheeler *et al.*, 2000) or the occurrence of dry spells, which can cause total crop failure, during the development stages in dry sub-humid and semi-arid regions (Laux *et al.*, 2009). Dry spells should also be analysed, additionally accounting for the different crop specific needs during all development stages in combination with the water balance of the location, because actual water stress depends on rainfall partitioning, water holding capacity of the soil, crop water demand, antecedent soil water and crop water uptake (Barron *et al.*, 2003).

Sultan *et al.* (2005) studied the impact of the regional variability of the West African monsoon on simulated yield at the plot scale. The response of attainable yield, limited by climate and water resources but not by mineral nutrition, to sowing date was studied for millet at Niamey (Niger) using the crop model SARRAH. It was found that variations in annual rainfall amounts and the intra-seasonal rainfall variability explained a large fraction of the variability of attainable crop yield. Moreover, information about the regional date of the ORS, characterized by an abrupt northward shift of the Intertropical Convergence Zone (ITCZ) from 5°N to 10°N, may contribute to a better choice of the sowing date, and thus to a significant improvement of crop productivity.

Modifying the approaches of Stern *et al.* (1981) and Sarria-Dodd & Jolliffe (2001), Laux *et al.* (2008) developed a fuzzy logic and rainfall-based definition for estimating the regional ORS in the Volta Basin of West Africa. The definition considered the following agricultural meaningful aspects:

- ensuring sufficient soil moisture content at the planting time;
- avoiding misinterpretations of single heavy showers as the ORS;
- avoiding occurrences of dry spells at the beginning of the growing season, when they can hinder germination and lead to total crop failure.

However, due to lack of the required input data for dynamical crop modelling, no evaluation of the calculated ORS dates in terms of crop yields could be conducted for the Volta Basin.

The purpose of this study was to evaluate the ORS definition of Laux *et al.* (2008) for deriving planting dates of the first (major) rainy season at different locations across Cameroon. The attainable crop yields following the ORS definition and traditional planting rules were compared. In a first step, the ORS definition, established for the Volta Basin in West Africa, was adjusted for two different crop varieties and five different locations in Cameroon using a Monte-Carlo approach and the physically-based crop model CropSyst.

RESEARCH AREA AND DATA

Climate and agriculture in Cameroon

Cameroon covers an area of about 475 440 km^2 and is located between 2°N and 13°N. It is ranked 172 out of 229 countries in the world in terms of per capita income. Nearly 40% of the population live on <2 US$ per day.

The research area is characterized by highly contrasting physical features, including approximately 400 km of coastline and mountainous regions with altitudes up to 4000 m (Fig. 1). Reflecting the topography and latitudinal range, very steep gradients of isohyets occur from the humid (>4000 mm annual rainfall amount) equatorial region in the southwest and the semi-arid (~400 mm annual rainfall amount) region in the north (ORSTOM, 1996). The intra-annual distribution of rainfall is modulated by the shift of the ITCZ. In the northern regions of Cameroon, between 7°N and 10°N (Garoua, Ngaoundéré), only one rainy season occurs, lasting roughly from May to October, whereas a bimodal rainfall distribution exists in the equatorial south (Bamenda, Batouri and Yaoundé). The first rainy season, which is longer and more profitable, ranges roughly from March to July, and the second one from August to November.

Agriculture is the mainstay of the economy of Cameroon, accounting for 45% of the gross domestic product; 80% of the labour force is employed in this sector and most of the country’s poor live in rural areas where small scale subsistence farming is predominantly practised.

The growing season is strongly related to the rainy season, and following the mean regional ORS, the traditional planting date for the equatorial south is set to 15 March and 15 August, and in the northern region to 15 May (Ndemah, 1999).

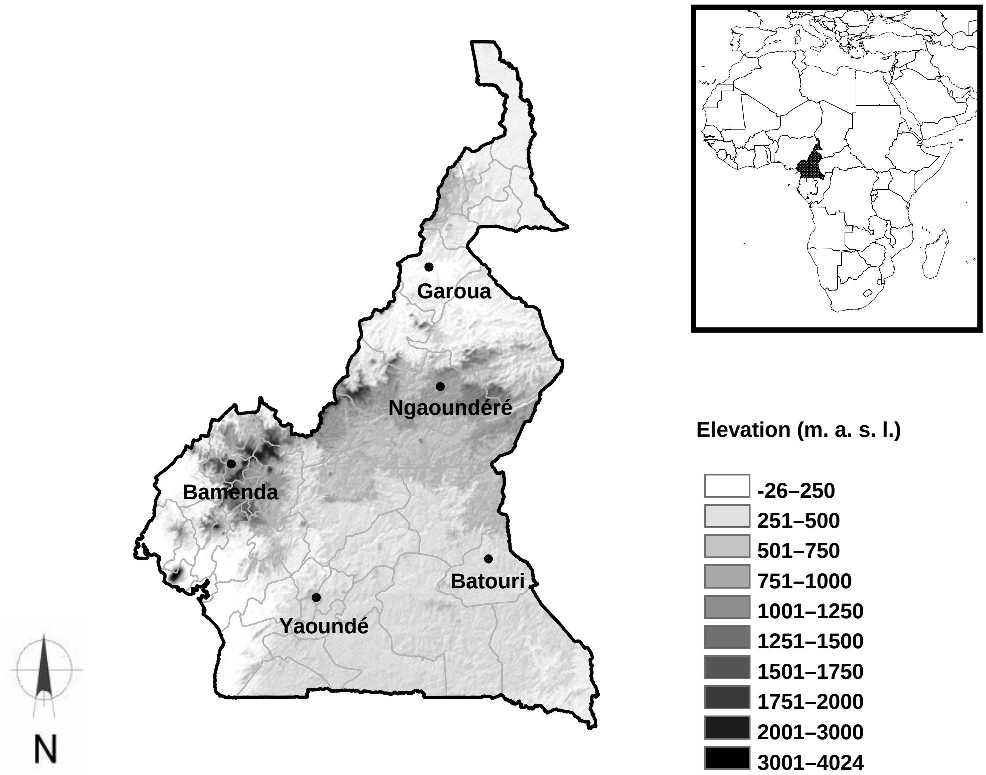

Fig. 1 Digital elevation model DEM of Cameroon and location of the five meteorological stations (data source: http://srtm.csi.cgiar.org/).

Table 1 Location and mean climatological characteristics of the five meteorological stations in Cameroon for 1979–2003.

Station	Latitude (°N)	Longitude (°E)	Elevation (m.a.s.l.)	Tmin (°C)	Tmax (°C)	Annual rainfall (mm)
Bamenda	6.05	10.10	1239	14.8	24.6	2378
Batouri	4.47	14.37	656	18.9	28.9	1499
Garoua	9.33	13.38	244	22.7	33.1	1090
Ngaoundéré	7.34	13.57	1104	15.5	28.1	1514
Yaoundé	3.83	11.51	760	19.6	27.7	1655

Data

For the crop modelling performed, daily meteorological data from 1979 to 2003 for five different meteorological observation stations in Cameroon were used (Fig. 1). Table 1 shows their coordinates and mean climatological characteristics, provided by the University Cooperation for Atmospheric Research (UCAR). Solar radiation data were not available and were empirically estimated by CropSyst.

The required soil properties, e.g. layer thickness or hydraulic properties were obtained from the International Soil Reference and Information Center (Batjes, 1995).

METHODOLOGY

The physically-based crop model CropSyst

CropSyst is a multi-year, multi-crop, daily time step cropping systems simulation model developed for studying the effect of the interaction of climate, soils and management on the productivity and environment of cropping systems (Stöckle *et al.*, 2003). The model simulates soil water budget, crop phenology, canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and salinity. These processes are affected by weather, soil and crop characteristics and cropping system management, such as crop rotation, cultivar selection, irrigation, nitrogen fertilization, soil and irrigation water salinity, tillage operations, and residue management.

The unstressed (potential) biomass growth is calculated as a function of crop intercepted photosynthetic active radiation (PAR) and potential transpiration. The actual biomass growth as well as the resulting crop yield, however, is limited by the stress intensity of water and nitrogen, expressed in terms of the harvest index (Monteith, 1981; Tanner & Sinclair, 1983). The simulated crop yield is calculated as the ratio between actual total biomass accumulated at physiological maturity and crop specific harvest index (harvestable yield/above ground biomass).

Crop growth is dependent on the thermal time required to reach specific development stages, expressed as growing degree days (GDD) accumulated throughout the growing season. Stress due to temperature and water reduces crop yield by accelerating the accumulation of thermal time (thereby reducing the GDD), and stress sensitivity is allowed to differ between specific crops in the development stages in the model.

The water budget is considered in the model via rainfall–runoff infiltration with redistribution in the soil profile, and evapotranspiration (interception by crop canopy and residues, crop transpiration, soil evaporation). Soil water dynamics are calculated using Richards equation, which is solved numerically using finite differences. More detailed information about CropSyst can be found in Stöckle *et al.* (2003).

In this study, CropSyst was used to study the effect of the planting date on annual crop yields for maize and groundnut at five locations across Cameroon. Parameterization of crop specific values was performed using the experience of Tingem *et al.* (2008a) and proposed values from the CropSyst user manual. Further parameters were obtained from minimizing the difference between observed and simulated crop yields. Phenological parameters (e.g. GDD) were calibrated using data provided by the Institute of Agricultural Research (IRA-Cameroon). The difference between modelled and observed yields lay within an acceptable range (Tingem *et al.*, 2008a,b).

For estimating the potential evaporation, the approach of Priestley & Taylor (1972) was applied using a Priestley-Taylor constant of 1.73 for Cameroon (Tingem, 2008).

Sensitivity analysis of the planting date

Fig. 2 illustrates the impact of the mean planting date (Day of Year, DOY) on mean crop yield for maize and groundnut (1979–2003) varying the planting date from DOY 1 to DOY 350 with an increment of 25 days. The five observation stations differ in physical and chemical soil properties (except for Garoua and Ngaoundéré) and the climatic conditions, which are affected by the elevation of the stations.

The attainable crop yield differs remarkably among the five stations. The highest yields were obtained for Garoua, Ngaoundéré and Yaoundé. These differences can be related to climatic as well as edaphic properties of the observation stations. In addition, the attainable mean crop yield is strongly related to the planting date, with most favourable yields planting on DOY 50 and DOY 250 (DOY 225) for groundnut (maize). The sensitivity analysis gives a rough estimation for the optimal mean planting dates at the different locations across Cameroon in terms of crop yield.

In order to improve the attainable crop yield, intra-seasonal rainfall variability must be considered. For this reason, the ORS definition of Laux *et al.* (2008) was used to estimate the optimal planting dates and is detailed in the following section.

The rainfall based ORS definition

The ORS determines the planting/sowing date and was calculated following the definition of Laux *et al.* (2008). This definition, established for the Volta Basin in West Africa, is based on rainfall data alone and can be adapted to different climatic regions and different crop varieties via fuzzy-

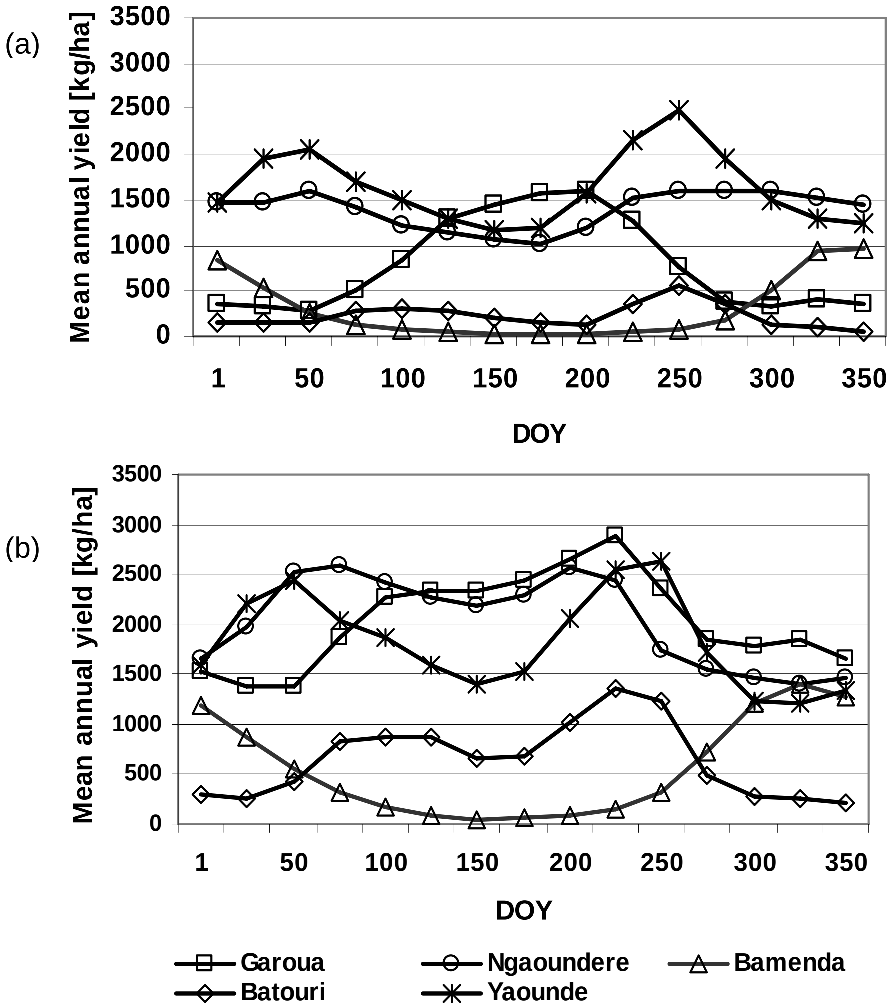

Fig. 2 Impact of the planting date (DOY) on the mean annual crop yield (1979–2003) for: (a) groundnut and (b) maize.

logic. Following the approach of Laux *et al.* 2008), the ORS is calculated as the first day of the year when the product γ of three different membership grades, γ_1, γ_2 and γ_3 exceeds a certain threshold, k. The threshold can range between 0 and 1. The membership grades are calculated by means of membership functions, accounting for rainfall amounts, number of rainy days and occurrence of dry spells.

The membership functions can be described as a special form of triangular fuzzy numbers (subscript T), in which the third number is assigned to $+\infty$. The first membership function of the ORS definition of Laux *et al.* (2008) is illustrated in Fig. 3(a). It is described by the triangular fuzzy numbers (18, 25, $+\infty$)T and accounts for the total amount of rainfall within a 5-day period. The membership grade, γ_1 of rainfall amounts less than 18 mm is attached to zero and amounts larger than 25 mm to unity. Between 18 and 25 mm rainfall, the membership grade is linearly interpolated.

The second membership function describes the number of rainfall events in a 5-day period and is allowed to vary between 1 and 5. It can be described as (1, 3, $+\infty$)T. The third function, the so-called false start criterion of the ORS definition, describes the number of consecutive days after the ORS, in which a dry spell (no rainfall) of 7 or more days occurs to reject the ORS. The respective fuzzy numbers are $(22, 30, +\infty)_T$.

The planting date is a function of 8 parameters: the marginal values, k_1 and k_2, of the threshold value, k, and the marginal values of the linearly interpolated definition domain of the first

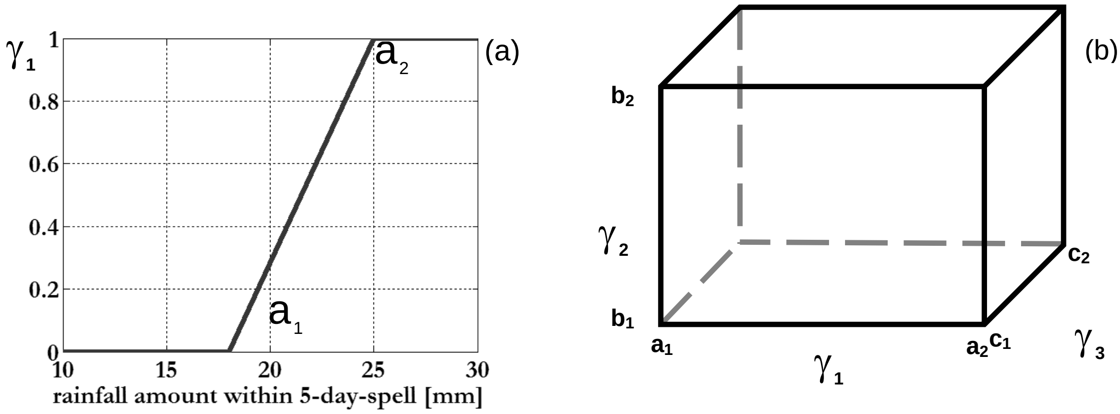

Fig. 3 (a) Membership function of the first definition criterion of the ORS definition of Laux *et al.* (2008) and (b) marginal values of the linearly interpolated range of all membership functions.

membership function, a_1, a_2, equally valid for the marginal values of the second and third membership function b_1, b_2, c_1, and c_2 (Fig. 3(b)). These parameters depend on the rainfall conditions at the location and the crop water requirement of the different species. More information about the ORS definition is given in Laux *et al.* (2008).

Optimization of the ORS definition using CropSyst

In order to optimize the ORS definition of Laux *et al.* (2008) for the crop species maize and groundnut and five different locations in Cameroon a Monte Carlo approach was applied, coupling the ORS definition to the physically-based crop model CropSyst. The objective function was to identify the best parameter domain for the ORS definition to maximize the mean annual crop yield for 1979–2003.

The optimization procedure includes the following steps:

– Initializing the ORS definition parameter domain for a_1, a_2, b_1, b_2, c_1, c_2, k_1 and k_2.
– Choosing randomly 8 parameters within the ORS definition parameter domain.
– Calculating the ORS dates from 1979 to 2003 using the ORS definition and assigning the ORS dates as planting dates to CropSyst (500 realizations).
– Simulating the annual crop yield for the period 1979–2003 and calculating the annual mean value (MCY).
– Repeating steps (a)–(d) 500 times. Deriving the parameter range of the best 5% of the 500 simulations in terms of MCY.
– Repeating steps (b)–(d) with the new parameter range obtained from step (e) until the increase in MCY falls below a certain threshold.

Prior to the optimization, a sensitivity analysis of k was performed to restrict the initial parameter range of k. Low values of k lead to early ORS dates with increasing risk of total crop failure, whilst high values drastically reduce the growing time (Laux *et al.*, 2008) and should be excluded to save computational time. For sensitivity analysis the initial values for a_1, a_2, b_1, b_2, c_1 and c_2 were taken to calculate the planting dates and the annual mean crop yields using varying k values from 0 to 1 in increments of 0.1. The upper and lower bounds of k leading to the highest yields were taken as k_1 and k_2. Fig. 4 shows the simulated mean annual yield of maize as a function of k. Hence, for station Garoua and maize, the initial parameter range of k was allowed to vary between $k_1 = 0.1$ and $k_2 = 0.9$. The initial marginal values of the three ORS definition criterions are shown in Table 2.

The restricted parameter domain of k for the five observation stations across Cameroon is shown in Table 3. For the two northernmost stations, Garoua and Ngaoundéré, only a small restriction of the parameter domain could be achieved, whereas at the southerly stations the k parameter domain could be restricted by more than 50%.

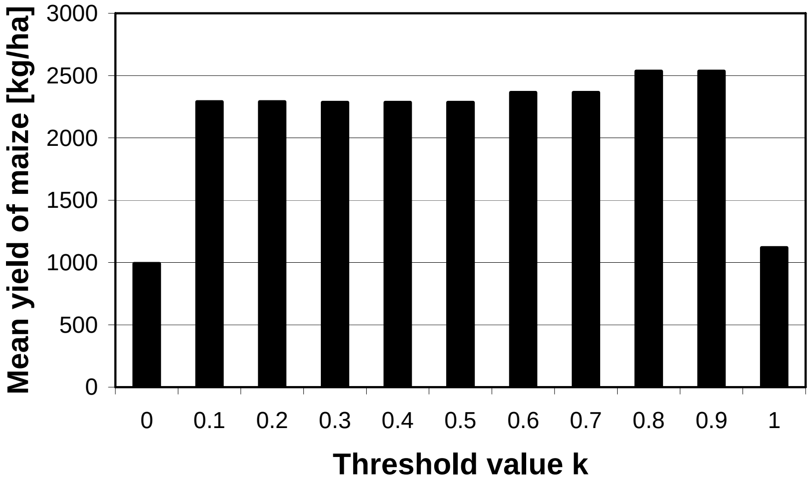

Fig. 4 Mean annual yield of maize (kg/ha) at station Garoua as a function of the threshold value k using the initial values for the 3 membership functions of the ORS definition.

Table 2 Initial parameters used for the optimization of the three ORS definition criteria.

a1	a2	b1	b2	c1	c2
10	30	1	5	5	40

Table 3 Restricted parameter domain of k for the meteorological stations across Cameroon separately for the crop species maize and groundnut. The lower bound of k is assigned to k_1 and the upper bound to k_2.

	Maize	Groundnut
Garoua	0.10 … 0.90	0.10 … 0.90
Ngaoundéré	0.10 … 1.00	0.10 … 0.90
Bamenda	0.10 … 0.50	0.10 … 0.50
Batouri	0.30 … 0.70	0.10 … 0.70
Yaoundé	0.10 … 0.70	0.10 … 0.70

RESULTS AND DISCUSSION

In this study the impact of the planting date on productivity of maize and groundnut was analysed in order to optimize the ORS definition of Laux *et al.* (2008) in Cameroon. Unlike traditional planting rules consisting of fixed planting dates, this ORS definition allows for interannual variability of the planting dates depending on the prevailing rainfall conditions. Therefore, the prevailing rainfall conditions are translated into planting dates based on the definition criteria. Eight parameters are required for calculating the dates of the ORS relating to the proposed planting dates.

A total of 500 simulations per iteration with randomized definition parameters were performed. After the iteration the parameter domain of the best 5% simulations was retained and assigned to the next iteration as boundary values. Thus, the initial parameter domain was restricted and a robust parameter set was finally obtained.

Fig. 5 illustrates the mean attainable crop yield (1979–2003) and the mean coefficient of variation (ratio of standard deviation and mean attainable crop yield) for the best 5% simulations of the first 10 iterations in terms of mean crop yield. Few iterations are necessary to considerably restrict the initial parameter domain of the ORS definition and to obtain a robust parameter set for the ORS definition. Six (seven) iterations lead to good mean yields and low CV values for groundnut (maize).

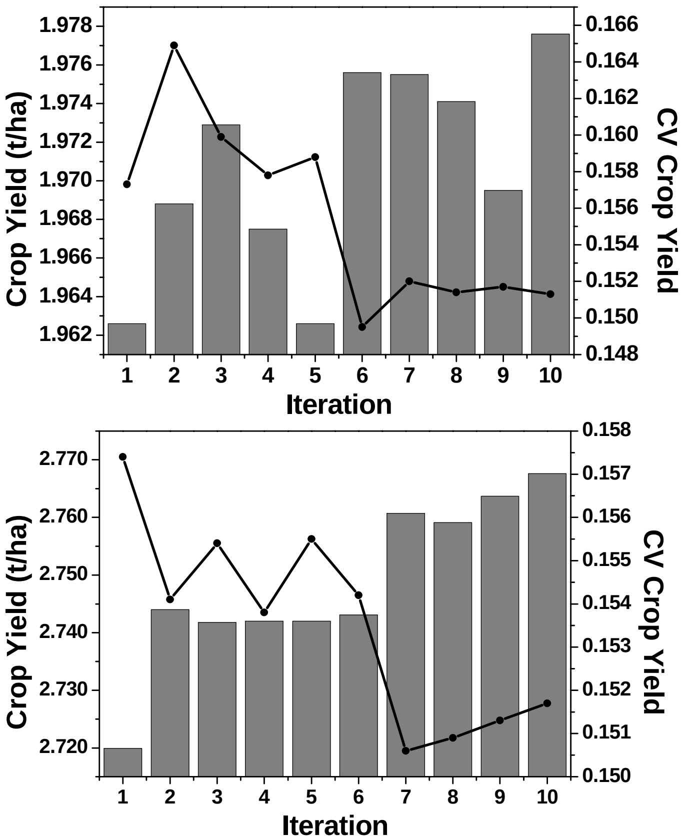

Fig. 5 Simulated mean crop yield (bars) and coefficient of variation (line) for groundnut (top) and maize (bottom) at Garoua. 10 iterations with 500 realizations were performed.

Even though CropSyst does not allow for total crop failure through hindered germination due to dry spells at the beginning of the growing season, the occurrence of dry spells after planting (*false start criterion*) influences the attainable crop yield (Fig. 6). During the optimization, the *false start criterion* could be greatly restricted.

Fig. 7 shows an example of the interannual differences in the simulated crop yield using the calculated planting dates (ORS definition) and the traditional planting date. Except for one (four)

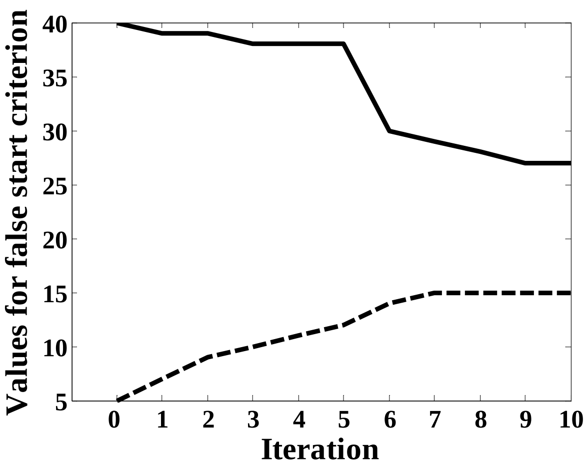

Fig. 6 Restriction of the parameter domain for the *false start criterion* of the ORS definition per iteration. The dashed line represents the definition parameter c1, the solid line the definition parameter c2; the initial values were at iteration 0.

year(s), the crop yield could be increased significantly for maize (groundnut) following the ORS definition of Laux *et al.* (2008). The mean value (standard deviation) of calculated planting date at Garoua is DOY 214 (29 days) for maize and DOY 180 (29 days) for groundnut. The traditional planting date at Garoua is DOY 135 (Ndemah, 1999).

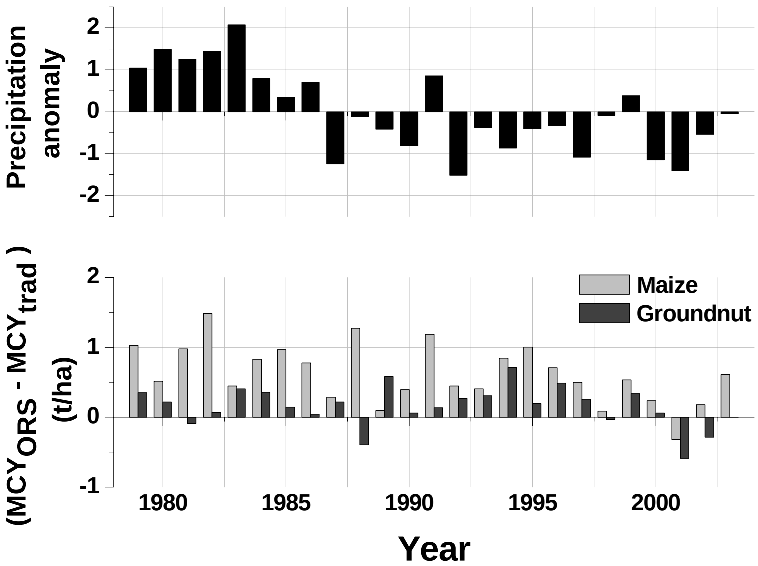

Fig. 7 Precipitation anomaly (top) and difference between simulated mean crop yield (MCY) using the ORS definition and simulated MCY using the traditional planting date (15 May, DOY 135) for maize and groundnut (bottom) at Garoua.

Compared to the traditional planting rules, using the ORS definition based planting dates could increase the mean attainable crop yields by up to 22.4% for maize and 7.8% at Garoua for groundnut. Higher increases of crop yield, in general, could be achieved in anomalously wet years. Similar increases of mean attainable crop yields using the ORS definition are found for the other observation stations (results not shown).

CONCLUSION

We present an evaluation of the ORS definition of Laux *et al.* (2008), originally developed for the Volta Basin in West Africa, for giving decision support about the planting date in Cameroon, where agricultural productivity is mainly dependent on the intra-seasonal distribution of rainfall.

The ORS definition is coupled to the physically based crop model CropSyst in order to derive annual attainable yields for the major rainy season. The criteria of the ORS definition are optimized to maximise the mean crop yield (averaged over the period 1979–2003). As the *false start criterion* of the ORS definition is greatly restricted by the optimization procedure, it can be concluded that the occurrence of dry spells during the early stages of growth is crucial for agricultural productivity.

Crop modelling using the optimized ORS definition led to higher crop yields than following traditional planting rules in Cameroon. The traditional and derived mean “ideal” planting dates can differ remarkably, depending on the location. According to the crop modelling results, it is concluded that accounting for the intra-seasonal rainfall characteristics at the plot-scale improved the choice of the planting time, and thus increased the attainable crop yield.

For subsistence farmers, who are more interested in relatively good yields in poor rainfall years than in good average yields (e.g. Brouwer *et al.*, 1993), the ORS definition could also be optimized to minimize the coefficient of variation.

The results presented are solely based on crop yield simulations accounting for water limitations. In order to verify the relevance of the ORS definition for planting decisions in Cameroon, the simulation results must be validated for on-farm conditions. Other environmental constraints, such as mineral nutrition and weed competition, as well as socio-economic constraints, were not considered in this study.

The ORS definition is potentially useful for other sub-arid to sub-humid regions in the world where rainfed agriculture prevails. It is proposed to adjust the ORS definition for region and crop species of interest prior to its application. Physically based crop models such as CropSyst are appropriate tools for this purpose.

For the Volta Basin of West Africa, the ORS definition has proved suitable for judging day by day whether the ORS has begun or not. However, the transferability of this ORS-Nowcasting-System to Cameroon still requires investigation.

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