Waha, K., Müller, C., Bondeau, A., Dietrich, J. P., Kurukulasuriya, P., Heinke, J., Lotze-Campen, H. (2012 Online first): Adaptation to climate change through the choice of cropping system and sowing date in sub-Saharan Africa. - Global Environmental Change

DOI: 10.1016/j.gloenvcha.2012.11.001

Adaptation to climate change through the choice of cropping system and sowing date in sub-Saharan Africa

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Final draft of the article published in Global Environmental Change
First decision: 07-Jul-2012, Accepted: 12-Nov-2012, Early online: 13-Dec-2012

ABSTRACT

Multiple cropping systems provide more harvest security for farmers, allow for crop intensification and furthermore influence ground cover, soil erosion, albedo, soil chemical properties, pest infestation and the carbon sequestration potential. We identify the traditional sequential cropping systems in ten sub-Saharan African countries from a survey dataset of more than 8600 households. We find that at least one sequential cropping system is traditionally used in 35 % of all administrative units in the dataset, mainly including maize or groundnuts. We compare six different management scenarios and test their susceptibility as adaptation measure to climate change using the dynamic global vegetation model for managed land LPJmL. Aggregated mean crop yields in sub-Saharan Africa decrease by 6 % to 24 % due to climate change depending on the climate scenario and the management strategy. As an exception, some traditional sequential cropping systems in Kenya and South Africa gain by at least 25 %. The crop yield decrease is typically weakest in sequential cropping systems and if farmers adapt the sowing date to changing climatic conditions. Crop calorific yields in single cropping systems only reach 40-55 % of crop calorific yields obtained in sequential cropping systems at the end of the 21st century. The farmers' choice of adequate crops, cropping systems and sowing dates can be an important adaptation strategy to climate change and these management options should be considered in climate change impact studies on agriculture.

Key words:

Multiple cropping, Sequential cropping systems, Crop modelling, Agricultural management, Adaptation options

◗ We show the distribution of multiple cropping systems in sub-Saharan Africa. ◗ We model six agricultural management strategies for adaptation to climate change. ◗ Crop yields greatly vary between crops, cropping systems and the timing of sowing. ◗ Low-tech adaptation options are able to reduce negative effects of climate change.

1 INTRODUCTION

The number of undernourished people remains highest in sub-Saharan Africa compared to other world regions and population will be more than doubled in 2050 compared to 2000 (FAO, 2006). Among effective strategies like fighting poverty, stabilizing economies and ensure access to food, increased food production in smallholder agriculture will be a key strategy for fighting hunger (FAO, 2008). Agricultural production can be increased by expanding agricultural land and by increasing the intensification of crop production through higher crop yields and higher cropping intensities. The cropping intensity in less-developed countries can be increased by about 5-10 % during the next 35 years if adequate amounts of input are available (Döös & Shaw, 1999). Multiple cropping systems allow for this intensification by growing two or more crops on the same field either at the same time or after each other in a sequence (Francis, 1986b; Norman *et al.*, 1995). They already are common farming systems in tropical agriculture today (Table 1). In multiple cropping systems the risk of complete crop failure is lower compared to single cropping systems and monocultures providing a high level of production stability (Francis, 1986a). Furthermore the second crop in a sequence may benefits from an increased amount of nitrogen derived from fixation (Bationo & Ntare, 2000; Sisworo *et al.*, 1990) or phosphorous from deep-rooted species (Francis, 1986a) as well as from decreased disease pressure (Bennett *et al.*, 2012) which helps to reduce the use of mineral fertilizer and pesticides. Cropping intensity is not only important in terms of agricultural production; the duration crops cover the soil will also influence albedo, ground cover, carbon sequestration potential and soil erosion (Keys & McConnell, 2005). In sub-Saharan Africa, multiple cropping systems mostly consist of cereal-legume mixed cropping dominated by maize, millet, sorghum and wheat (Van Duivenbooden *et al.*, 2000). Maize- and cassava-based mixed cropping systems are common in humid East and West Africa, whereas millet-based mixed cropping is widely applied in dry East and West Africa (Francis, 1986b). Intercropping is the traditional and most frequently applied multiple cropping system in sub-Saharan Africa, however sequential cropping and mixed sequential cropping systems are also common indigenous management practices (Table 1).

Table 1 Definition of terms.

Term	**Definition, description**
Single cropping	A cropping system with only one crop growing on the field (Bennett *et al.*, 2012). Interchangeable with monoculture or continuous cropping.
Sequential cropping	A cropping system with two crops grown on the same field in sequence during one growing season with or without a fallow period. A specific case is double cropping with the same crop grown twice on the field.
Mixed sequential cropping	A cropping system with two intercropping systems grown on the same field in sequence during one growing season with or without a fallow period.
Growing period	The period of time from sowing to maturity determined by the sum of daily temperatures above a crop-specific temperature threshold = phenological heat unit sum (PHU).
Growing season	The period of time in which temperature and moisture conditions are suitable for crop growth, in the sub-tropical and tropical zones determined by the start and end of the main rainy season.
Multiple cropping	" […] may refer to either growing more than one crop on a field during the same time (intercropping), after each other in a sequence (sequential cropping) or with overlapping growing periods (relay cropping)" (Francis, 1986b; Norman *et al.*, 1995). Examples in sub-Saharan Africa are: - groundnut-millet succession in the northern part of central Africa (de Schlippe, 1956) - wheat-chickpea succession in Ethiopia (Berrada *et al.*, 2006) - maize double cropping in western Nigeria (Francis, 1986b) - cowpea-maize sequence cropping in the moist Savannah zone of northern Nigeria (Carsky *et al.*, 2001), - soybean and wheat sequences in Zimbabwe (Beets, 1982), - sorghum and pigeonpea in northern Nigeria (Francis, 1986a), - sorghum double cropping in southern Guinea and Savannah zones of West Africa (Kowal & Kassam, 1978).

Agricultural activities and consequently the livelihoods of people reliant on agriculture will be affected by changes in temperature and precipitation conditions in large parts of sub-Saharan Africa (Boko *et al.*, 2007; Christensen *et al.*, 2007; Müller *et al.*, 2011). Under climate change, many areas in sub-Saharan Africa are likely to experience a decrease in the length of the growing season, while in some highland areas rainfall changes may lead to a prolongation of the growing season (Thornton *et al.*, 2006). The degree of climate change impacts on agricultural production differs between crops (Challinor *et al.*, 2007; Liu *et al.*, 2008; Schlenker

& Lobell, 2010; Thornton *et al.*, 2011) and agricultural systems (Thornton *et al.*, 2010). Therefore the farmers' choice of an adequate cropping system and crop cultivar, especially in precipitation-limited areas, might be an important adaptation strategy to changing climate conditions (O´Brien *et al.*, 2000; Thomas *et al.*, 2007). Lobell *et al.* (2008) note that the identification of practicable adaptation strategies for cropping systems should be prioritized for regions impacted by climate change. However, few studies investigate the impact of climate change on agriculture in sub-Saharan Africa considering the cropping system applied or make an effort to identify the least impacted cropping systems. The study of Thornton *et al.* (2009) is an exception, analysing crop yield response to climate change of a maize-bean cropping sequence in East Africa under which beans grow in a separate second growing season.

Analysing different multiple cropping systems in a climate impact study for sub-Saharan Africa requires a dataset reporting their spatial distribution in the region, which to our knowledge is not available. Some crop calendars available at the global (Portmann *et al.*, 2010; Sacks *et al.*, 2010) or African scale (FAO, 2010) report the growing periods of individual crops but lack reporting calendars for multiple cropping systems, while some others only cover Asian regions (Frolking *et al.*, 2006; Frolking *et al.*, 2002). Fischer *et al.* (2002) identified potential double and triple cropping zones by comparing temperature and moisture requirements of four crop groups with climatic conditions worldwide. Thornton *et al.* (2006) developed a classification for agricultural systems in Africa by combining a global livestock production classification system, a farming system classification, and global land cover maps. Both datasets do not report the crop cultivars or the cropping systems.

The knowledge about the spatial distribution of multiple cropping systems needs to be expanded by more detailed information on the sub-national level. We analyse a household survey (Dinar *et al.*, 2008) carried out in 385 districts and provinces containing more than 8600 households in ten countries of sub-Saharan Africa to fill this gap. From this survey we are able to identify the traditional rainfed sequential cropping systems with two crops grown within one year. As these are advantageous management strategies because they allow for risk spreading and increased crop productivity, we test their susceptibility to future climatic conditions in comparison to alternative management strategies by simulating crop yields with the dynamic global vegetation model for managed land LPJmL (Bondeau *et al.*, 2007). We analyse the ability of each management strategy to maximize future crop productivity or lower negative impacts from climate change on crops. We perform this analysis in locations where sequential cropping systems are already applied by local farmers today and also for the entire region of sub-Saharan Africa in order to estimate potential benefits.

2 MATERIALS AND METHODS

2.1 Input data for current and future climate data

To describe current climatic conditions, we used time series of monthly temperature and precipitation as well as the number of wet days from the climate database CRU TS 3.0 (Mitchell & Jones, 2005) for the 30-year period 1971 to 2000 on a spatial resolution of 0.5° x 0.5°. Future climatic conditions for the 30-year period 2070-2099 were projected from the three Global Circulation Models (GCMs) MPI-ECHAM5 (Jungclaus *et al.*, 2006), UKMO-HadCM3 (Cox *et al.*, 1999), and NCAR-CCSM3 (Collins *et al.*, 2006) as in the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl *et al.*, 2007). As there is little consistency between GCM projections on precipitation (Boko *et al.*, 2007) they were chosen to show a wide range of possible future precipitation patterns without being outliers (Fig. 1). NCAR-CCSM3 is among the “wet GCMs” projecting mostly increases in annual precipitation while MPI-ECHAM5 is among the “dry GCMs”, projecting a strong drying in southern Africa which is less pronounced in UKMO-HadCM3. We choose climate projections for the SRES A2 emission scenario as this generally shows highest average global warming of 3.4°C until the end of the 21st century compared to the SRES A1b and B2 (2.8°C and 1.8°C) which are also available in the WCRP CMIP3 dataset (Meehl *et al.*, 2007). The monthly mean temperature and precipitation sums from these three GCMs were interpolated to a finer spatial resolution of 0.5° x 0.5° using bilinear interpolation and smoothed using a 30-year running mean. The temperature and precipitation anomalies from each GCM were calculated relative to the 1971-2000 average climate from CRU TS 3.0 and were then applied to this baseline while preserving observed variability (Gerten *et al.*, 2011). Daily mean temperatures were obtained by linear interpolation between mean monthly temperatures, and daily precipitation data was provided by a weather generator which distributes monthly precipitation to the number of observed wet days in a month, considering the transition probabilities between wet and dry phases (Geng *et al.*, 1986; Gerten *et al.*, 2004). We kept the number of wet days constant at their average number from the time period 1971-2000. Geng *et al.* (1986) confirms that the rainy days as well as the amount of precipitation generated from this procedure are in general very close to observations in different environments. In this analysis we keep atmospheric CO_2 concentrations constant at 370 ppm. Increasing atmospheric CO_2 concentrations can increase the productivity of plants (especially C3 plants), but the effectiveness on increasing crop yields is uncertain (Long *et al.*, 2006; Tubiello *et al.*, 2007) and does require adaptation in management (Ainsworth & Long, 2005).

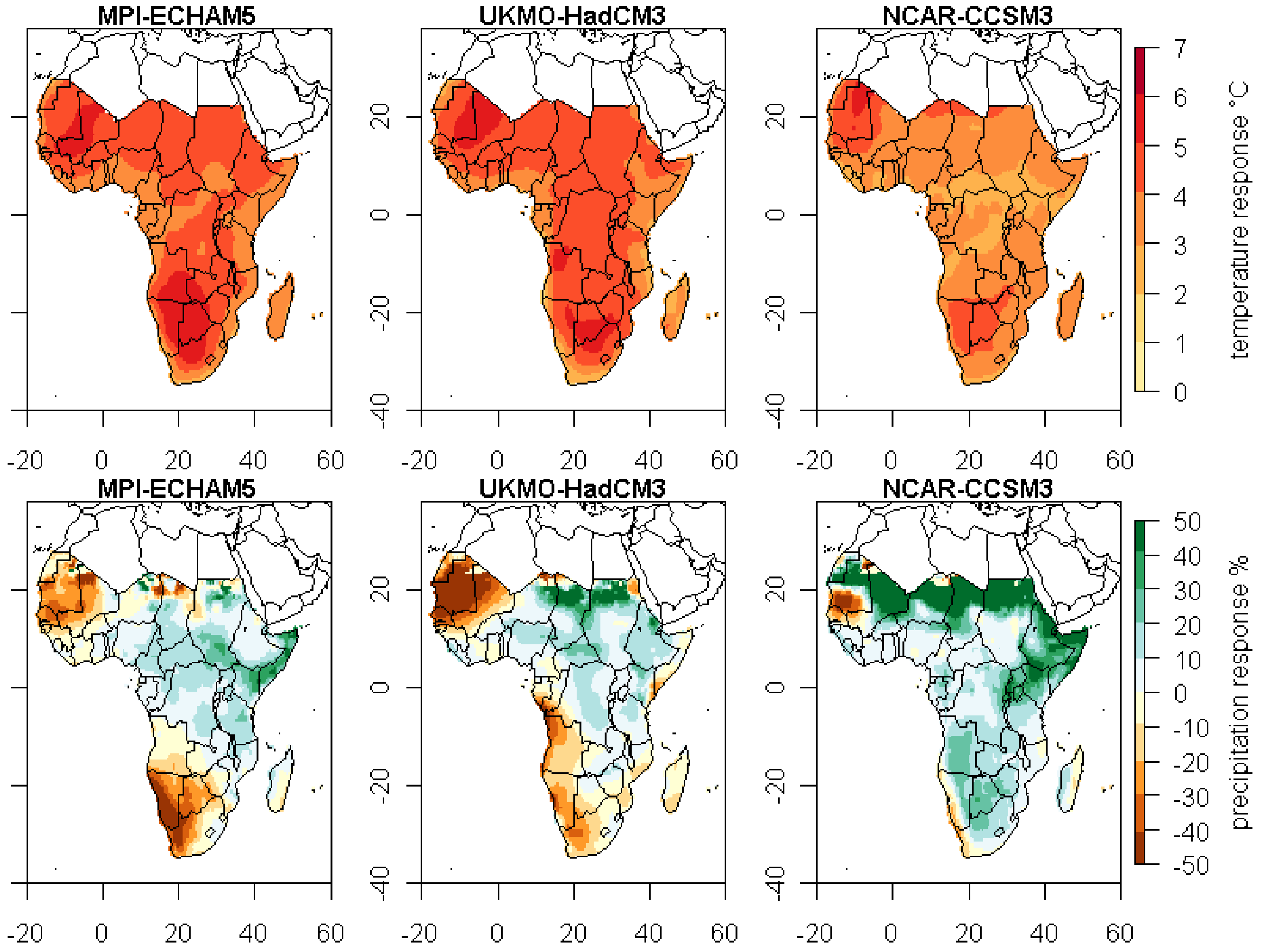

Figure 1 Change in annual mean temperature and annual mean precipitation from the periods 1971-2000 to 2070-2099 projected from three GCMs under the SRES A2. Brown and green colours in the lower three panels indicate a decrease or an increase in annual mean precipitation respectively.

2.2 Household survey dataset

A subset of a household survey (Dinar *et al.*, 2008) containing 8697 households in ten sub-Saharan African countries (Burkina Faso, Cameroon, Ethiopia, Ghana, Kenya, Niger, Senegal, South Africa, Zambia, and Zimbabwe) is used to calculate the growing periods (Table 1) of crops grown in different cropping systems. This dataset is the product of a World Bank/Global Environmental Facility project that was coordinated by the Centre for Environmental Economics and Policy for Africa (CEEPA) at the University of Pretoria, South Africa.

Half of the households are small-scale farmers, the other half are medium- or large-scale farmers. Each farm type was surveyed in each country but in Zimbabwe, Zambia and Ghana more than 80 % of the households are smallholders. In contrast, 73 % of all households in Senegal belong to a large-scale farm. The household survey reports sowing and harvest dates from 56 crops which are grown on up to three plots in up to three seasons within 12 months. In the households surveyed up to six crops are grown simultaneously on a plot. For each of these countries, data from 416 to 1087 households in 17 to 61 representative sample units (district or province) were collected for only one farming season (2002/2003 or 2003/2004). Sowing and harvest dates were reported on a daily, weekly or monthly basis and were converted into a uniform date specification using the day of the year. For weekly data we assumed the first day of the week, for monthly data the 15th day of the month is assumed. The length of the growing period in days is derived from these daily sowing and harvest dates for each crop. As harvest sometimes occurs shortly after sowing but the year of sowing and harvest events is not always reported, we assume a minimum length of 2 months for the growing period (6 months for cassava).

2.2.1 Identification of sequential cropping systems

We identify the sequential cropping and single cropping systems applied within one farming season in a sample unit by combining the information of the crops´ growing periods in each plot and season. As only nine out of 56 crops (cassava, cowpea, groundnut, maize, millet, rice, soybean, sunflower, and wheat) are included in the dynamic global vegetation model we combine the remaining crops to a group of “other crops”.

We assume sequential cropping systems if two crops are reported to be planted one after another without overlaps of more than 15 days and if their growing periods sum up to less than 365 days (Fig.2 D-G) i.e. the growing period of a crop here is restricted by the occurrence of the associated crop on the plot. In contrast, we assume single cropping systems if only one single crop is reported to grow on a plot (Fig. 2 B) or if more than one crop is grown on a plot but the sum of their growing periods is larger than 365 days and/or their growing periods overlap by more than 15 days (Fig.2 C, A), i.e. the conditions for a sequential cropping system are not met.

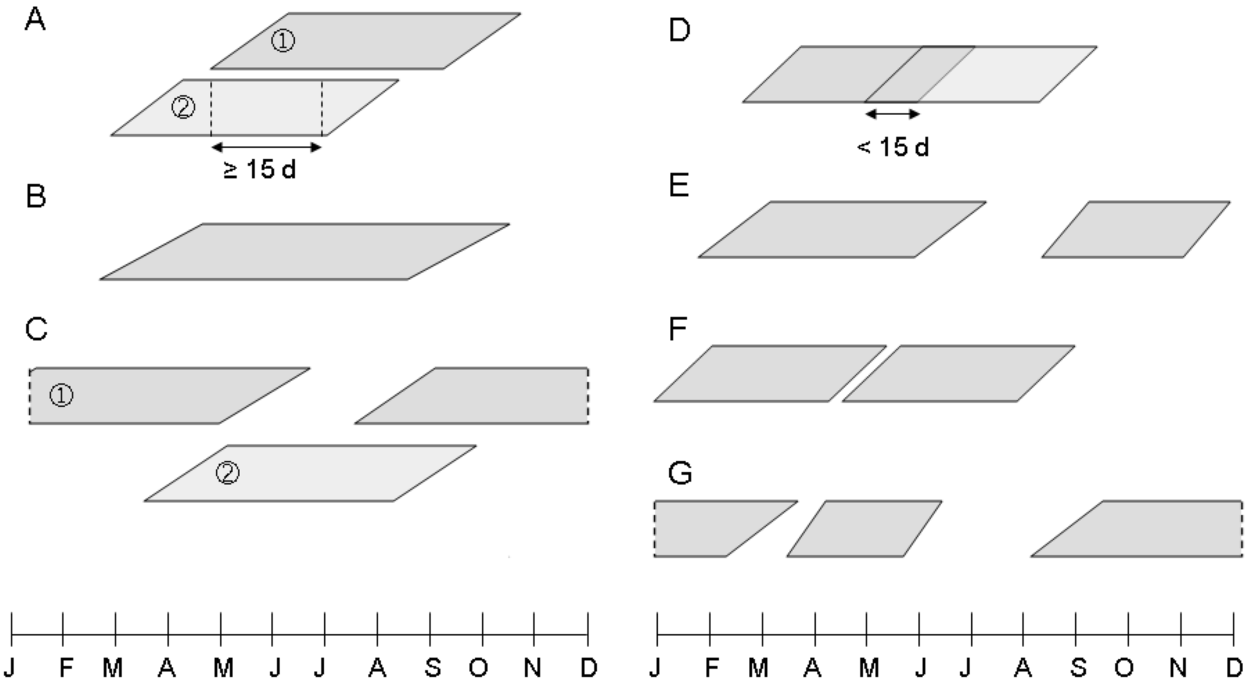

Figure 2 Scheme of possible timing and length of growing periods of crops in single cropping systems (A-C) and sequential cropping systems (D-G) according to the definition used in this study. A: two single cropping systems with large overlap, B: one single cropping system, C: two single cropping systems, one spanning the turn of the year and with the sum of the growing periods exceeding 365 days, D: sequential cropping system with small overlap, E: sequential cropping system with long fallow period, F: sequential cropping system with short or no fallow period, G: sequential cropping system spanning the turn of the year with sum of growing periods below 365 days.

An overlap of 15 days corresponds to the maximum possible error in sowing and harvest dates owing to the conversion from monthly to daily data. We only consider rainfed systems in this study because irrigation systems are rarely available in sub-Saharan Africa. If various sequential cropping systems exist within a district, we identify the most frequently applied sequential cropping system in a district and assume this system to be the traditionally applied sequential cropping system. Based on the distance between the centre coordinates of the districts and those of the 0.5° x 0.5° grid cells, the sequential cropping systems found in a district are allocated to the closest grid cell. If a district covers more than one grid cell the sequential cropping systems are distributed to all corresponding grid cells.

2.3 Management scenarios for adaptation

Farmers choose a cropping system according to economic market trends, consumer demands, availability of inputs such as seeds, fertilizer and pesticides, agronomy traditions as well as current land-use, climatic conditions and soil properties (Bennett *et al.*, 2012; Castellazzi *et al.*, 2008) in order to maximize their yield and profit and/or to minimize the risk of crop failure through diversification. Rainy seasons long enough for growing two crops in a sequential cropping system allow for intensification and more harvest security for farmers because crop yields are obtained two or more times a year (Andrews & Kassam, 1976). If necessary, farmers respond to perceived changes and variability in climate by e.g. changing the sowing date of cultivated crops or switching to a more suitable crop or crop cultivar with a different growing period, heat tolerance or drought resistance. These strategies were already observed in Tanzania (O´Brien *et al.*, 2000), semi-arid West Africa (Mation & Kristjanson, 1988), and South Africa (Benhin, 2006). It can thus be expected that farmers will adapt their traditional cropping system to a changing climate to some extent. We define three management scenarios, analyzing different cropping system with the aim of comparing changes in crop yields with changing climate of the 21st century in order to find the most suitable strategy:

- TS: Traditional sequential cropping system: The baseline strategy. Farmers grow the sequential cropping system most frequently applied in their district composed of two short-growing crop cultivars.

- SC: Single cropping system: Farmers only grow one long-growing cultivar of the first crop of the traditional sequential cropping system.

- HS: Highest-yielding sequential cropping system: Farmers grow the sequential cropping system composed of two short-growing crop cultivars with the highest yields.

Sowing dates in these scenarios change dynamically with changes in the start of the main rainy season allowing for inter-annual variability. In order to assess the importance of adapting sowing dates to changing climate or weather conditions three additional scenarios are designed in which the sowing dates are kept constant with the simulated sowing dates in the first simulation year 1971.

- TSco: Traditional sequential cropping system as described above with constant sowing dates.
- SCco: Single cropping system as described above with constant sowing dates.
- HSco: Highest-yielding sequential cropping system as described above with constant sowing dates.

Accordingly, each of the six management scenarios is a combination of a specific cropping system and sowing date setting, as these are important management options for farmers.

We assume that farmers prefer short-growing crop cultivars in sequential cropping systems in order to reduce the risk of crop failure in the second half of the growing season (Table 1) or, alternatively, long-growing crop cultivars in single cropping systems in order to increase the yield. Sequential cropping systems are advantageous farming systems but cannot be applied if the growing season is too short. In this case a single cropping system may be the most suitable cropping system. Adapting sowing dates to shifts in the start of the rainy season ensures optimal growing conditions and low risk of drought at important crop growth stages and, therefore, allows for better use of rainwater and potentially increased crop yields (Van Duivenbooden *et al.*, 2000).

2.4 Dynamic global vegetation model for managed land LPJmL

LPJmL is a process-based global vegetation model for natural and agricultural vegetation, simulating biophysical and biogeochemical processes as well as productivity and yield of the most important crops (Bondeau *et al*., 2007; Sitch *et al.*, 2003).Carbohydrates from photosynthesis are allocated to different crop organs at daily time steps depending on the phenological stage of the crop and environmental conditions. To simulate the phenological development of a crop, the heat unit theory is applied (Bondeau *et al.*, 2007). Heat units (in degree-days [°Cd]) are calculated from daily temperatures above a base temperature (Table 2) and are summed over all phenological stages (potential heat unit sum, PHU [°Cd]). This empirically derived quantitative measurement describes the effect of air temperature on the growth of crops (Boswell, 1926) and reflects the length of a crop's growing period.

Temperature and water stress influence crop development and growth (Bondeau *et al.*, 2007). Increasing temperatures lead to a shortened growing period because crops reach maturity earlier in the year and crop yields potentially decrease. Stress due to extreme temperatures does not damage the crop irreversibly in the model, but temperatures beyond the optimal temperatures for photosynthesis reduce productivity. A water stress factor is calculated from the ratio of water supply through plant water uptake from the soil and atmospheric water demand (Sitch *et al.*, 2003) and influences leaf growth (Bondeau *et al.*, 2007). We extended this approach to also account for changes in root growth in response to water stress (Appendix A). Water stress effecting leaf and root growth negatively might occur more frequently in the second crop cycle because water stored in the soil was already consumed by the preceding crop.

It is possible to simulate different crop cultivars with LPJmL for wheat and rapeseed (spring and winter cultivar), as well as for maize and sunflower (temperate and tropical cultivar) by varying the PHU (Bondeau *et al.*, 2007). We extend this approach by calculating PHUs for a short-growing crop cultivar grown in sequential cropping systems (PHU_{seq}) and a long-growing crop cultivar grown in single cropping systems (PHU_{sin}) from observed growing periods and daily temperatures in sub-Saharan Africa. The base temperatures are taken from LPJmL (Bondeau *et al.*, 2007) for groundnut, millet, rice, soybean, sunflower and wheat and from SWAT (Neitsch *et al.*, 2002) for cassava, cowpea and maize (Table 2).

The start of the growing season in subtropical and tropical environments is determined by the start of the main rainy season and is simulated dynamically in LPJmL from monthly climatology (Waha *et al.*, 2012). This procedure follows the commonly used approach of identifying the onset and end of the rainy season with a criterion based on the average rainfall or radiation of a specific period, e.g. 5 days (Marengo *et al.*, 2001; Omotosho *et al.*, 2000; Wang & Ho, 2002). This criterion is defined here as the three-month averaged ratio between precipitation and potential evapotranspiration which is based on the methodology for the global scale described in Waha *et al.* (2012) but additionally allows for calculating the end of the growing season.

$$\frac{P}{PET} = \frac{1}{12} \times \sum_{i=1}^{12} \sum_{m=i}^{m+3} \frac{P}{PET}_m$$

where P/PET is the mean three-month averaged precipitation-to-potential evapotranspiration ratio, P/PET_m is the precipitation-to-potential evapotranspiration ratio of each individual month m. Potential evapotranspiration is calculated in LPJmL using the Priestley-Taylor equations (Priestley & Taylor, 1972) with a Priestley-Taylor coefficient of 1.391 (Gerten *et al.*, 2004).

Consequently, the onset of the growing season is defined as the first month in a three-month period where precipitation-to-potential-evapotranspiration ratios exceed the mean ratio. Within this month the growing period of an individual crop starts at the first wet day with daily precipitation above 0.1mm; in sequential cropping systems the following crop is assumed to be sown immediately after the harvest of the first crop. In temperate environments such as parts of South Africa the start of the growing season is determined by daily temperature as described in Waha *et al.* (2012). The start of the main rainy season in sub-Saharan Africa as simulated here agrees well with the observed start of the main growing season derived from satellite data (Appendix B). A second growing season which occurs in areas with a bimodal rainfall distribution is not simulated.

The growing period is limited to a maximum of 330 days allowing for a short fallow period between two consecutive years. The simulated harvested carbon in gC/m^2 is converted to crop yield in Mcal/ha to allow for a comparison between crops and cropping systems with:

$$Y_{Mcal} = \frac{H}{0.45} \times \frac{100}{DM} \times Cal \times 10^4$$

where Y_{Mcal} is the calorific yield in Mcal/ha, H the harvested carbon in gC/m^2, DM the crop-specific dry matter content in %, and Cal the crop-specific calorie content in Mcal/g fresh matter (Table 2). 0.45 converts from gC/m^2 to gDM (Rojstaczer *et al.*, 2001). Dry matter content and calorie content of crop products are taken from Wirsenius (2000) and from FAO Food Balance Sheets (FAO, 2001). The overall crop yield in sequential cropping systems is the sum of two individual crop yields in Mcal/ha.

Management intensity in a cropping system is described by three parameters: the maximal attainable leaf area index, the maximal harvest index and a parameter scaling leaf-level biomass to field level as described in Fader *et al.* (2010). The management intensities per crop and country were chosen to match observed production levels of FAO in the 5-years-period 1999-2003 (Appendix C).

2.5 Modelling the spatial variation of PHU_{sin} and PHU_{seq}

PHU_{sin} and PHU_{seq} are calculated by accumulating daily temperatures above a base temperature threshold (Table 2) summed over the growing period that is reported in the household survey. In order to estimate PHU_{sin} for each crop in each grid cell in sub-Saharan Africa, we use a multiple linear regression model between PHU_{sin} and climatic parameters in each grid cell. We found a correlation, although light for maize and groundnut, between PHU_{sin}, mean annual temperature and moisture conditions during the growing season:

$$PHU_{sin} = \alpha + \beta T + \gamma P_{gs} + \delta PET_{gs}$$

where T is the annual mean temperature, P_{gs} the sum of monthly precipitation during the growing season, PET_{gs} the sum of monthly potential evapotranspiration during the growing season, and α, β, γ and δ are empirical parameters.

Precipitation and potential evapotranspiration represent the atmospheric water supply and water demand, respectively. Thus their ratio in the growing season represents the water availability during the period of high agricultural activity. The start and end of the growing season is calculated using the criterion described in the previous section.

We compare PHU_{sin} and PHU_{seq} with the aim of verifying the assumption that farmers apply short-growing crop cultivars in sequential cropping systems and long-growing crop cultivars in single cropping systems. We test if PHU_{sin} is statistically greater than PHU_{seq} for each crop using the non-parametric Wilcoxon signed-rank test (Wilcoxon, 1945). In order to estimate PHU_{seq} for each crop in each grid cell, we derive a uniform crop-specific factor PHU_{gap} from the calculated PHU_{sin} and PHU_{seq} to account for the deviation between them:

$$PHU_{gap} = \frac{PHU_{seq}}{PHU_{sin}}$$

Table 2 Crop-specific parameters for estimating PHUs in single and sequential cropping systems and calculating fresh matter crop yields in kcal/ha.

	Parameters for estimating PHU$_{sin}$ and PHU$_{seq}$ in LPJmL $PHU_{sin} = \alpha + \beta T + \gamma P_{gs} + \delta PET_{gs}\ and\ PHU_{gap} = \frac{PHU_{seq}}{PHU_{sin}}$												**Dry matter DM [c] and calorie content Cal [d]**	
Crop	Base temperature[a,b] [°C]	α [°Cd]	β [d]	γ [°Cd/ mm]	δ [°Cd/ mm]	R	R^2	Min PHU$_{sin}$ [°Cd]	Max PHU$_{sin}$ [°Cd]	N	PHU$_{gap}$ [-] ‡	N	DM [%]	Cal [kcal/g]
Cassava	14	-4910	327	0.5	-0.6	0.75	0.56	910	4510	213	0.67 ± 0.26 ***	50	35	1.09
Cowpea	14	-470	44	-0.2	0.9	0.58	0.34	740	1910	190	0.75 ± 0.21 ***	33	90	3.41
Groundnut	14	470	32	-0.2	0.4	0.48	0.23	1070	1990	336	0.99 ± 0.29 *	117	94	4.14
Maize	8	1740	0.1	-0.1	0.7	0.48	0.23	1880	3640	472	0.92 ± 0.21 ***	224	88	3.56
Rice	10	250	21	0	1.3	0.65	0.42	1450	2700	102	0.88 ± 0.19 *	16	87	2.80
Wheat	0	-390	146	0.8	-0.2	0.76	0.58	2180	4310	61	0.87 ± 0.34 *	26	88	3.34

[a] Bondeau *et al.* (2007), [b] Neitsch *et al.* (2002), [c] Wirsenius (2000), [d] FAO (2001).

‡ Values are means ± standard deviation for PHU$_{gap}$. Level of significance (*** p<0.001, ** p<0.01, and * p<0.05) is given for the hypothesis that PHU$_{seq}$ < PHU$_{sin}$ (Wilcoxon signed-rank test).

2.6 Theoretical potential of sequential cropping systems

In addition to the analysis of climate change impacts on crop yields in districts where sequential cropping systems are already grown, we apply a similar analysis to the entire region of sub-Saharan Africa that currently has growing periods larger than 5 months (Harvest Choice, 2010a) to analyze the adaptation potential of sequential cropping systems. Crop yields from 13 sequential cropping systems and six single cropping systems are simulated with LPJmL and compared in all sub-Saharan Africa grid cells that are currently used for crop production following Fader *et al.* (2010).

3 RESULTS

3.1 Sequential cropping systems in sub-Saharan Africa

In 35 % of the surveyed districts one or more sequential cropping system exist, but only in seven out of ten surveyed countries and about 17 % of the districts sequential cropping systems are composed of crops included in our model. The remaining sequential cropping systems consist of at least one crop other than the LPJmL crops, most of them are vegetables, fruits, beans, peas or perennial crops. Figure 3 shows the distribution of the 13 traditional sequential cropping systems in the surveyed districts. The sequential cropping systems frequently applied are mostly based on groundnut and maize and to a smaller extent also on cassava, rice, wheat, and cowpea, but only few sequential cropping systems exist with sunflower or soybean, which are of minor importance in the surveyed households. In Eastern Africa all sequential cropping systems are based on maize, whereas in Southern Africa wheat-maize systems are additionally applied. Systems based on groundnut as the first crop can be found in Ghana and in Cameroon, which is the country with the highest diversity in sequential cropping systems. The highest-yielding among all 13 traditional sequential cropping systems are mostly based on maize (Table 3).

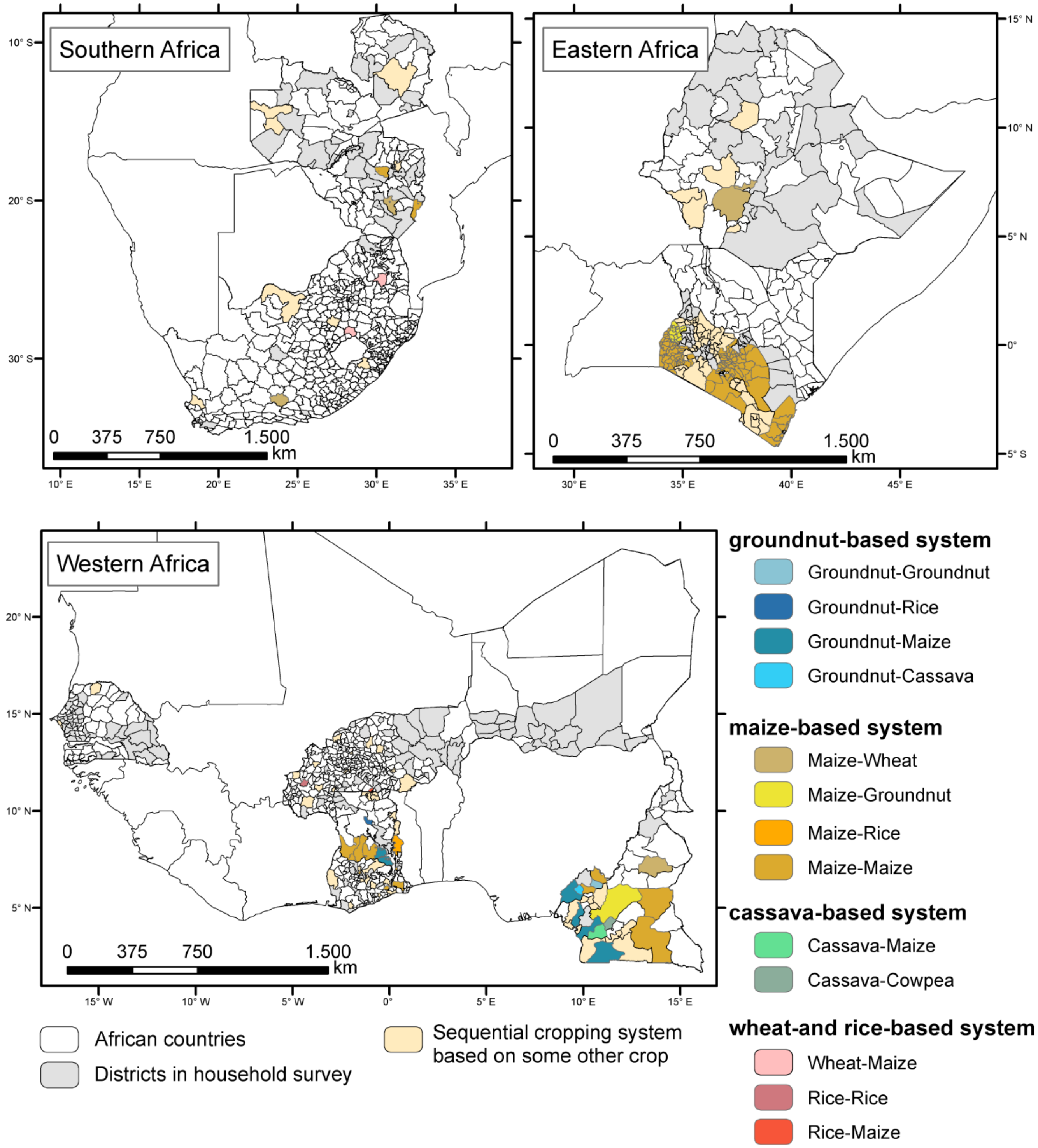

Figure 3 Most frequently applied rainfed sequential cropping systems in districts in sub-Saharan Africa. The classification of sequential cropping systems used for legend titles is based on the first crop grown in the sequence.

Table 3 Highest-yielding rainfed sequential cropping systems in the period 1971-2000 in 63 districts in seven sub-Saharan Africa countries depending on the location within the country. Sequential cropping systems in Niger, Senegal and Zambia are based on some other crop than the crops in this study.

Country	**System**	**Country**	**System**
Burkina Faso	Maize-Rice, Rice-Rice	Ghana	Cassava-Cowpea
Cameroon	Wheat-Maize, Maize-Wheat, Maize-Maize, Cassava-Maize	Kenya	Wheat-Maize, Rice-Rice, Maize-Maize, Cassava-Maize, Cassava-Cowpea, Groundnut-Cassava, Groundnut-Groundnut
		South Africa	Wheat-Maize, Maize-Wheat, Cassava-Maize, Cassava-Cowpea
Ethiopia	Cassava-Cowpea	Zimbabwe	Wheat-Maize
Results of this analysis are derived by simulating crop yields from 13 sequential cropping systems found in the household survey.			

3.2 Growing periods and PHUs of different crop cultivars

The lengths of the growing periods calculated from the household survey of most of the crops lie within the range of values found in the literature, except for cowpea, groundnut and maize (Table 4). The growing periods from the household survey and the corresponding PHUs differ significantly between single and sequential cropping systems as well as between crops (see level of significance and PHU_{gap} in Table 2). The results of the Wilcoxon signed-rank test indicate that PHU_{sin} significantly exceeds PHU_{seq} by 900 °Cd on average. The deviation between large PHU_{sin} and small PHU_{seq} per individual crop is significant as well and can be described by the crop-specific factor PHU_{gap}, which accordingly is less than 1 (Table 2).

Using the multiple regression model to determine the heat sum requirements for phenological development, simulated growing periods from LPJmL differ from growing periods in the household survey: for wheat, rice and cowpea simulated growing periods are on average 5 to 32 days shorter than the growing periods in the household survey while those for groundnut, cassava and maize are on average 7 to 33 days longer than the growing periods reported in the household survey (Fig.4).

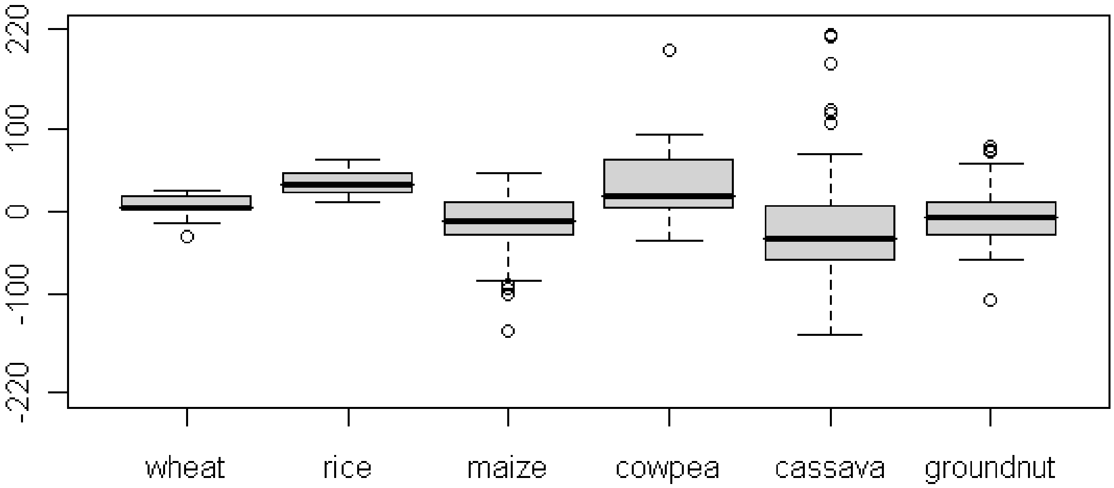

Figure 4 Deviations in days between simulated and observed length of growing period in 2002/03 in single cropping systems (observed – simulated). Each box stretches from the 0.25-quantil to the 0.75-quantil of deviation with the bold line showing the 0.5-quantil of deviations. Whiskers show the 1.5-fold interquartile range, points indicate individual outliers.

Table 4 Time from sowing to harvest in months for different crop cultivars found in household survey and in literature.

Crop	**Household survey**	**Literature**
Cassava	6 – 11	6 – 24 (Alves, 2002)
Cowpea	2 – 9 ½	1 ½ – 6 (FAO, 2010; Madamba *et al.*, 2006)
Groundnut	2 – 10 ½	2 ½ – 6 (Ntare, 2006; Schilling & Gibbons, 2002; Virmani & Singh, 1986)
Maize	2 – 9	2 ½ – 6 ½ (Badu-Apraku & Fakorede, 2006)
Rice	2 – 6 ½	3 – 7 (Badu-Apraku & Fakorede, 2006; Meertens, 2006)
Wheat	3 – 6	3 – 5 ½ (Belay, 2006; FAO, 2010; Rehm & Espig, 1991)

3.3 Changes in crop yields

3.3.1 Decreasing crop yields

Future crop yields averaged over all locations contained in the household survey (Figure 3) decrease between 6 % and 24 % because of climate change depending on the GCM and management scenario (Table 5). The decrease is always weakest in the management scenarios with traditional sequential cropping systems. There are differences in mean crop yields and crop yield changes between the three GCMs, with the highest crop yields under CCSM3 and the lowest under ECHAM5. Southern and Western Africa are the most heavily impacted regions with declines in crop yield of up to 45 % and 18 % respectively depending on the management scenario (Figure 5). However, impacts in Southern Africa are diverse and crop yields in some locations also increase by up to 6 % in the TS scenario. Some traditional sequential cropping systems based on rice in Burkina Faso and based on groundnut in Ghana and Cameroon are most heavily impacted with crop yield declines by at least 25 % (Table D1). In contrast, some traditional sequential cropping systems based on maize and wheat in Kenya and South Africa gain by at least 25 %. Mean future crop yields are higher (+ 11-17 %) in the TS, SC and HS scenarios with adapted sowing dates compared to the corresponding TSco, SCco and HSco scenarios with constant sowing dates (Table 5). As an exception, adapting sowing dates is not beneficial for crop productivity under climate change in some single and sequential cropping systems. These are the rice single cropping system at Bama/Burkina Faso, maize double cropping system in Nyong-et-Kelle/Cameroon, groundnut-maize systems in Manyu/Cameroon and several cropping systems in Aberdeen/South Africa where crop yields in scenarios with adapted sowing dates is lower than in scenarios with constant sowing dates under current and future climate (Table D1).

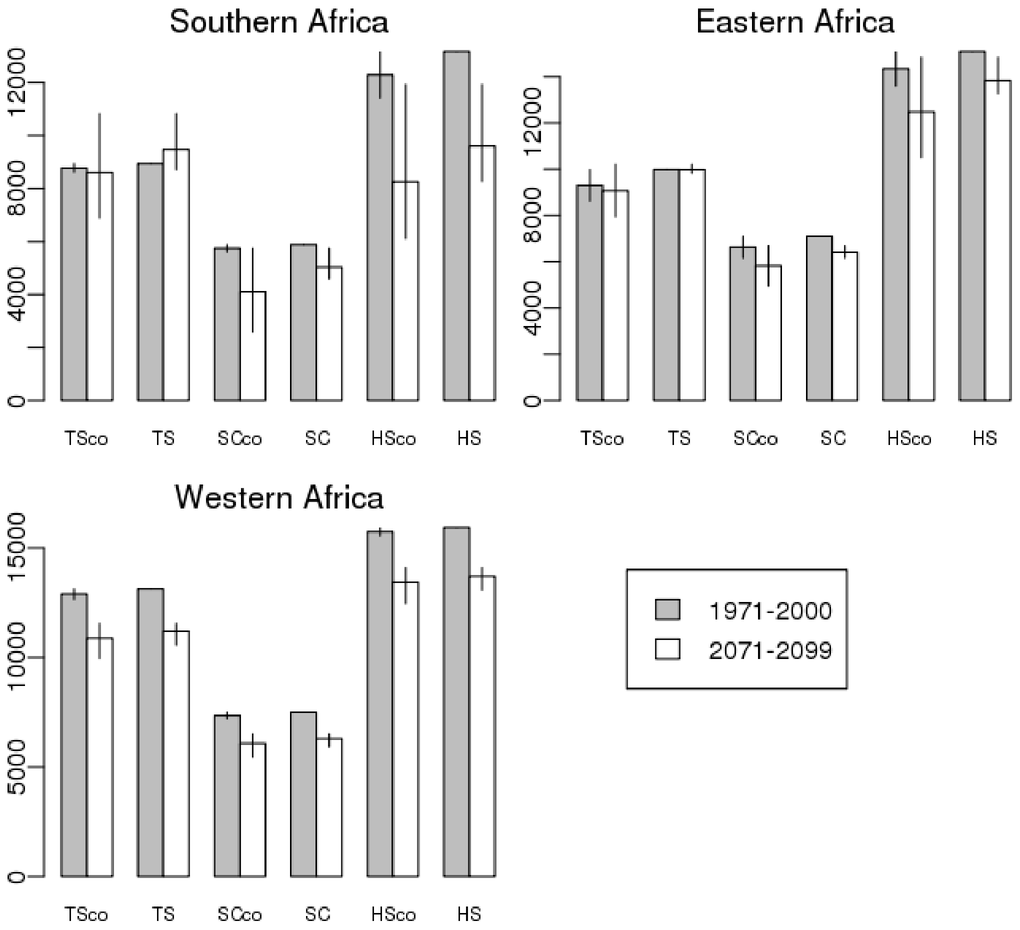

Figure 5 Mean crop yields [Mcal/ha] per region in the periods 1971-2000 and 2070-2099 if TS/TSco (the traditional sequence cropping systems), SC/SCco (only the first crop of the traditional sequential cropping systems), or HS/HSco (the highest-yielding sequential cropping systems) are applied, “co” indicating management scenarios with constant sowing dates. Vertical lines show the range of minimum to maximum crop yield from three GCMs. The countries of Zimbabwe and South Africa are combined into the region Southern Africa, Kenya and Ethiopia are combined into Eastern Africa and Burkina Faso, Cameroon and Ghana are combined into Western Africa.

Table 5 Mean crop yields and crop yield changes per GCM and management scenario in 63 districts of seven sub-Saharan Africa countries in the period 2070-2099 compared to the period 1971-2000 in six management scenarios.

	Crop yield 1971-2000 [Mcal/ha]	**Crop yield 2070-2099 [Mcal/ha]**		
Management Scenario	ECHAM5/HadCM3/CCSM3	ECHAM5	HadCM3	CCSM3
SCco	6660	5041 (-24%)	5459 (-18%)	5669 (-15%)
SC	7203	5894 (-18%)	6399 (-11%)	6393 (-11%)
TSco	10748	8942 (-17%)	9427 (-12%)	9799 (-9%)
TS	11564	10132 (-12%)	10677 (-8%)	10927 (-6%)
HSco	14435	11180 (-23%)	11676 (-19%)	12688 (-12%)
HS	15368	12796 (-17%)	13266 (-14%)	14095 (-8%)

TS/TSco: Traditional sequential cropping system, SC/SCco: Single cropping system, HS/HSco: Highest-yielding sequential cropping system, “co” indicating management scenarios with constant sowing dates

3.3.2 Sequential cropping systems vs. single cropping systems

Crop calorific yields in management scenarios with single cropping systems (SC/SCco) only reach 38 to 54% of crop calorific yields obtained in management scenarios with sequential cropping systems (TS/TSco and HS/HSco) under current climatic conditions averaged over all locations contained in the household survey (Table 5). As an exception, the single cropping systems (SC/SCco) with maize in Kenya and South Africa yield higher in some locations than the traditional sequential cropping system, but only under current climatic conditions (Table D1).

Crop yields in the highest-yielding sequential cropping systems (HS) exceed crop yields in the traditional sequential cropping systems (TS) by 24 to 28 % depending on the GCM (Table 5). However, frequently the traditional sequential cropping systems are more resilient against negative climate change impacts than the highest-yielding sequential cropping systems like e.g. groundnut-cassava systems in Cameroon, maize-maize systems in some locations in

Kenya, wheat-maize systems in some locations in South Africa and maize-wheat systems in Zimbabwe (Table D1).

3.3.3 Potential of sequential cropping systems in sub-Saharan Africa

If only the most stable sequential cropping systems would be chosen everywhere in sub-Saharan Africa, crop yields would be also less impacted by climate change than crop yields in single cropping systems in many locations (Fig.6). Crop yields in both systems mostly decline, most severely in western Mali, southern Mauritania and Senegal, but increase in small parts of South Africa, Kenya and Ethiopia. However, in the last-mentioned locations there is also the highest variability of climate change impacts on crop yields. The single cropping systems least impacted by climate change are cassava and maize, and to a smaller extent also rice. The sequential cropping systems least impacted are groundnut-cassava, rice-maize systems, but also maize-maize and maize-groundnut.

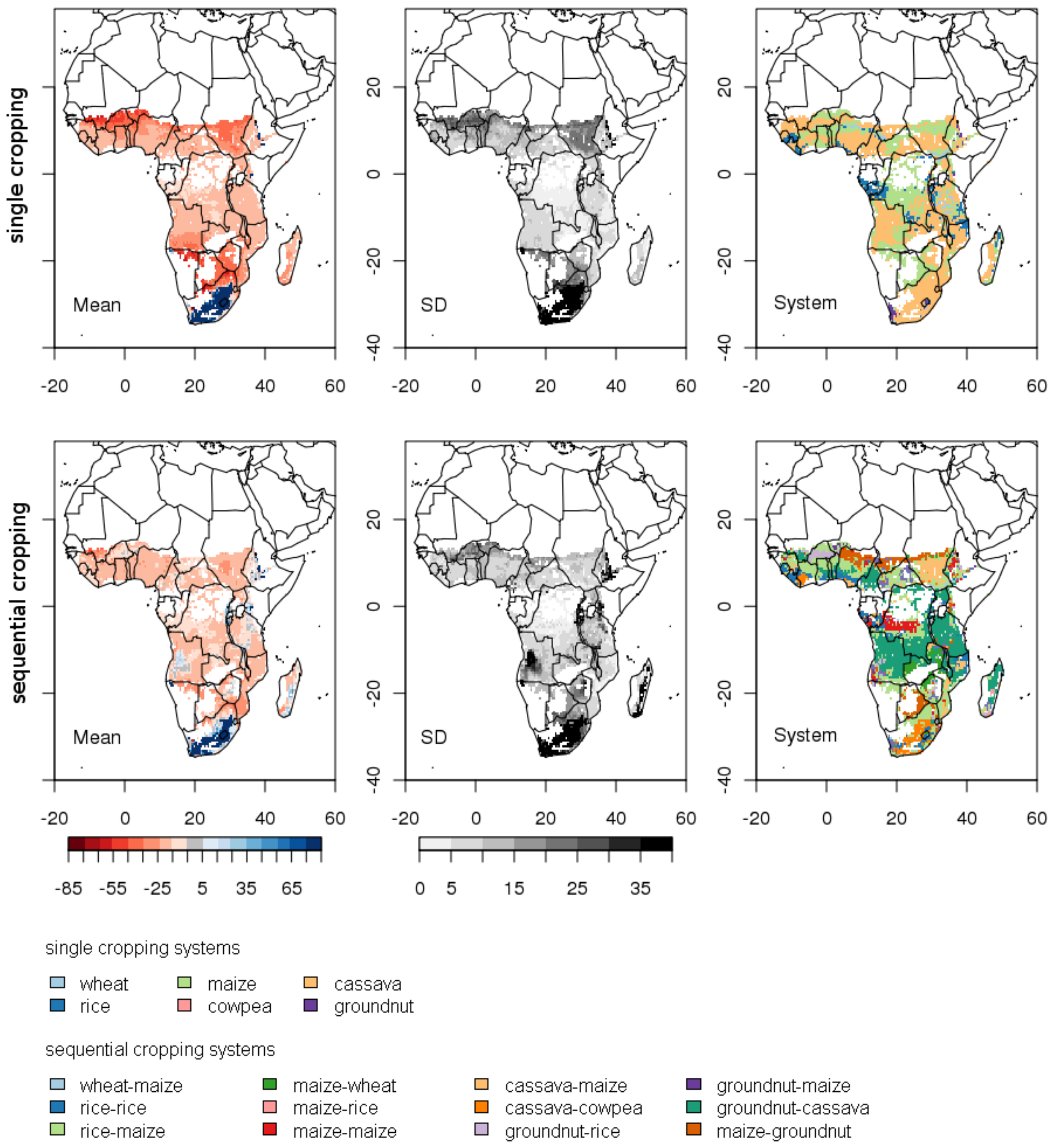

Figure 6 Mean crop yield changes (%) in 2070-2099 compared to 1971-2000 with corresponding standard deviations (%) in six single cropping systems (upper panel) and thirteen sequential cropping systems (lower panel). Maps in the last column show the systems with lowest crop yield declines or highest crop yields increases. White areas in sub-Saharan Africa are excluded because the crop area is smaller than 0.001% of the grid cell area or the growing season length is less than five months. The high standard deviation in Southern Africa is mainly determined by the large difference in climate projections.

4 DISCUSSION

4.1 Changes in crop yield

Crop yield decreases, mostly for single cropping systems, were reported by other studies as well (Jones & Thornton, 2003; Lobell *et al.*, 2008; Schlenker & Lobell, 2010; Thornton *et al.*, 2011). Lobell *et al.* (2008) show declines in crop yield by up to 30% for maize in Southern Africa, millet in Central Africa and cowpea in Eastern Africa as early as 2030. In contrast to our results, Thornton *et al.* (2011) report higher mean production decreases for maize in 2090 in Western Africa than in Southern Africa, but in line with our results they project higher declines than in Eastern Africa. However, a comparison between these results and our study is difficult due to different time horizons, methodological approaches, climate projections and crop parameterization.

Mean crop yield decreases on average are most severe in Western and Southern Africa due to climate change (Table 6). Increasing annual temperatures in all regions lead to an accelerated phenological development and thus reduce growing periods by 31 to 65 days. Furthermore, growing season precipitation decreases in Southern Africa indicating a higher risk of water stress, in contrast to Eastern Africa with considerable increases in growing season precipitation. Water stress during the growing period affects photosynthesis as well as leaf and root growth, depending on the phenological stage (Figure A1). Therefore, total biomass as well as the biomass of harvested crop organs is reduced, depending on the crop type and cropping system. In contrast, in the temperate zone of South-East Africa precipitation is projected to increase or to remain constant from all three GCMs, leading to increased crop yields in some traditional sequential cropping systems (Figure 5) and also in some single cropping systems (Table D1).

Table 6 Change in climate and length of the crops´ growing period in the period 2070-2099 compared to the period 1971-2000 in six management scenarios using climate projections from three GCMs.

	Southern Africa	Eastern Africa	Western Africa
ECHAM5			
Change in annual temperature [°C]	4,1	3,8	3,8
Change in annual precipitation [%]	-4,9	+11,4	+12,0
Change in growing season precipitation [%] [a]	-3,3	+11,4	+4,0
Change in length of crops´ growing period [b]	-65 days (-23%)	-35 days (-14%)	-36 days (-18%)
HadCM3			
Change in annual temperature [°C]	4,4	3,6	3,8
Change in annual precipitation [%]	-7,0	+9,7	-0,4
Change in growing season precipitation [%] [a]	-6,2	+12,8	+0,4
Change in length of crops´ growing period [b]	-60 days (-22%)	-31 days (-12%)	-36 days (-18%)
CCSM3			
Change in annual temperature [°C]	3,6	3,1	3,3
Change in annual precipitation [%]	+11,1	+24,8	+6,8
Change in growing season precipitation [%] [a]	+11,0	+24,7	+0,5
Change in length of crops´ growing period [b]	-43 days (-15%)	-29 days (-12%)	-31 days (-15%)

[a] growing season as indicated from satellite data providing the time of greening-up and greening down (HarvestChoice, 2010a)

[b] growing period as simulated from LPJmL for different crops in six management scenarios

4.2 Benefit of adapting the sowing date and the cropping system

Farmers can lower the negative impact of changing climate on crop yields by adapting the sowing date to the start of the main rainy season, which is already done in many locations today. While in the Northern provinces of South Africa only 3% (Gbetibouo, 2009) and in the Nile Basin of Ethiopia only 5% (Deressa *et al.*, 2009) of surveyed farmers shift their planting dates to match delayed or early rainfall, Hassan & Nhemachena (2008) found that 16% of more than 8000 households in 11 African countries change planting dates as response to perceived changes in temperature and precipitation.

Simulation studies for Cameroon indicated that crop yields of maize and groundnut with an optimal planting date are usually higher compared to crop yields obtained using traditional planting dates if climate changes (Laux *et al.*, 2010; Tingem & Rivington, 2009). This is in agreement with our findings, as the adaptation of sowing dates in our study usually results in higher crop productivity in most regions and cropping systems (Table 7). The benefits from adapting sowing dates at two locations in Cameroon are even higher in these studies, as they optimize the sowing date in order to maximize crop yields whereas in our study the sowing date is adapted to a shifted start of the rainy season.

Table 7 Comparison of simulated crop yields in Cameroon from literature and this study.

Location[a], crop	**Reference**	**Change to baseline, without adaptation**	**Change to baseline, with adaptation**	**Deviation between yield without and with adaptation**
Tiko/Moungo, groundnut	Tingem & Rivington (2009)	-5.1 %	+28.9 %	-
	this study	-25-29 %	-22-21 %	-
Ngaoundere/Vina, maize	Laux *et al*. (2010)	-	-	+1%
	this study	-19 %	-14-15%	+10.4-12.3%
Bamenda/Mbam and Bui, maize	Laux *et al*. (2010)	-	-	+16 %
	this study	-11-12 %	-12 %	-1.8- +2.9 %

Bamenda/Mbam and Bui, groundnut	Laux *et al*. (2010)	-	-	-9 %
	this study	-38 %	-32 %	+9.2 %

[a] locations in literature studies or related district in this study, e.g. the neighbouring district(s)

Attention should be paid to the different GCMs used in the studies in the literature and in this study. Crop yields from literature are shown for only one GCM (GISS), whereas in this study the results from three different GCMs are averaged. The SRES scenario and time horizon is identical.

There are, however some exceptions with lower crop yields in scenarios with adapted/optimized sowing dates in both studies as well as in our study. One reason for this is that at some locations, temperature and not precipitation is the limiting factor for agricultural production like in the case of a mountainous location in Cameroon (Laux *et al.*, 2010) and South Africa (this study). At other locations, the method of calculating the start of the main rainy season might not be detailed enough to adapt sowing dates to changing precipitation patterns.

With few exceptions, mean crop yields in sequential cropping systems exceed mean crop yields in single cropping systems because the second harvest will often also be successful under changing climatic conditions. The most productive sequential cropping systems are not always the most stable systems against negative climate change impacts. Instead the traditional sequential cropping systems which are already applied today will provide lower but more stable crop yields in many locations and poor farmers which rely on stable crop production will prefer them to highest-yielding cropping systems.

4.3 Limitations of the modeling approach

LPJmL is a vegetation model for managed land designed and parameterized for global or regional studies driven by aggregate soil and climate information. Detailed local soil and climatic conditions, specific agronomic practices, the occurrence of pests and diseases, various socio-economic aspects - despite their importance for local crop yields and farmers management decisions - therefore cannot be considered. Crop growth in advanced development stages is not terminated in the model by severe heat stress or desiccation. Crop yields are expected to decline by more than 10 % per °C temperature increase considering the effect of heat damage on maize grown in areas with growing season temperatures of more than 25 °C (Lobell *et al.*, 2011). However, temperature and water stress negatively affect photosynthesis, leaf and root growth and the production of storage organs during the growing period in the model and crop growth is terminated under poor growing conditions at the beginning of the phenological development. Therefore resowing within the same month is possible. The crop's influence on soil properties is not considered in the model but can noticeably benefit the yield of the subsequent crop by e.g. leaving nitrogen in the soil if cowpea is grown (Madamba *et al.*, 2006) or by improving the P-uptake of subsequent maize through mycorrhizal associations (Adjei-Nsiah, 2007) if cassava is grown. Furthermore crop rotations can reduce disease pressure from soil-or root-borne pathogens and pests and weed densities (Bennett *et al.*, 2012), which is not considered in our study.

As the cultivated area of each cropping system within the study area is still unknown, it remains unclear how the total crop production will be affected by climate change in each country if sequential cropping systems are considered. Furthermore, developments in the demand for certain agricultural products, population size and availability of land and water resources must be considered when deciding on the most suitable management strategy for a location. The positive effects of elevated atmospheric CO_2 concentrations and technology development on crop yields are not considered in this study. Crop yields are expected to increase by 10-20 % for C_3 crops (e.g. wheat, rice) and 0-10 % for C_4 crops (e.g. maize, millet) if atmospheric CO_2 concentrations rise from 380 ppm to 550-600 ppm (Tubiello, 2007), but only if other biotic (like pests) or abiotic (like nutrients) factors do not become limiting (Long *et al.*, 2006). It is therefore unlikely that CO_2 fertilization will have a strong effect on crop yields at current management intensities in sub-Saharan Africa. If effective to some extend, the CO_2 fertilization effect will potentially reduce the superiority of maize-based systems, with maize being a less affected C_4 crop.

4.4 Uncertainties from the household survey

Although the questionnaire used in the household survey only asked for crops cultivated within one farming season, the length of the growing periods calculated for single and sequential cropping systems indicates that farmers also reported agricultural activities beyond that period. Despite excluding some obvious cases from the study it remains unclear if the reported farming activities refer to only one farming season in all cases. Moreover, crop failure was not reported in the survey, leading to uncertainty about the validity of the reported sowing and harvest dates in cases where farmers were forced to resow the chosen crop but did not report the new sowing date. In addition some crops, such as cassava, maize or legumes might have an extended harvest period because of uneven ripening, better in-ground than out-of-ground storability or because multiple harvest products can be obtained from one crop (green and dry maize) (Fermont & Benson, 2011) This might lead to longer growing periods reported in the household survey than found in literature (Table 4). The geographic position of the households interviewed for the survey is not known, only the position of the districts they are located in. These were later used for the conversion from districts to grid cells. Therefore a considerable range of different cropping systems and growing periods can be found in a single grid cell, leading to some uncertainty in the multiple regression model between PHU_{sin} and the climate parameters which were used to describe the crop's development. However, the simulated lengths of growing periods differ only slightly between 5 and 33 days on average from those reported in the household survey, but with 50% of all values having a deviation of up to 58 and 65 days for cassava and groundnut respectively (Figure 4).

4.5 Farmers' adaptation options

Although sequential cropping systems are advantageous in terms of maximizing crop yields and minimizing climate change impacts compared to single cropping systems in many locations, farmers in 65% of the surveyed administrative units do not apply them. The growing season length in e.g. Senegal, Niger and parts of Ethiopia is not suitable to grow more than one crop. In districts climatically suitable for sequential cropping systems, growing a second crop requires sufficient labour and is risky if the rainy season ends too early and the crop fails. The first crop needs to be harvested, processed and stored or sold on the market during the period of land preparation and sowing of the second crop, which leads to a high demand for labour and possibly for draught animals (Gill, 1991). Moreover, introducing an unknown cropping system may also require some adjustments to current technology and management, which is often made more difficult by a lack of inputs like seeds or fertilizer, missing knowledge about cultivation and processing of the new cropping system and lacking market access to sell the products (Lotze-Campen & Schellnhuber, 2009). It therefore remains unclear if farmers will be able to apply the most beneficial cropping system.

Farmers will not only decide on the crop and cropping system with respect to productivity but also pay attention to other crop characteristics, such as its performance on local soils, the colour, shape and taste of harvestable organs, bacterial tolerance, market acceptability and storability (Haugerud & Collinson, 1990; Sperling *et al.*, 1993). In West Africa, farmers prefer e.g. an early-maturing millet cultivar at the beginning of the growing season because their food supply is very low after a long dry season and they need to harvest fast (Kowal & Kassam, 1978). In addition to adapting the cropping system and the crops' growing period to the best growing conditions, the farmers' options for adapting to changing climate include managing water resources by using e.g. water harvesting techniques (Kahinda *et al.*, 2007; Rost *et al.*, 2009), managing biodiversity, integrating animals into farming systems (Mortimore & Adams, 2001), diversifying livelihoods (Cooper *et al.*, 2008) and diversifying the whole agricultural system (Lin, 2011). We consider none of these options in our analysis here. In Tanzania, 33 different practices which are potentially suitable for adaptation to climate change, ranging from agricultural water management practices and adjustments of farm and crop management to diversification beyond the farm, are already used by farmers today (Below *et al.*, 2011). Indigenous soil conservation techniques and agro-forestry practices are additional examples for adaptation options not covered in this study. They are well known and already applied in local communities, as they conserve soil moisture and soil carbon (Nyong *et al.*, 2007) and protect crops from dry spells, extreme temperatures and storm events (Lin, 2011).

5 SUMMARY AND CONCLUSIONS

Farmers in sub-Saharan Africa grow a wide range of crops and apply different cropping systems, but as shown in our study clearly prefer long-growing crop cultivars in single cropping systems and short-growing crop cultivars in sequential cropping systems. For the first time, this study also shows the spatial distribution of sequential cropping systems applied in seven sub-Saharan Africa countries and enables us to analyse climate change effects on crop yields considering the cropping system type. They need to be included in climate change impact studies because simulated crop yields differ considerably between crops and cropping systems and also depend on the timing of sowing. Our newly developed modelling approach therefore helps to identify the best management strategy for adaptation to climate change. In single cropping systems crops grow longer but are only harvested once a year, leading to lower crop yields than in sequential cropping systems with shorter growing periods but higher cropping intensities. However, only farmers in regions with adequate temperature, precipitation and solar radiation can benefit from higher cropping intensities in sequential cropping systems. It is important to note that farmers are able to reduce the negative effects of climate change and minimize the risk of crop failure by applying low-tech adaptation options on a farm level. Despite the advantage of sequential cropping systems over single cropping systems in many locations, since both higher crop yields and lower declines in crop yield in future are possible, farmers might not always be able to apply them if inputs and labour for agricultural production are lacking. This implies that farmers would benefit from improved knowledge and further field studies about crops and cropping systems, also ones currently uncommon in their country, and from reliable weather and seasonal climate forecasts. Furthermore stable economic and political conditions would support private trading and the further development of market opportunities. Such conditions would strengthen the farmers' adaptive capacity, perhaps also allowing them to take advantage of sequential cropping systems while at the same time facing the challenge of changing climate conditions.

6 APPENDICES

Appendix A Water stress affecting root biomass.

Appendix B Comparison of the start of the growing season to satellite data.

Appendix C Validation of crop yields simulated with LPJmL in sub-Saharan Africa.

Appendix D Detailed list of simulated crop yields per location.

Appendix E Sequential cropping systems per district, Microsoft Excel file

APPENDIX A Water stress affecting root biomass

Without water stress, root biomass decreases from 40 % at the beginning of the phenological cycle to a minimum of 20 % of total biomass at maturity (Neitsch *et al.*, 2002) (Figure A1 A).

$$froot = froot_{max} - frootmin_{min} \times fphu$$

With increasing water stress the fraction of total biomass allocated to the roots now increases exponentially between that minimum and a maximum of 40 % of total biomass (similar to the reduction in the harvest index with increasing water stress described in (Neitsch *et al.*, 2002)) in order to enhance water uptake from an extensive root system during dry periods (Figure A1 B).

$$froot = (froot_{max} - frootmin_{min} \times fphu) \times \frac{wsf}{wsf + e^{6.13 - 0.00883 \times wdf}}$$

As the above ground biomass thus more strongly responds to water stress, the harvest index is no longer scaled by water stress as originally described by (Bondeau *et al.*, 2007).

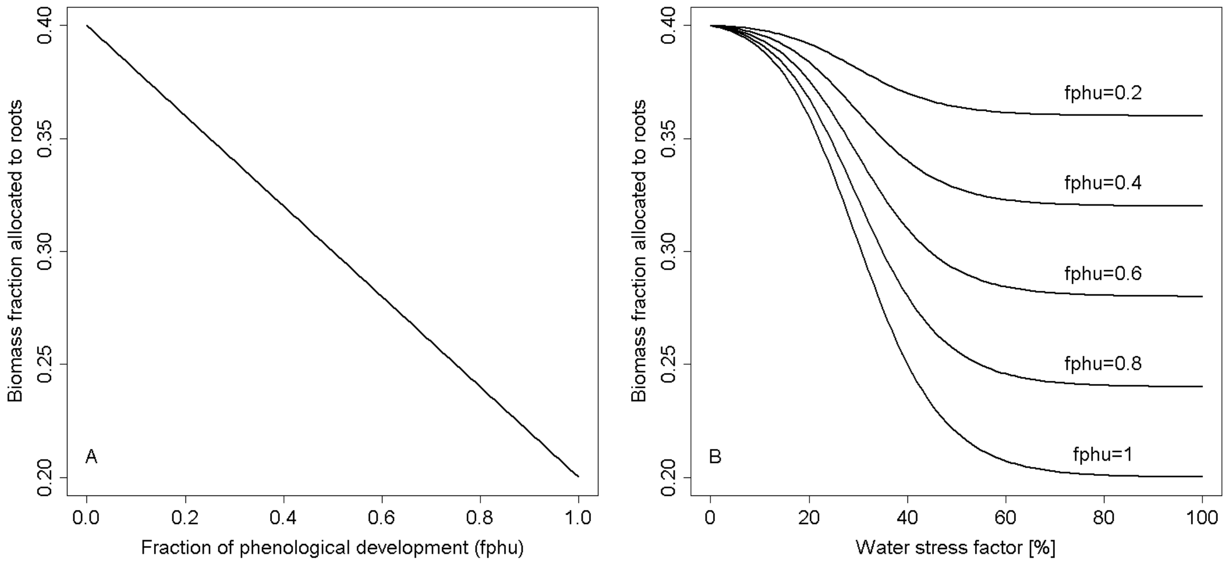

Figure A1 Biomass fraction allocated to the roots, A: without water stress as a function of phenological development, and B: depending on the water stress factor at different phenological stages as simulated in LPJmL. A water stress factor of 0 indicates high water stress.

APPENDIX B Comparison of the start of the growing season to satellite data

We compare the start of the main rainy season simulated by LPJmL to the start of the growing season obtained from MODIS satellite data providing the time of greening up (Figure B1) in order to validate the correct timing of a crop’s sowing date.

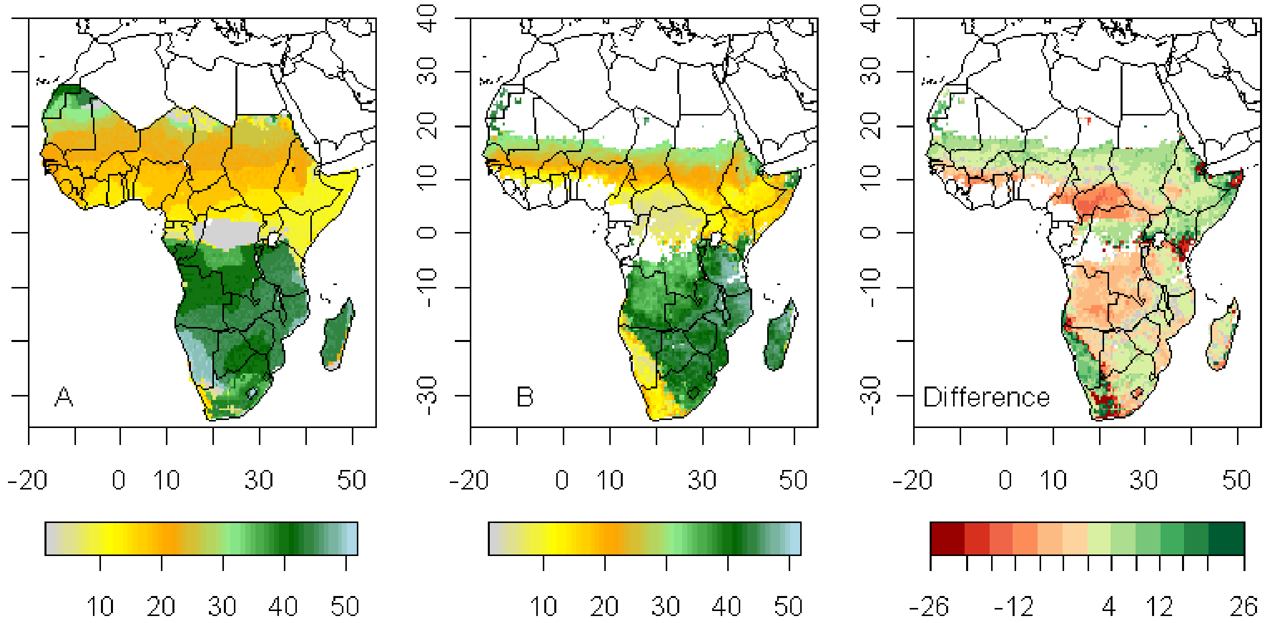

Figure B1 Comparison of simulated (A) and observed (B) start of growing season (in weeks). Simulations were made with LPJmL and observed start of the growing season is derived from MODIS satellite data (HarvestChoice, 2010a). White areas indicate no data.

The differences between the simulated and observed start of the growing season are low with a mean error of 2 ¾ weeks, and a Willmott coefficient of agreement of 0.56. There are considerably larger disagreements than 20 weeks in the mountainous regions of Eastern Africa and desert regions of Namibia.

APPENDIX C Model ability to simulate national crop yields in sub-Saharan Africa.

To provide an assessment of the validness of crop yields simulated with LPJmL we compare country-averaged yields from six crops used in this study in 48 countries of sub-Saharan Africa for the five-year period from 1999 to 2003 to FAO yields (FAO, 2011). The annual fractional coverage of individual crop area per grid cell is prescribed using a newly developed land-use dataset (Fader *et al.*, 2010). As a measure of agreement we calculate the Willmott coefficient of agreement (W) (Willmott, 1982) and the Nash-Sutcliffe efficiency (EF) (Nash & Sutcliffe, 1970) from the area-weighted deviations between simulated and observed yields:

$$W = 1 - \frac{\sum_{i=1}^{N} (S_i - O_i)^2 \times A_i}{\sum_{i=1}^{N} \left(|S_i - \overline{O}| + |O_i - \overline{O}| \right)^2 \times A_i} \qquad EF = 1 - \frac{\sum_{i=1}^{N} (S_i - O_i)^2 \times A_i}{\sum_{i=1}^{N} \left(O_i - \overline{O} \right)^2 \times A_i}$$

where, S_i is the simulated LPJmL and O_i the observed FAO yield (t FM/ha) in a country *i*, $\overline{O}$ the mean observed FAO yield, A_i the cultivated area (ha) of a crop in country *i*, and *N* the number of countries. The Nash-Sutcliffe efficiency ranges from -∞ to 1 (perfect fit), and the Willmott index of agreement ranges from 0 to 1 (perfect fit).

As the rice yield in Somalia of 5.88 t/ha reported from FAO seems to be far too high and is based on unofficial statistics, we used SPAM data (HarvestChoice, 2010b; You & Wood, 2004), which gives a rice yield of 1.85 t/ha for the year 2000 for comparison to LPJmL rice yield.

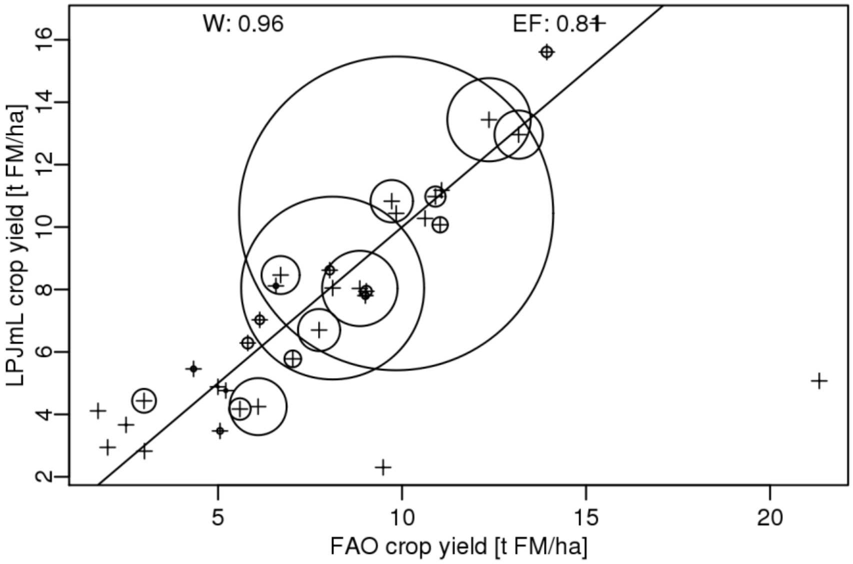

Figure C1 Comparison of LPJmL and FAO cassava yields. Circle radius indicates the size of total cropland under cassava in an individual country.

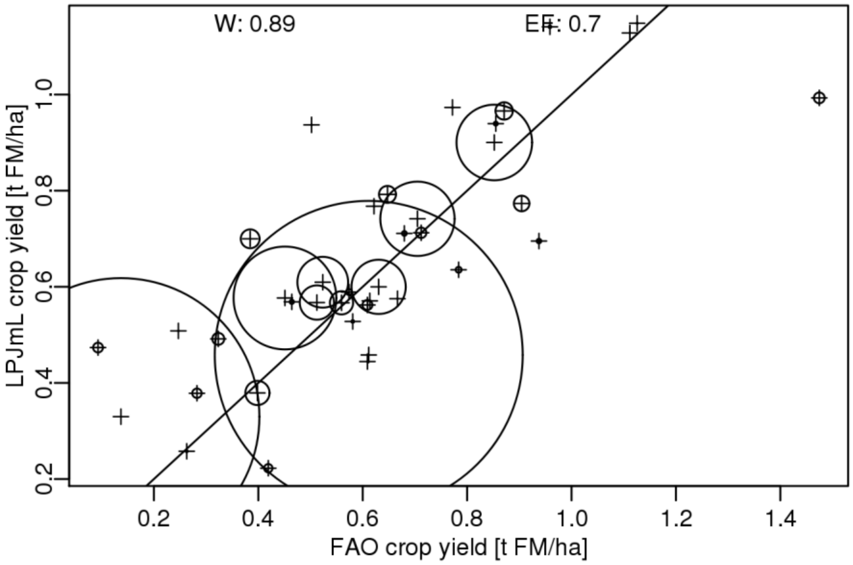

Figure C2 Comparison of LPJmL and FAO cowpea yields. Circle radius indicates the size of total cropland under cowpea in an individual country.

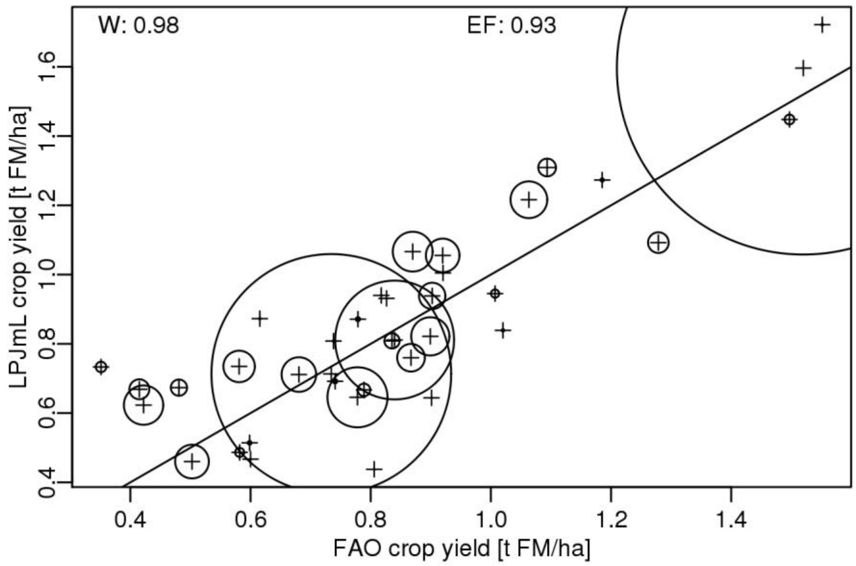

Figure C3 Comparison of LPJmL and FAO groundnut yields. Circle radius indicates the size of total cropland under groundnut in an individual country.

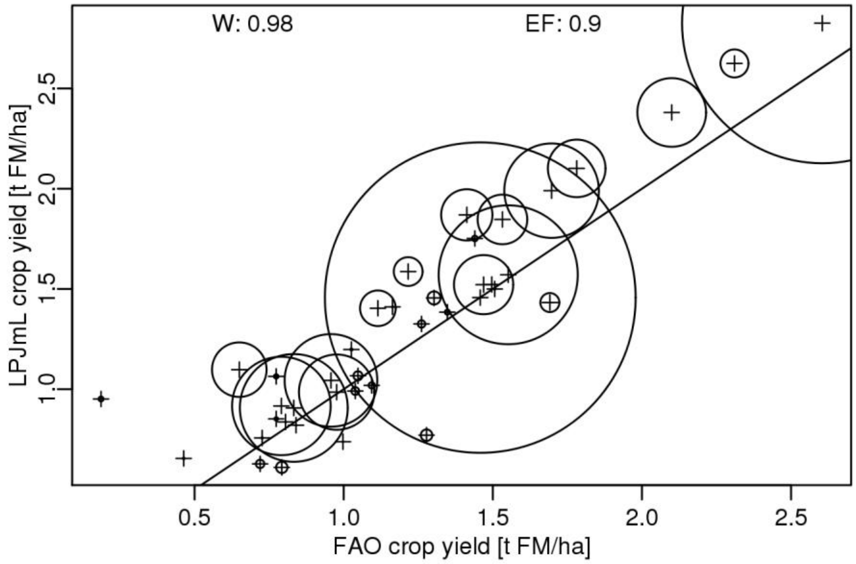

Figure C4 Comparison of LPJmL and FAO maize yields. Circle radius indicates the size of total cropland under maize in an individual country.

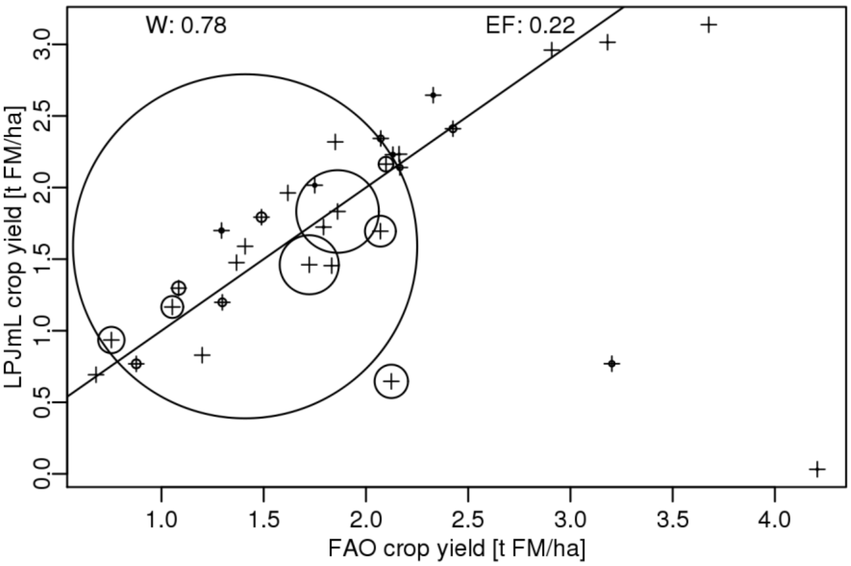

Figure C5 Comparison of LPJmL and FAO rice yields. Circle radius indicates the size of total cropland under rice in an individual country.

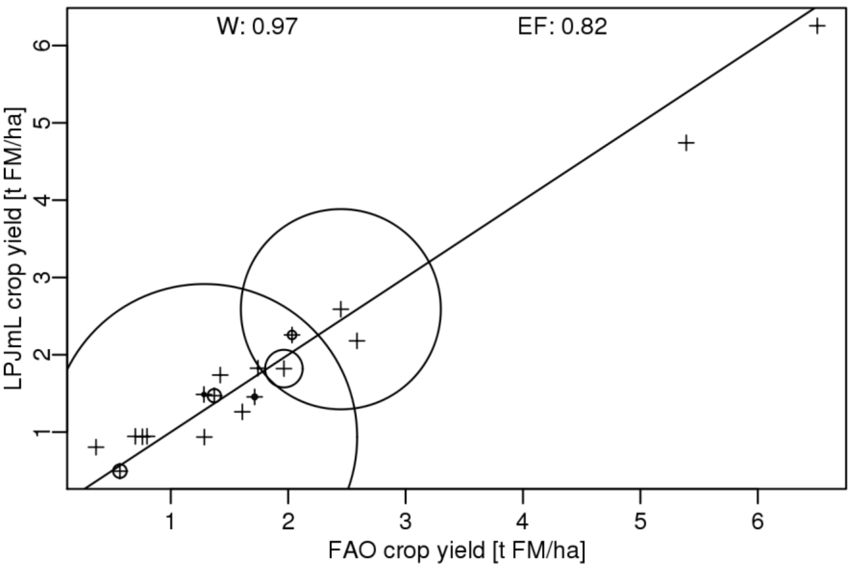

Figure C6 Comparison of LPJmL and FAO wheat yields. Circle radius indicates the size of total cropland under wheat in an individual country.

APPENDIX D Detailed list of simulated crop yields per location

Table D1 Overview of mean crop yields and crop yield changes per country and management scenario in 2070-2099 compared to 1971-2000 averaged over three GCMs. Values are mean crop calorific yields in grid cells with a specific combination of a traditional sequential cropping system (TS/TSco) and a highest-yielding sequential cropping system (HS/HSco).

Country and administrative unit		**Crop yield 1971-2000 [Mcal/ha]**						**Crop yield 2070-2099 [Mcal/ha]**					
		TSco	TS	SCco	SC	HSco	HS	TSco	TS	SCco	SC	HSco	HS
Burkina Faso	Bama	Rice-Rice		Rice		Rice-Rice		Rice-Rice		Rice		Rice-Rice	
		13666	18717	11204	10498	13666	18717	12222	12849	4769	4057	12222	12849
								(-11%)	(-31%)	(-57%)	(-61%)	(-11%)	(-31%)
	Tiebele	Rice-Maize		Rice		Maize-Rice		Rice-Maize		Rice		Maize-Rice	
		7907	10135	2418	6105	16012	16196	5531	6521	479	2181	10939	12629
								(-30%)	(-36%)	(-80%)	(-64%)	(-32%)	(-22%)
Cameroon	Sanaga-Maritime	Groundnut-Maize		Groundnut		Wheat-Maize		Groundnut-Maize		Groundnut		Wheat-Maize	
		9668	9633	3218	3189	14247	14093	7989	8136	2360	2502	11475	12003
								(-17%)	(-16%)	(-27%)	(-22%)	(-19%)	(-15%)
	Mbam-et-Inoubou	Maize-Groundnut		Maize		Wheat-Maize		Maize-Groundnut		Maize		Wheat-Maize	
		12210	12239	8671	8701	16388	16484	10090	10176	7757	7616	12947	13841
								(-17%)	(-17%)	(-11%)	(-12%)	(-21%)	(-16%)
	Vina	Maize-Wheat		Maize		Maize-Wheat		Maize-Wheat		Maize		Maize-Wheat	
		18120	19317	10977	11571	18120	19317	16356	17953	8909	9813	16356	17953
								(-10%)	(-7%)	(-19%)	(-15%)	(-10%)	(-7%)
	Moungo, Sanaga-Maritime	Groundnut-Maize		Groundnut		Maize-Wheat		Groundnut-Maize		Groundnut		Maize-Wheat	
		9839	9906	3239	3270	14850	14802	7967	8233	2312	2535	12347	12652
								(-19%)	(-17%)	(-29%)	(-22%)	(-17%)	(-15%)
	Momo	Groundnut-Cassava		Groundnut		Maize-Wheat		Groundnut-Cassava		Groundnut		Maize-Wheat	
		8496	8694	3557	3619	15944	15958	10127	8448	2528	2774	13208	13545
								(19%)	(-3%)	(-29%)	(-23%)	(-17%)	(-15%)
	Vina	Maize-Wheat		Maize		Maize-Maize		Maize-Wheat		Maize		Maize-Maize	
		17808	18189	9736	10253	18937	19144	14243	15900	7887	8858	14956	16163
								(-20%)	(-13%)	(-19%)	(-14%)	(-21%)	(-16%)

Continuation Table D1

Cameroon	Various (>3)	Maize-Maize		Maize		Maize-Maize		Maize-Maize		Maize		Maize-Maize	
		16188	16729	9050	9349	16188	16729	13824 (-15%)	14384 (-14%)	7686 (-15%)	8103 (-13%)	13824 (-15%)	14384 (-14%)
	Nyong-et-Kelle	Cassava-Maize		Cassava		Maize-Maize		Cassava-Maize		Cassava		Maize-Maize	
		11352	11355	10788	10984	14382	14193	10886 (-4%)	11650 (3%)	10587 (-2%)	10329 (-6%)	12788 (-11%)	12410 (-13%)
	Lekie	Cassava-Cowpea		Cassava		Maize-Maize		Cassava-Cowpea		Cassava		Maize-Maize	
		11737	11741	10803	10787	14776	14825	11304 (-4%)	10572 (-10%)	10114 (-6%)	10283 (-5%)	12865 (-13%)	12729 (-14%)
	Moungo, Ntem	Groundnut-Maize		Groundnut		Maize-Maize		Groundnut-Maize		Groundnut		Maize-Maize	
		8388	8797	3944	3932	14399	14412	6870 (-18%)	7806 (-11%)	2948 (-25%)	3103 (-21%)	12676 (-12%)	12715 (-12%)
	Mbam-et-Inoubou	Maize-Groundnut		Maize		Maize-Maize		Maize-Groundnut		Maize		Maize-Maize	
		12291	12487	9055	9251	17016	17181	9824 (-20%)	10377 (-17%)	7931 (-12%)	8168 (-12%)	14045 (-17%)	14420 (-16%)
	Bui	Groundnut-Groundnut		Groundnut		Maize-Maize		Groundnut-Groundnut		Groundnut		Maize-Maize	
		8263	8290	6501	6529	15094	15223	8301 (0%)	8516 (3%)	4039 (-38%)	4411 (-32%)	17384 (15%)	16852 (11%)
	Manyu	Groundnut-Maize		Groundnut		Cassava-Maize		Groundnut-Maize		Groundnut		Cassava-Maize	
		7445	7362	2560	2590	11670	11715	4911 (-34%)	4420 (-40%)	1700 (-34%)	2036 (-21%)	10159 (-13%)	10170 (-13%)
Ethiopia	Kembata-Timbaro, Wolaita	Maize-Wheat		Maize		Cassava-Cowpea		Maize-Wheat		Maize		Cassava-Cowpea	
		11659	12490	10212	10942	16854	18755	9542 (-18%)	10958 (-12%)	8214 (-20%)	9321 (-15%)	14539 (-14%)	17797 (-5%)
Ghana	Nkwanta	Maize-Rice		Maize		Cassava-Cowpea		Maize-Rice		Maize		Cassava-Cowpea	
		11840	12033	5554	5814	13458	13645	8155 (-31%)	9452 (-21%)	4329 (-22%)	4915 (-15%)	11524 (-14%)	11904 (-13%)
	Various (>3)	Maize-Maize		Maize		Cassava-Cowpea		Maize-Maize		Maize		Cassava-Cowpea	
		9794	10361	5212	5756	14449	14829	8008 (-18%)	8847 (-15%)	4077 (-22%)	4882 (-15%)	12040 (-17%)	12719 (-14%)

Continuation Table D1

Ghana	Tolon-Kumbungu	Groundnut-Rice		Groundnut		Cassava-Cowpea		Groundnut-Rice		Groundnut		Cassava-Cowpea	
		11210	11606	4681	5104	12368	12725	6181 (-45%)	7873 (-32%)	1948 (-58%)	3134 (-39%)	10432 (-16%)	10861 (-15%)
	Sene	Groundnut-Maize		Groundnut		Cassava-Cowpea		Groundnut-Maize		Groundnut		Cassava-Cowpea	
		10755	10328	5361	5243	12882	13536	7551 (-30%)	7575 (-27%)	3334 (-38%)	3398 (-35%)	11310 (-12%)	11840 (-13%)
Kenya	Muranga, Nyeri, Embu	Maize-Maize		Maize		Wheat-Maize		Maize-Maize		Maize		Wheat-Maize	
		4815	4847	5167	5170	10051	10601	8615 (79%)	9614 (98%)	7878 (52%)	8115 (57%)	15968 (59%)	17462 (65%)
	Nyeri	Maize-Maize		Maize		Rice-Rice		Maize-Maize		Maize		Rice-Rice	
		5267	5339	5659	5685	9883	9870	8757 (66%)	9292 (74%)	8147 (44%)	8481 (49%)	15563 (57%)	15945 (62%)
	Kajiado, Kitui	Maize-Maize		Maize		Maize-Maize		Maize-Maize		Maize		Maize-Maize	
		5986	8008	3123	4527	5986	8008	5006 (-16%)	7399 (-8%)	2678 (-14%)	4350 (-4%)	5006 (-16%)	7399 (-8%)
	Various (>3)	Maize-Maize		Maize		Cassava-Maize		Maize-Maize		Maize		Cassava-Maize	
		10038	10959	6325	7144	16262	17009	9929 (-1%)	11398 (4%)	5205 (-18%)	6332 (-11%)	12330 (-24%)	15549 (-9%)
	Kakamega	Maize-Groundnut		Maize		Cassava-Maize		Maize-Groundnut		Maize		Cassava-Maize	
		16128	17086	6753	7546	22401	23206	10850 (-33%)	13313 (-22%)	5436 (-20%)	6780 (-10%)	15162 (-32%)	19433 (-16%)
	Various (>3)	Maize-Maize		Maize		Cassava-Cowpea		Maize-Maize		Maize		Cassava-Cowpea	
		7541	9497	4714	5885	12010	13991	6658 (-12%)	8831 (-7%)	3891 (-17%)	5154 (-12%)	9414 (-22%)	11822 (-15%)
	Bungoma	Maize-Groundnut		Maize		Cassava-Cowpea		Maize-Groundnut		Maize		Cassava-Cowpea	
		9473	9862	9267	9784	27098	28204	16435 (73%)	18003 (83%)	7335 (-21%)	8172 (-16%)	23307 (-14%)	26014 (-8%)
	Various (>3)	Maize-Maize		Maize		Cassava-Cowpea		Maize-Maize		Maize		Cassava-Cowpea	
		5177	7501	4269	5708	7744	9118	4592 (-11%)	7497 (0%)	3544 (-17%)	5049 (-12%)	3494 (-55%)	7026 (-23%)

Continuation Table D1

Kenya	Bomet	Maize-Maize		Maize		Groundnut-Groundnut		Maize-Maize		Maize		Groundnut-Groundnut	
		9666	9676	10376	10388	19512	19586	15287 (58%)	14988 (55%)	8776 (-15%)	8922 (-14%)	18422 (-6%)	16283 (-17%)
South Africa	Bethlehem, Lydenburg	Wheat-Maize		Wheat		Wheat-Maize		Wheat-Maize		Wheat		Wheat-Maize	
		15923	15888	12742	12831	15923	15888	15268 (-4%)	16875 (6%)	7110 (-44%)	9341 (-27%)	15268 (-4%)	16875 (6%)
	Aberdeen	Maize-Wheat		Maize		Wheat-Maize		Maize-Wheat		Maize		Wheat-Maize	
		3446	3495	3664	3705	10581	10396	3961 (15%)	4974 (42%)	2550 (-30%)	4417 (19%)	7011 (-34%)	3555 (-66%)
	Lydenburg	Wheat-Maize		Wheat		Maize-Wheat		Wheat-Maize		Wheat		Maize-Wheat	
		8985	9802	8541	8283	15620	15660	14090 (57%)	21531 (120%)	3617 (-58%)	13177 (59%)	17318 (11%)	19634 (25%)
	Aberdeen	Maize-Wheat		Maize		Cassava-Maize		Maize-Wheat		Maize		Cassava-Maize	
		3978	3922	4300	4234	4199	4155	3792 (-5%)	3556 (-9%)	3839 (-11%)	3054 (-28%)	3872 (-8%)	3900 (-6%)
	Aberdeen	Maize-Wheat		Maize		Cassava-Cowpea		Maize-Wheat		Maize		Cassava-Cowpea	
		4827	4898	5124	4964	4900	5129	4987 (3%)	4732 (-3%)	4580 (-11%)	3847 (-22%)	706 (-86%)	2703 (-47%)
Zimbabwe	Masvingo	Maize-Wheat		Maize		Maize-Wheat		Maize-Wheat		Maize		Maize-Wheat	
		13063	12505	4160	4179	15299	15931	9130 (-30%)	11357 (-9%)	1542 (-63%)	3082 (-26%)	3954 (-74%)	9161 (-42%)
	Chegutu, Chipinge	Maize-Maize		Maize		Maize-Maize		Maize-Maize		Maize		Maize-Maize	
		6042	7091	2966	3840	9791	14778	4256 (-30%)	5632 (-21%)	1527 (-49%)	2763 (-28%)	3857 (-61%)	8347 (-44%)

TS/TSco: Traditional sequential cropping system, SC/SCco: Single cropping system, HS/HSco: Highest-yielding sequential cropping system, “co” indicating management scenarios with constant sowing dates

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