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Change in crop management strategies could double the maize yield in Africa

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Abstract

Change in cropping practices is required to address the food security issues in Africa. Yet, testing of the performance of such changes, in particular at large scales, often needs significant investments. Crop models are widely used tools to quantify the effects of agronomic decisions on cropping systems and to identify the most promising areas for their advancement and implementation. Here in this study we quantify the impacts of individual and combined change in management scenarios including changes in (i) rates of nitrogen application, (ii) supplementary irrigation and (iii) new cultivar (with higher radiation use efficiency) on maize cropping systems over Africa based on 30 years (1980-2010) of climate, soil and management information obtained from global datasets at 0.5° x 0.5° spatial resolution. The crop model SIMPLACE was used in this study and it was tested against FAO statistics to evaluate the model performance under the current management conditions with traditional cultivars and average nitrogen application rates of <10 kg N ha^{-1}. The model results showed that the combined changes in crop management could improve the range of maize yield from 1.2 t ha^{-1} to 2.9 t ha^{-1} over the study period in Africa. The magnitude of the yield improvement is country and scenario specific. The largest maize yield improvements were obtained in the combined innovations rather than individual practices in particular for the supplementary irrigation. We conclude that it is essential to implement combined technology packages to fill the gap between attainable and current yield in Africa and that will require appropriate incentives, and investment in extension services, fertilizer distribution networks and farmer capacity strengthening. We also need to combine the results with a robust economic model to evaluate the benefits and risks of the required investments for such changes in crop management.

Keywords: Grain maize, nitrogen, irrigation, cultivar, Africa

JEL Codes: Q, O13, O32

1. Introduction

1.1. Food security and cereal production in Africa

Food security has continued to be a top priority for the national and international communities and a vital topic in academic development research and central component of the development of societies (Lipton and Warren-Rodríguez, 2016). The global food production tripled in the period 1961 to 2007 (Pretty et al., 2011) nevertheless, it needs to substantially increase (60%) by 2050 based on the projected demands (Alexandratos and Bruinsma, 2012). Producing more food is required to serve the growing population for the coming decades, in spite of opposing current food insecurity issues, is a big challenge for Africa (Garrity et al., 2010; Lobell et al., 2008). 26 percent of the population above 15 years (153 million) of sub-Saharan Africa suffered from food insecurity in 2014/2015 based on the FAO Africa food security and nutrition report (Amegbeto, 2017). In the period 2014 to 2016, the number of undernourished people varied between 124 million and 3.2 million in Eastern Africa and Southern Africa, respectively (Amegbeto, 2017).

The cereal crops cover 45 percent of arable lands of Africa (Galati et al., 2014) and supply almost 60 percent of the human diet in African countries (Temba et al., 2016). Maize is the most important staple crop in Africa (Burke et al., 2009) and contributed to 37 percent of cereals production (Figure 1). The long term change in yield trend of cereals and maize showed a slight increase (0.14 and 0.19 ton per decade for cereals and maize, respectively) in the period 1961 to 2014 (Figure 1) based on FAO statistics in Africa. However, the magnitude of yield increase in Africa was remarkably smaller than the changes in global yield of cereals (0.50 ton per decade) and maize (0.72 ton per decade) (Figure 1).

1.2. The yield gap of maize in Africa

The yield gap demonstrates the difference between actual yield and attainable crop yield which is limited by rainfall, temperature, solar radiation, CO_2 level in the atmosphere and cultivar properties (Van Ittersum et al., 2013). The largest yield gap over the global scale was projected for Africa across the major cereal crops (Mueller et al., 2013). The recorded yield in Africa reaches only 20 percent of the attainable yield in contrast to 56 to 84 percent of the attainable yield in European, Asian and North American sites (Hoffmann et al., 2017). The outsized yield gap in Africa could be explained by larger level of biotic and abiotic stressors, poor crop management (water and nutrient management), cultivar selection and socio-economic constrains (Audebert and Fofana, 2009; Fermont et al., 2009; Mueller et al., 2013; Verdoodt et al., 2006). Maize and rice showed the highest potential of yield increase (largest yield gap) in Africa (Licker et al., 2010).

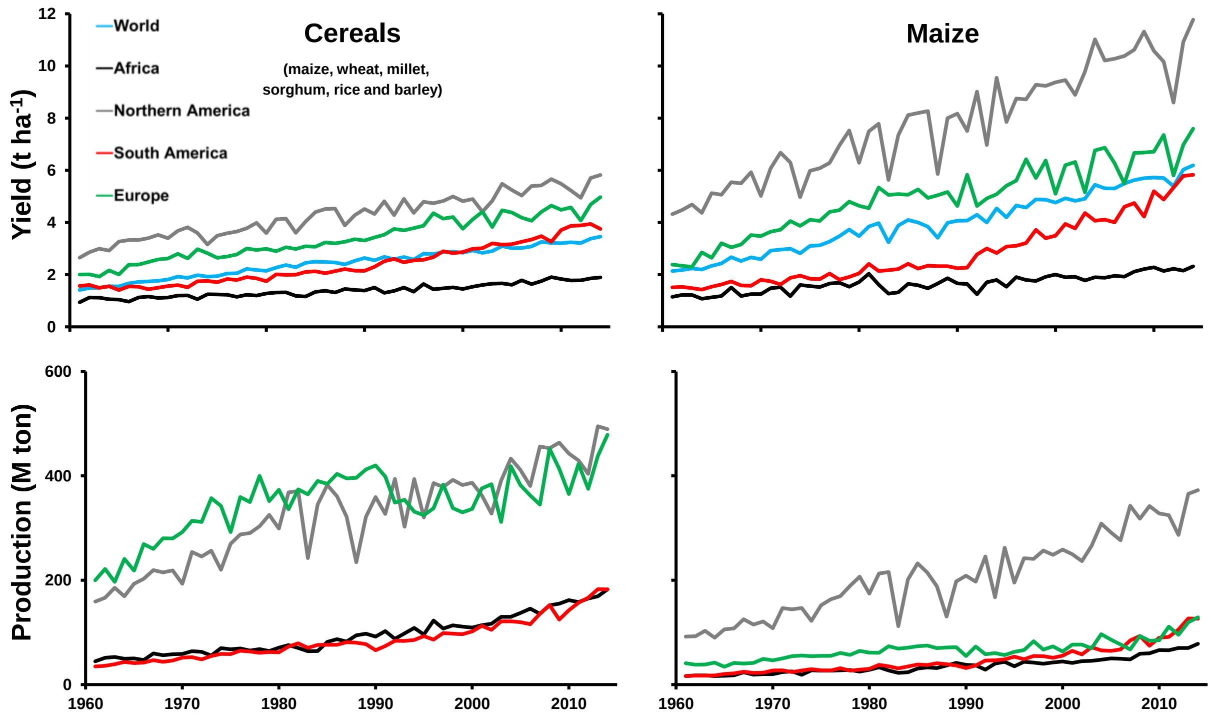

Figure 1. The long term (1961-2014) trend of cereals and maize yield and production in different parts of the globe obtained from FAO-STAT (FAO, 2014).

1.3. The possible options to close the yield gap of maize in Africa

Drought and low soil fertility are the primary yield limiting factors of maize cropping systems in Africa (Vanlauwe et al., 2011; Weber et al., 2012). Rainfed maize covers most of the maize based cropping systems (~90%) in Africa (Portmann et al., 2010a). The maize yield showed a linear increasing trend with increasing annual precipitation sum up to 500 mm per year over Africa (Folberth et al., 2014). Deficit irrigation has been extensively evaluated as a suitable strategy to reduce the negative impacts of drought stress on crop yield in dry regions (Geerts and Raes, 2009). Implementation of supplementary irrigation could double the legume and wheat yield in West Asia and North Africa and could be considered as a practice to close the yield gap (Oweis and Hachum, 2006).

The nitrogen application rate for maize is restricted from 0 to 30 kg N ha^{-1} over Africa which is much smaller than other regions of the world (Mueller et al., 2013). Introducing new cultivars and improving the plant nutritional status could also be possible options to close the maize yield gap in Africa (Hoffmann et al., 2017). Nitrogen limitation was the main limiting factor of maize yield and changing the phosphorus application rate had no significant impact on maize yield in Togo (Wopereis et al., 2006). Changing nitrogen application rate from 30 kg ha^{-1} to 60 kg ha^{-1} increased the grain yield of maize from 1.8 t ha^{-1} to 2.7 t ha^{-1} in Southern Guinea (Carsky et al., 1999). Optimum fertilizer application increased the maize yield from 2 t ha^{-1} to 4 t ha^{-1}

in Kenya (Vanlauwe et al., 2014). Combination of nitrogen fertilizer and manure increased the maize yield in the range of 55% to 120% depending on the year of application in West Africa (Abunyewa et al., 2007).

1.4. Modelling of the crop management strategies

Crop growth models which simulate the crop growth interacting with climate, soil and management are useful tools to understand the impacts of different management strategies and environmental factors on cropping systems (Rötter et al., 2016). The effect of change in management practices such as fertilization management, cultivar selection and watering regime have been tested in field experiments (Shadish et al., 2008). However, such field experiments are expensive and time consuming and limited to the environmental conditions of the study site (de Reffye et al., 1998; Heng et al., 2007; Rinaldi, 2001). Testing of the efficiency of changes in management practices is challenging at larger scale (Therond et al., 2011). Crop models are suitable tools to upscale the effects of management strategies on crop yields and agricultural production from the field scale to the national or continental scale (Gaiser et al., 2010).

1.5. Gap of knowledge and objectives

Many studies have been conducted to evaluate the effects of change in fertilization management, supplementary irrigation and new cultivars at different regions of Africa but little is known about the effects of combined changes of management practices at the Africa scale. The main objective of this study was to explore the potential of individual and combined increase in fertilizer application dose, implementation of irrigation and introducing of the new cultivars with higher radiation use efficiency on maize cropping systems over Africa. A schematic diagram illustrating data, models and workflow used in our study is shown in Figure 2, while a detailed description of materials and methods is provided in the next section.

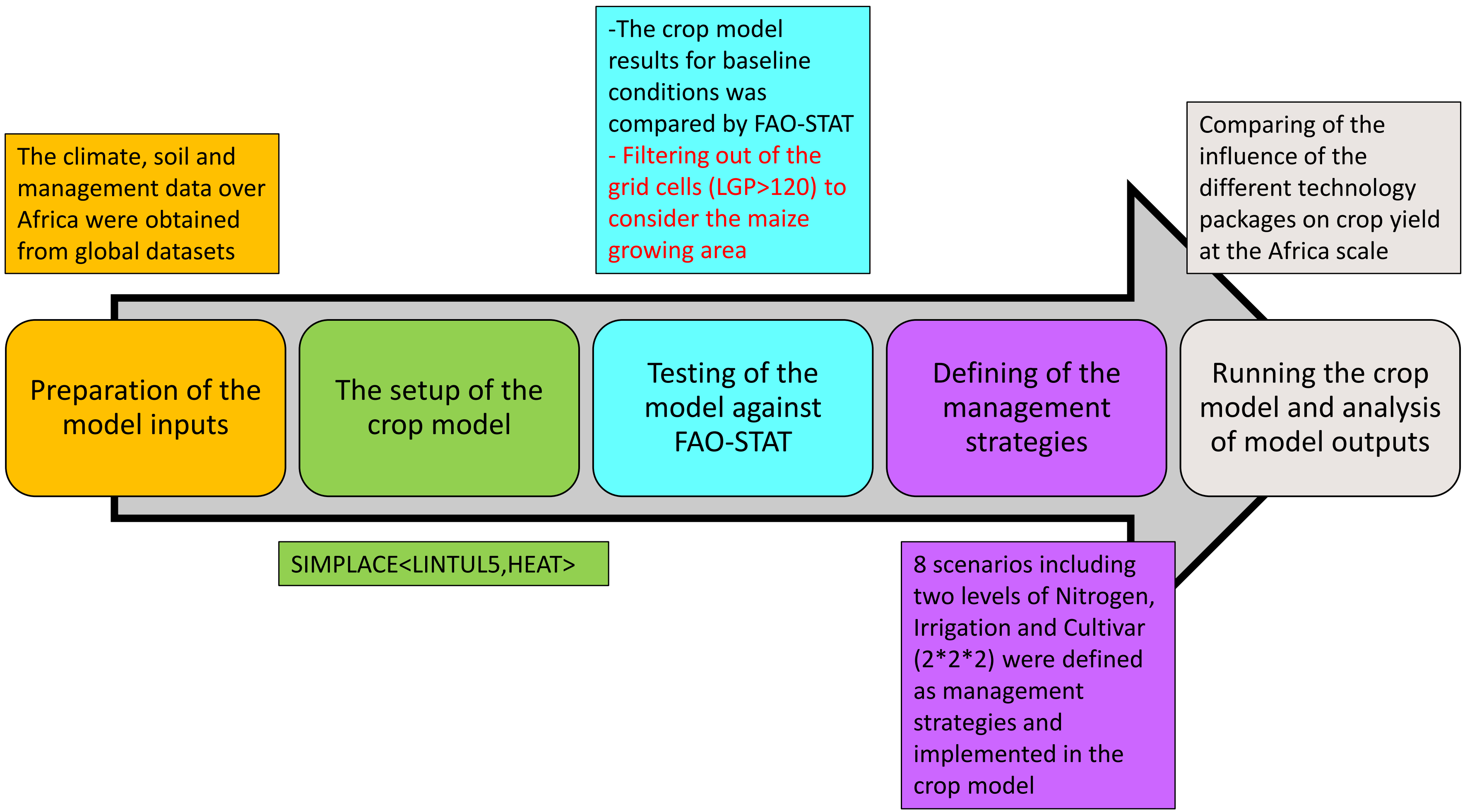

Figure 2. Schematic diagram of the stepwise data preparation and analysis of the current study.

2. Materials and methods

2.1. Input data preparation

2.1.1. Climate and soil data

The AgMERRA climate forecasting dataset for agricultural modeling (Ruane et al., 2015) was used as a climate input for yield simulations at the African scale. The dataset includes daily temperature, precipitation, radiation and wind speed at global scale (0.5° × 0.5°) in the period 1980-2010 (Figure 3). The dataset was in gridded format and the Africa related grid cells were extracted from the global dataset. The dataset was exclusively developed for crop modeling proposes based on a reanalysis approach using ground measurements and satellite observations (Rienecker et al., 2011).

The physical (field capacity, wilting point and profile available water capacity) and chemical (total nitrogen density) properties at 0.5° × 0.5° resolution were obtained from ISRIC wise and Global Gridded Surfaces of Selected Soil Characteristics, respectively (Batjes, 2012, 1995). The soil depth information was obtained from the FAO soil depth dataset and restricted to 1 m to be compatible with other soil information (Batjes, 1997).

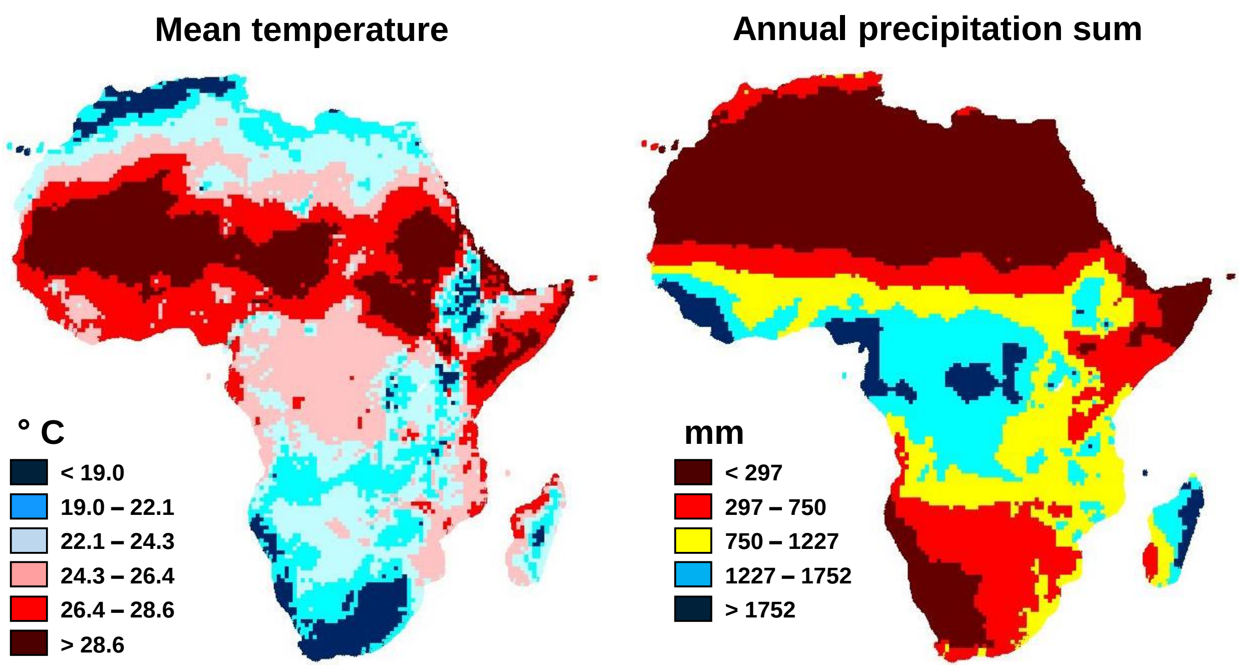

Figure 3. The mean annual temperature and annual precipitation sum over Africa in the period 1980-2010 at 0.5° × 0.5° spatial resolution obtained from the AgMERRA dataset (Ruane et al., 2015).

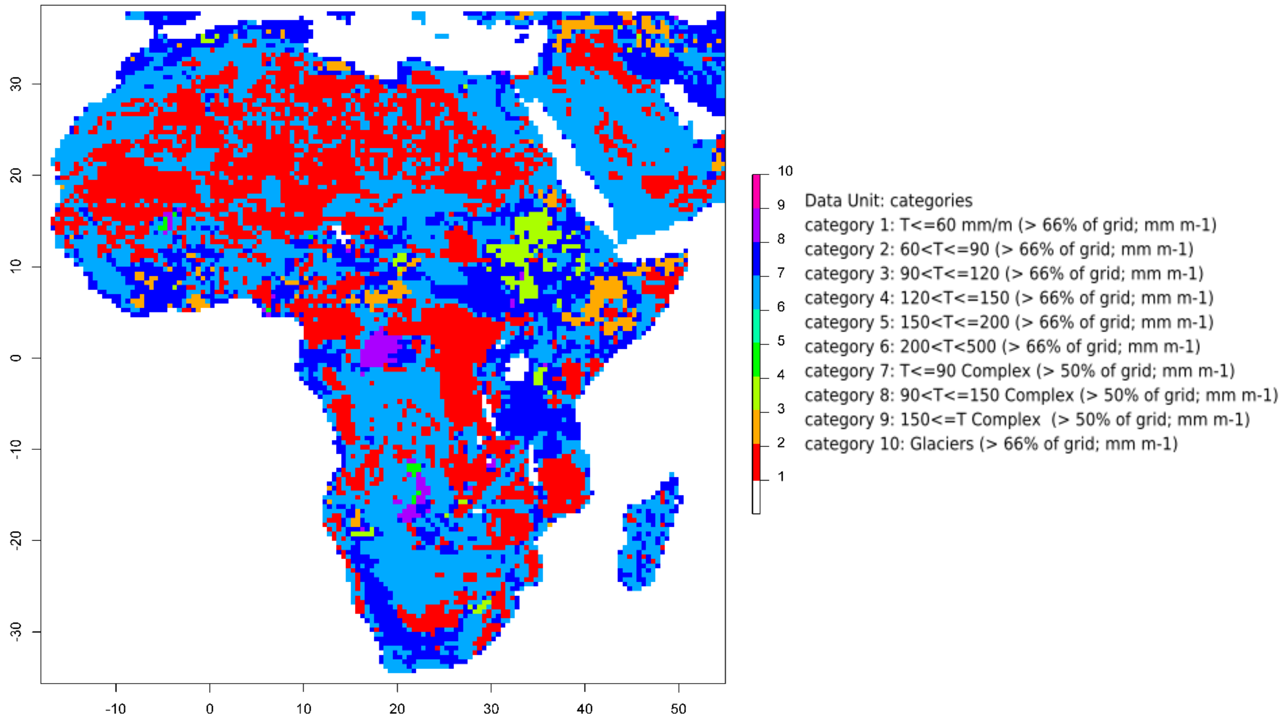

Figure 4. The total available water capacity at 1 m soil depth over Africa obtained form ISRIC-WISE global dataset (Batjes, 2012).

2.1.2. Management data

The information of the cropping calendar (sowing and harvest dates) of rainfed maize was gained from MIRCA2000 dataset (Portmann et al., 2010) which is representative for the time period 1998 to 2002 (Figure 5). The nitrogen fertilizer application rate of the African countries for maize was obtained from set of global datasets (Liu et al., 2010; Mueller et al., 2013; Potter et al., 2010) (Figure 6). This dataset was built by using International Fertilizer Industry Association (IFA) information for 88 countries. The fertilizer use in these 88 countries account for over 90% of global fertilizer consumption (Potter et al., 2010). Due to the lack of phenology information at the Africa scale, we calculated the corrected temperature sum (corrected for photoperiod effect) from sowing to harvest date and assumed that 50% of the temperature sum contributed to the vegetative phase (emergence to anthesis) and the other half contributed to the reproductive phase (anthesis to maturity) of maize (van Bussel et al., 2015).

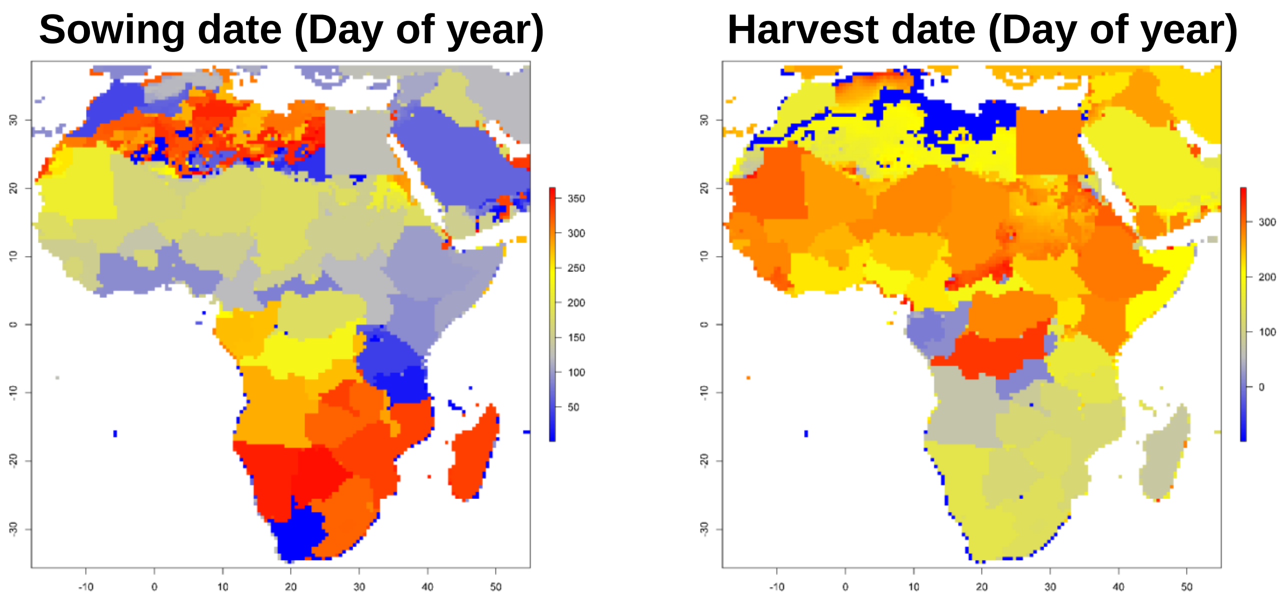

Figure 5. The sowing and harvest dates of the rainfed maize at the African scale obtained from MIRCA2000 dataset (Portmann et al., 2010a).

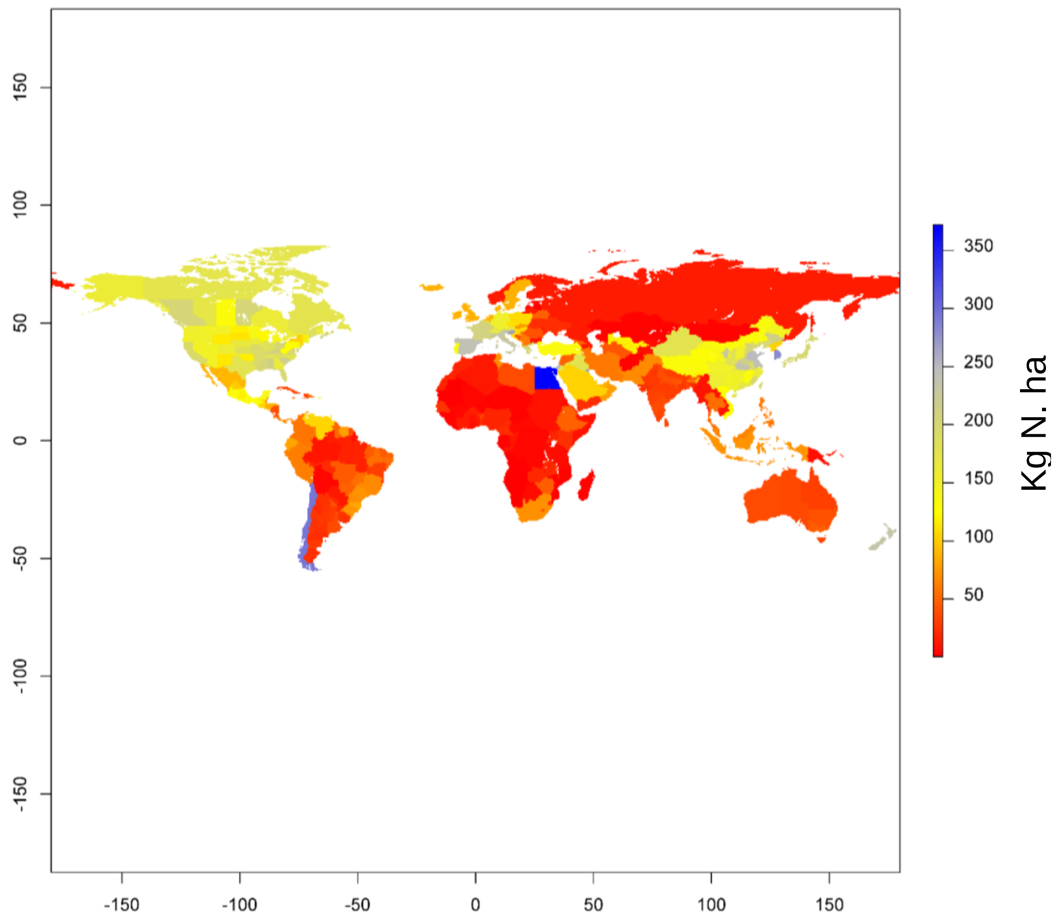

Figure 6. The global nitrogen application rate for major cereals such as maize (Liu et al., 2010; Mueller et al., 2013; Potter et al., 2010).

2.2. The setup of the crop model

SIMPLACE (Scientific Impact assessment and Modeling Platform for Advanced Crop and Ecosystem management (http://www.simplace.net/Joomla/)) is a modeling framework based on the concept of encapsulating the solution of a modeling problem in discrete, replaceable, and interchangeable software units called Sim-Components or sub-models (Enders et al., 2010). A specific combination of sub-models within the SIMPLACE framework is called a model solution (Gaiser et al., 2013).

All Sim-components except phenology and heat stress on grain yield (Eyshi Rezaei et al., 2015) were followed an approach given in the crop model LINTUL5 (Wolf, 2012). The final model solution is called SIMPLACE<LINTUL5,HEAT>. The yield limiting factors of the crop model were drought, heat and nitrogen stress. Biotic stressors are currently not implemented in the model solution. The simulations were restricted to the grid cells where the length of the growing season is greater than 120 days in Africa based on the global Agro-ecological Zones (Fischer et al., 2012) to have a more realistic overview of maize growing areas over Africa (Figure 7). The performance of the model was tested against 10 years (2000-2010) FAO yield statistics at national scale (FAO, 2014). The Root Mean Squared Error (RMSE), mean squared error (MSE) and Pearson correlation coefficient (r) were computed to test the crop model’s prediction error and relationships between modelled and observed data (Brisson et al., 2002):

$$RMSE = [n^{-1} \sum_{i=1}^{n} (S_i - O_i)^2]^{0.5} \quad \text{Eq. 1}$$

$$MSE = n^{-1} \sum_{i=1}^{n} (S_i - O_i)^2 \quad \text{Eq. 2}$$

where *Si* and *Oi* indicate the simulated and observed data.

2.3. Identification of crop management scenarios

The selected crop management scenarios were limited to 2 × 2 × 2 combinations of nitrogen application rate, irrigation and new cultivar over Africa. All of the scenarios were implemented in the crop model and run for each grid cell in the period 1980 to 2010. The recommended nitrogen application rate of maize ranged between 50 kg N ha-1 to 100 kg N ha^{-1} depending on the study region (Bello et al., 2012; CIMMYT, 1997; J. O. S. Kogbe and Adediran, 2003). However, there was an stagnating trend in maize yield increase when applying more than 60 kg N ha^{-1} in African cropping systems (Azeez et al., 2006; Kimetu et al., 2004). We selected as scenarios the current nitrogen application rate and 60 kg N ha^{-1} at sowing. The watering scenarios were rainfed and supplementary irrigation (automatically applied in the crop model) whenever the actual soil water content dropped below 50% of the field capacity. Two cultivar scenarios were introduced as current cultivar and new cultivar with 20% higher radiation use efficiency. The increase in radiation use efficiency is confirmed as an effective breeding strategy for new maize hybrids (Tollenaar and Aguilera, 1992).

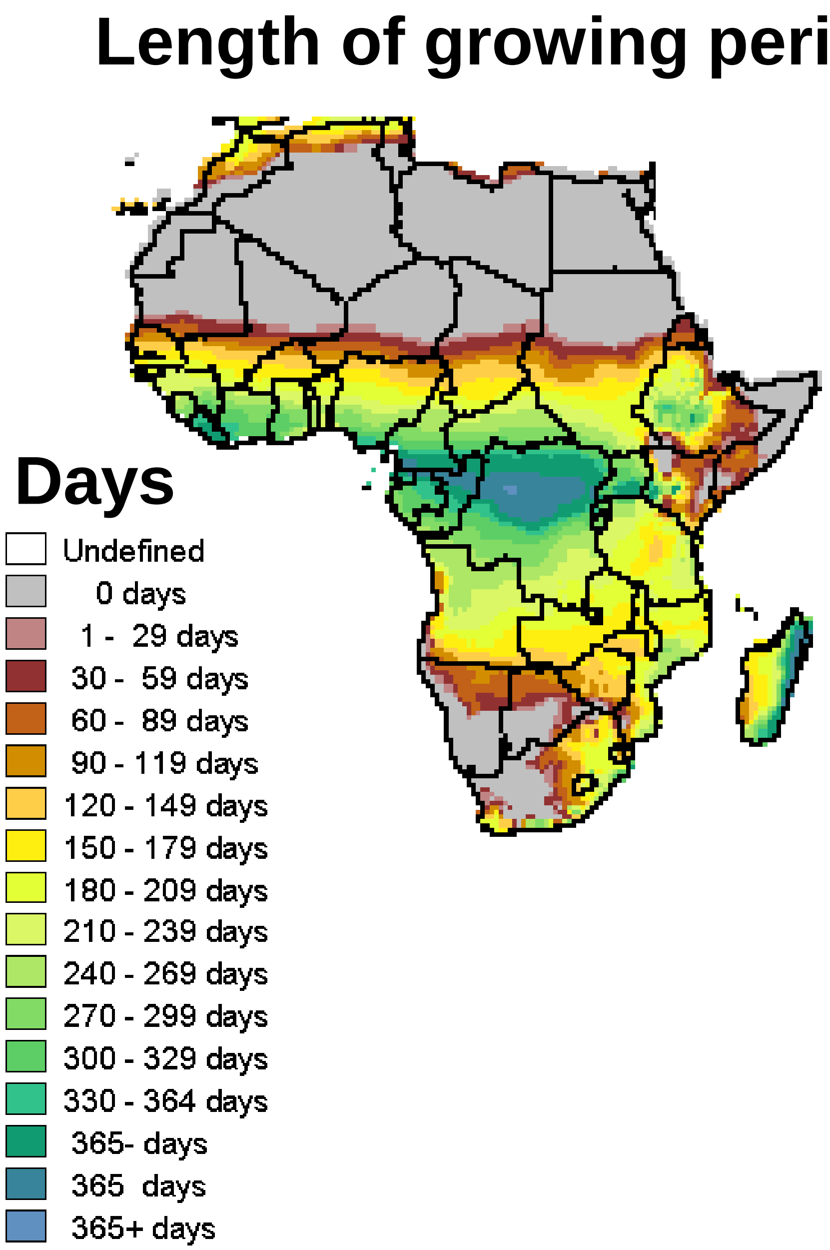

Figure 7. The length of growing period (LGP) zones in Africa obtained from FAO/IIASA Global Agro-Ecological Zoning dataset (https://goo.gl/FzPz1y).

3. Results and discussion

3.1. The crop model performance

The median of the national scale of maize yield (FAO, 2014) ranged between 0.6 t ha^{-1} to 3.2 t ha^{-1} in the period 2000 to 2010 over 36 African countries (Figure 8a). The crop model was able to reproduce the variability of the observed yield (r = 0.65 and MSE = 0.27) (Figure 8b). The accuracy of the yield predictions was in an acceptable range (RMSE = 0.52 t ha^{-1}). We selected the last 10 years of the study period to test the model performance to minimize the effect of technological change on the FAO statistics. However, the change in management practices including cultivars or fertilization dosage could still have an effect on yields even in such short period of time. For instance, the governmental subsidies of maize farmers in Malawi substantially changed during the period between 2000-2010 (Holden and Lunduka, 2010). The crop model parameters were set based on the yield level for the period 2000-2010 conditions. The crop model was not able to account for such changes due to the lack of data at the continental scale. Therefore, this could be one of the error sources in the model outcomes. Another source of uncertainty in the simulations is the effect of pests and diseases which was not implemented in the crop model although biotic stressors can be an important yield reduction factor for maize in Africa (Ndemah et al., 2002; Oerke, 2006). Finally, we used a single cultivar parameter set over Africa due to the lack of data in cultivar characteristics at higher resolution which could also explain some uncertainty in yield predictions.

3.2. The impacts of individual change in fertilization, irrigation and cultivars on maize yield in Africa

Implementation of the fertilization, irrigation and cultivar scenarios indicated a substantial changed in maize yield over Africa (Figure 9). The largest improvement in simulated maize yield (1.2 t ha^{-1} to 2.7 t ha^{-1}) was obtained by increasing the nitrogen application rate to 60 kg N ha^{-1} over Africa (Figure 9). Application of supplementary irrigation also showed a remarkable rise in simulated maize yield (1.8 t ha^{-1} to 2.3 t ha^{-1}) in the period 1980-2010 across Africa (Figure 9). However, changing of the cultivar properties showed a negligible change (<5%) when compared to current cultivars (Figure 9).

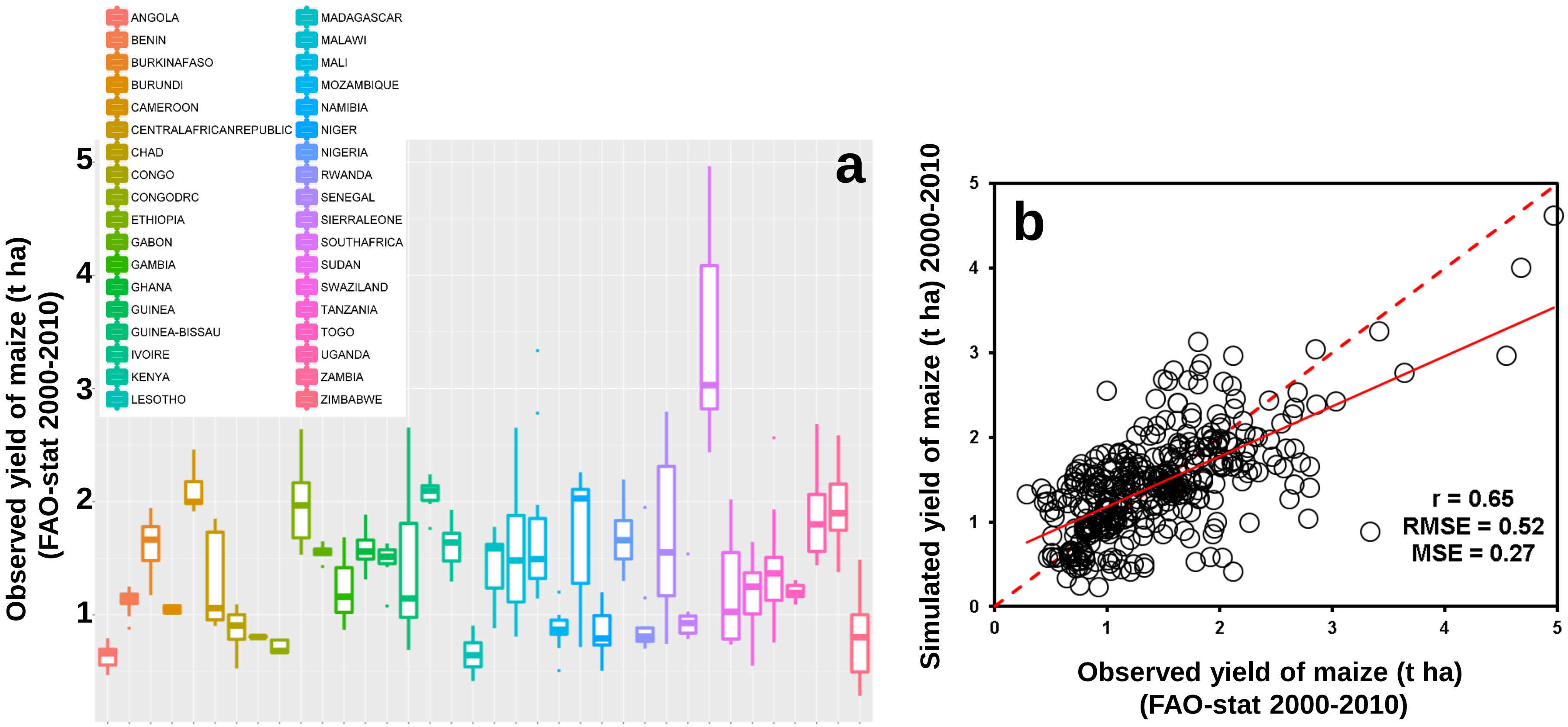

Figure 8. The boxplot of the observed yield of maize in the period 2000-2010 over 36 African countries (a) and 1:1 plot of simulated and observed yield of maize in the period 2000-2010 (b).

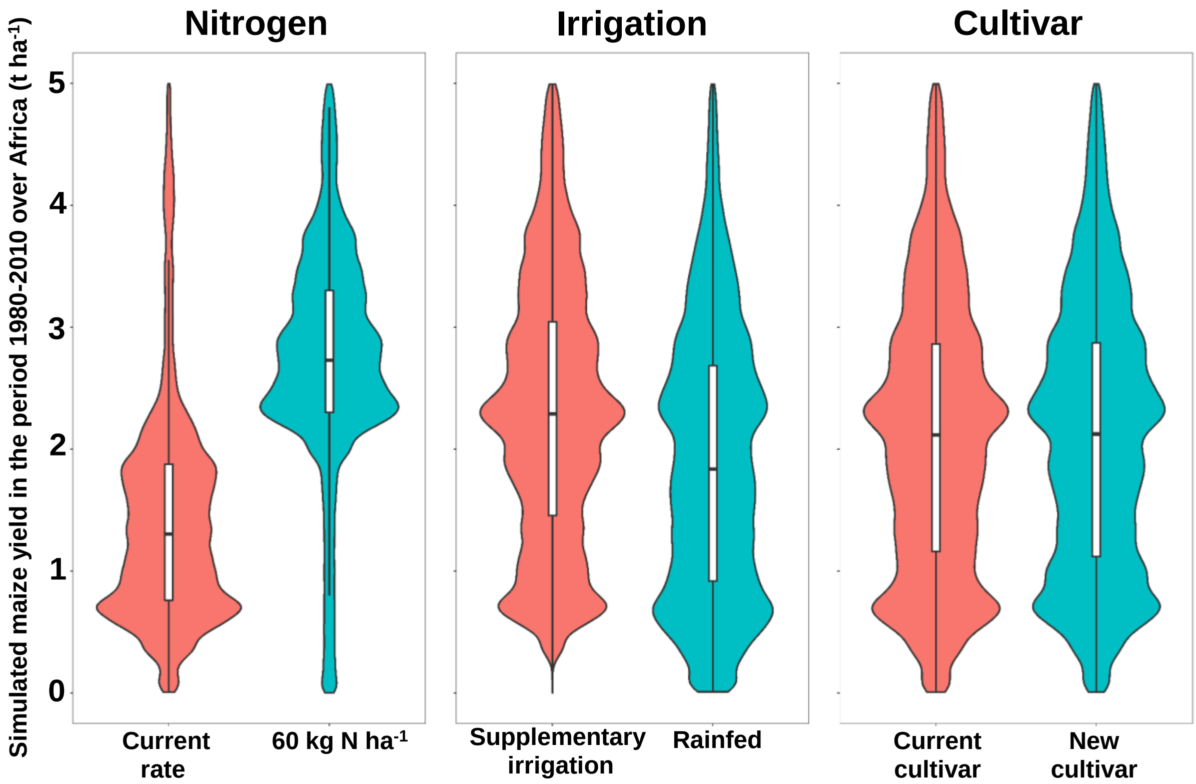

Figure 9. The probability distribution function (violin plot) and boxplot of the simulated maize yield with different fertilization, irrigation and cultivar scenarios in the period 1980-2010 over Africa.

The current nitrogen application rates in African countries are significantly lower than in North-America, Europe and China (Figure 6) (Potter et al., 2010). Application of 100 kg N ha^{-1} increased the maize yield from less than 1 t ha^{-1} to 2.9 t ha^{-1} in savanna zone of Nigeria (Kogbe and Adediran, 2003). Results of a simulation study showed that increasing of the nutrient supply to the level commonly applied in high-input regions amplified the maize yield from 1.4 t ha^{-1} to 4.5 t ha^{-1} in Sub-Saharan Africa (Folberth et al., 2013). Implementation of supplementary irrigation (by water harvesting infrastructure) increased the maize yield (1998-2000) by 15% to 35% in semi-arid regions of Kenya (Barron, 2004; Barron and Okwach, 2005). An increase of the radiation use efficiency (new cultivar) did not improve the maize yield (Figure 9). However, results of field experiments showed that cultivation of hybrid cultivars considerably improved the maize yield under high input conditions in Africa (Oikeh et al., 2007). It seems that the change in single characteristic of a cultivar (for instance, radiation use efficiency) is not an effective strategy to improve the maize yield in Africa. The total biomass production may increase by improving the radiation use efficiency but the carbon remobilization rate must also change to take advantage of higher biomass production (improvement in harvest index).

3.3. The effects of combined change in fertilization, irrigation and cultivars on maize yield in Africa

The maize yield response to combined change in fertilization, irrigation and cultivars was considerably different over the African countries (Figure 10 and 13). The countries located in dry and semi-dry regions of Africa such as Algeria, Morocco, Tunisia and South Africa showed a strong response to the supplementary irrigation in the period 1980-2010 (Figure 10 and 11). On the other hand, increasing of the nitrogen fertilizer application rate was the main driver of the yield increase in other countries (Figure 10 and 12). A specific focus on effects of technology packages in a subset of PARI countries showed the dominance of increase in nitrogen application rate on maize yield compared to supplementary irrigation and cultivar scenarios (Figure 11). However, supplementary irrigation remarkably reduced the variability of simulated yield, for instance, the variability of yield simulations under high level of fertilizer application reduced by 70% with the application of supplementary irrigation (Figure 11).

The scenario combinations could increase the yield of maize from 1.2 t ha^{-1} (current conditions) to 2.9 t ha^{-1} (60 kg N ha^{-1} + supplementary irrigation + new cultivar) in the period 1980-2010 over Africa (Figure 13). Due to the model configuration, we cannot exclude that at higher yield levels phosphorus or micro-nutrient (Zn, Mo) deficiencies may become an additional limiting factor. Particularly, further studies are required to test the effects of combined changes in nitrogen and phosphorus levels in Africa because of the importance of phosphorus deficiency over Africa especially in East Africa and the Sahel (Sanchez, 2002). The yield improvement due to the supplementary irrigation was smaller than effects of nitrogen fertilization but the irrigation treatment considerably reduced the simulated yield variability (Figure 13, right panel). The required amount of water to avoid drought stress on maize production in Africa ranged between 50 mm to 800 mm per growing season in the period 1980-2010 (Figure 14). However, most of the regions could overcome the drought by 150 mm to 250 mm per growing season of supplementary irrigation (Figure 14).

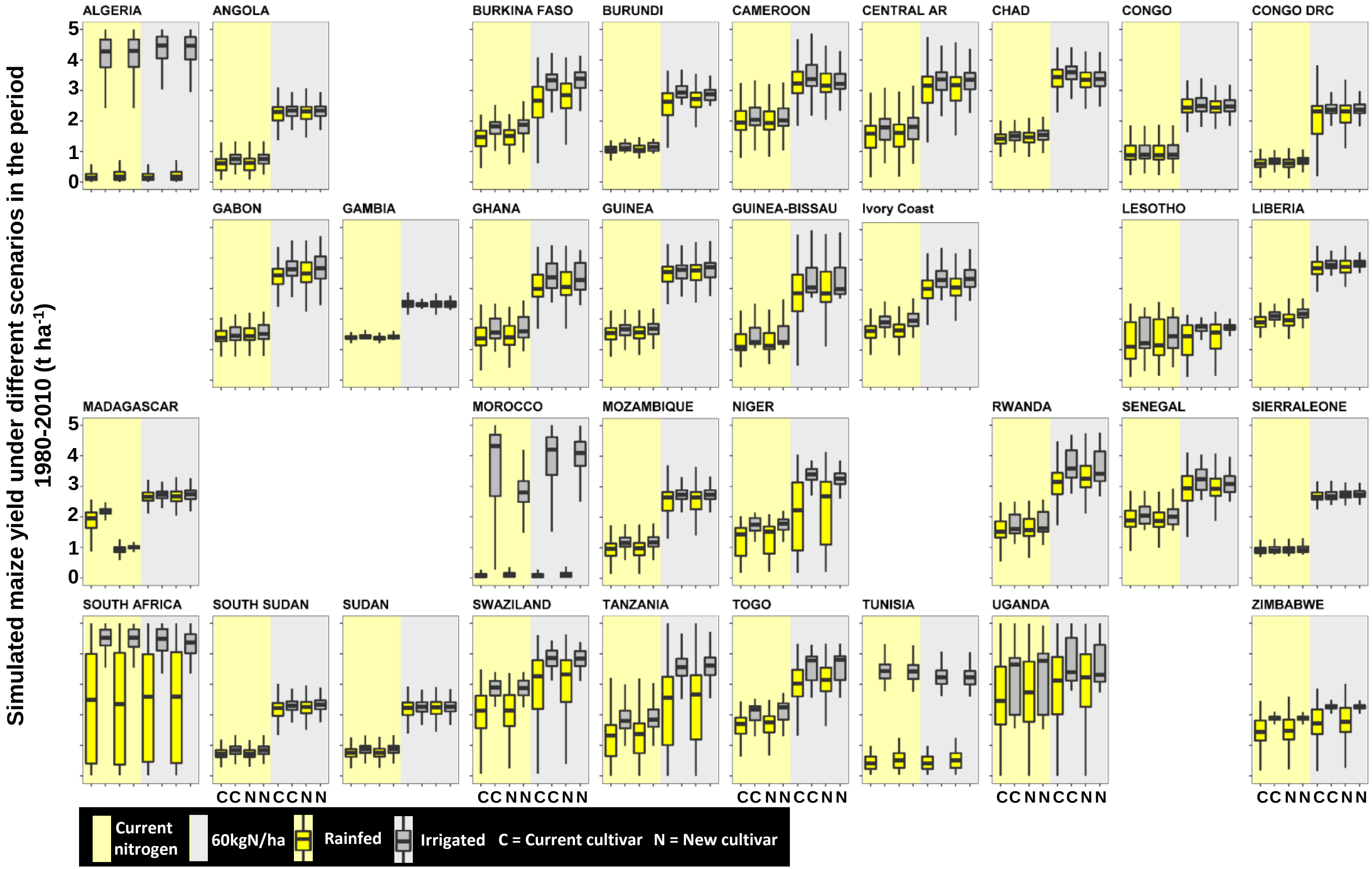

Figure 10. Boxplots of the simulated maize yield under combined fertilization, irrigation and cultivar scenarios in the period 1980-2010 over the African countries.

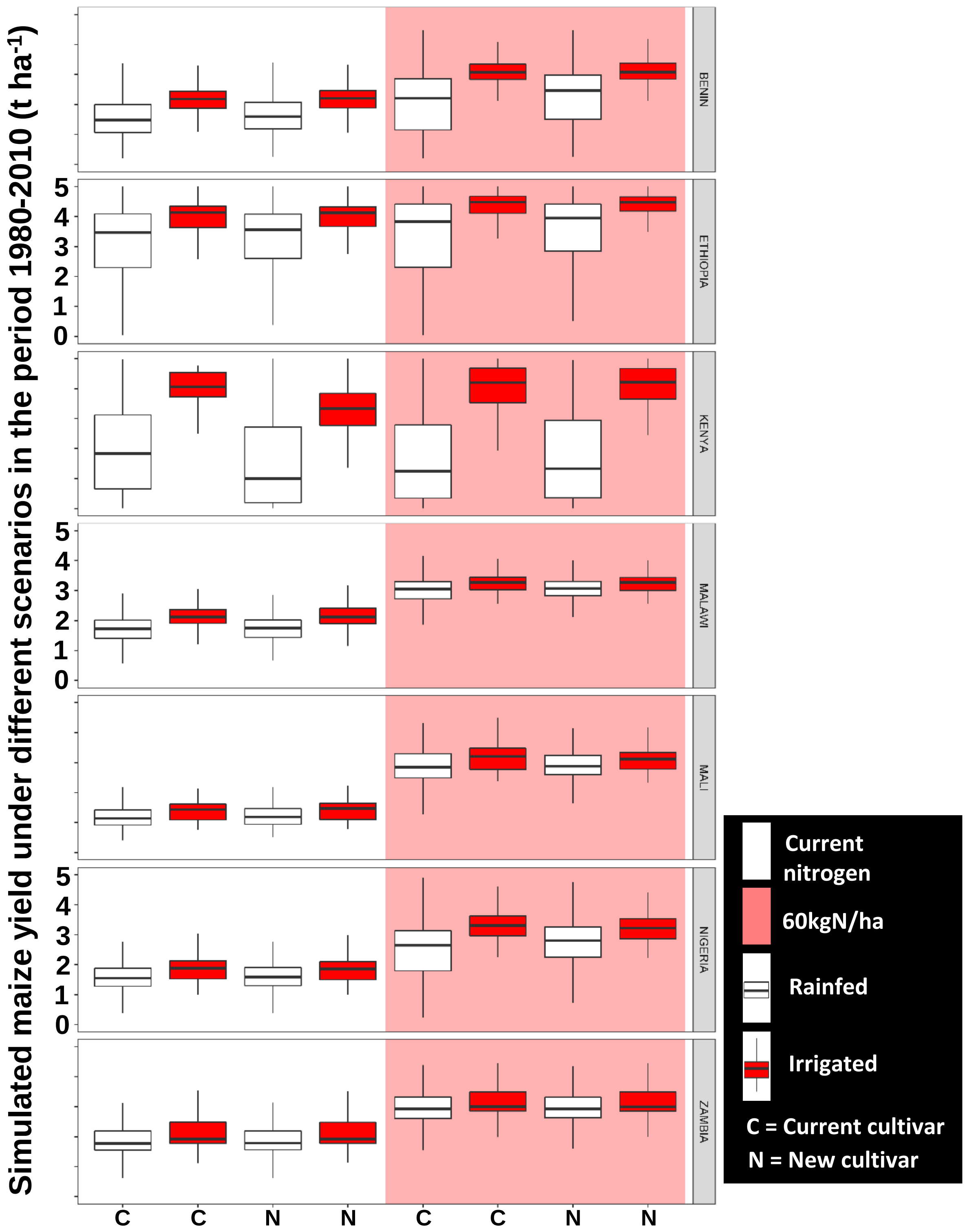

Figure 11. Boxplots of the simulated maize yield under combined fertilization, irrigation and cultivar scenarios in the period 1980-2010 over the subset of PARI countries including Benin, Ethiopia, Kenya, Malawi, Mali, Malawi, Nigeria and Zambia.

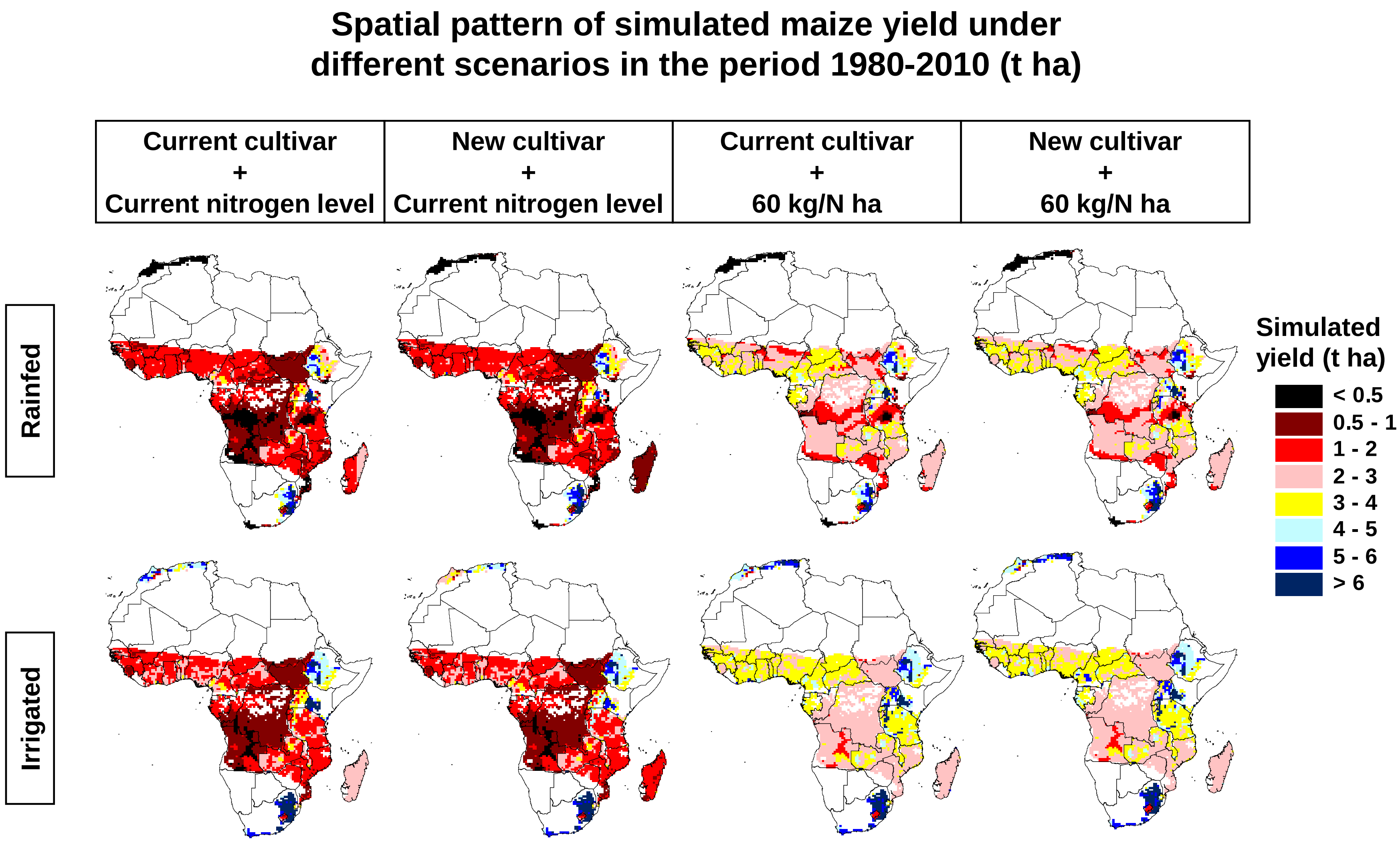

Figure 12. The spatial pattern of the mean simulated maize yield under combined fertilization, irrigation and cultivar scenarios for the period 1980-2010 over Africa.

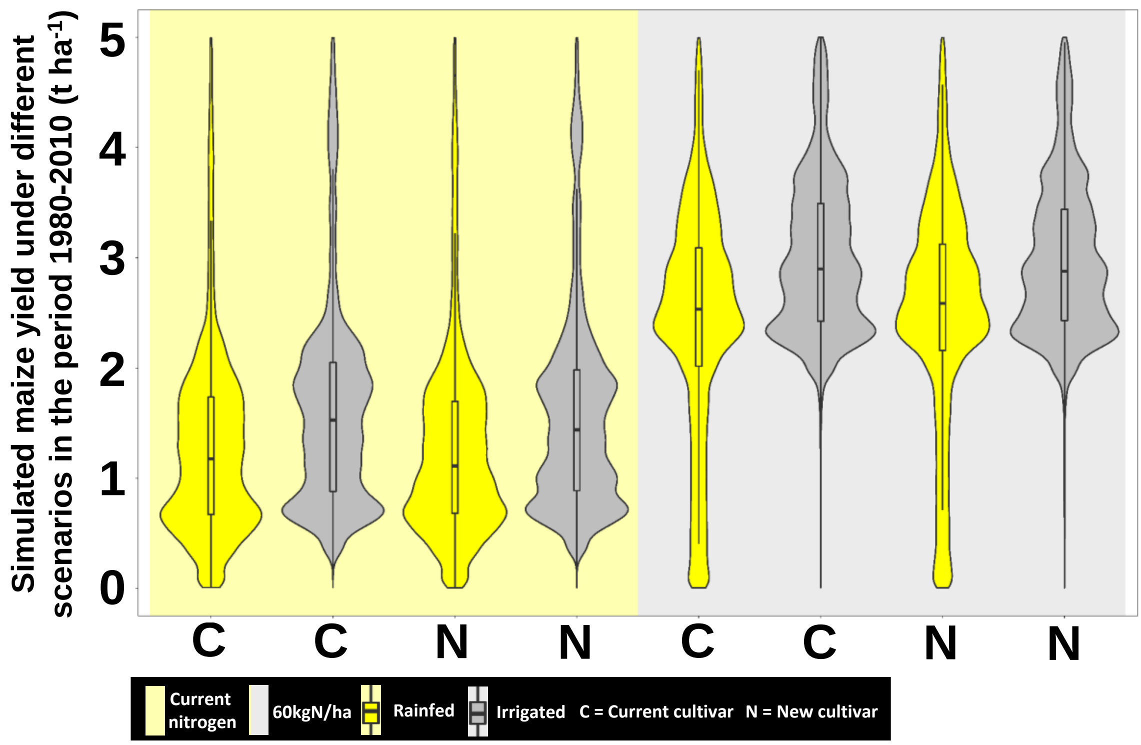

Figure 13. The probability distribution function (violin plot) and boxplot of the simulated maize yield under combined fertilization, irrigation and cultivar scenarios in the period 1980-2010 over Africa.

The long term mean of the precipitation sum was not the main reason for drought stress in the majority of the maize growing areas in Africa. However, the annual and inter-annual variability is one of the main sources of the maize yield losses (Ingram et al., 2002; Tadross et al., 2005). Based on our results even a small amount of irrigation at the critical growing stage of maize could avoid a large yield loss.

In SW Tanzania, Igbadun et al. (2008) reported that deficit/supplementary irrigation in any growth stage reduced the biomass and grain yield of maize due to the nutrient leaching (Igbadun et al., 2008). In South Africa, the yield improvement obtained by introducing of irrigation schemes did not improve the income of the smallholder maize farms (Yokwe, 2009). The individual application of deficit irrigation and nitrogen application was not able to improve the grain yield of maize in a Sahelian environment, however, the combined optimization of nitrogen and irrigation resulted to a significant yield improvement (Pandey et al., 2000). A remarkable maize yield improvement was obtained with the combination of proper fertilizer management and use of improved varieties by increasing the nitrogen use efficiency of new hybrid cultivars in sub-Saharan Africa (Vanlauwe et al., 2011).

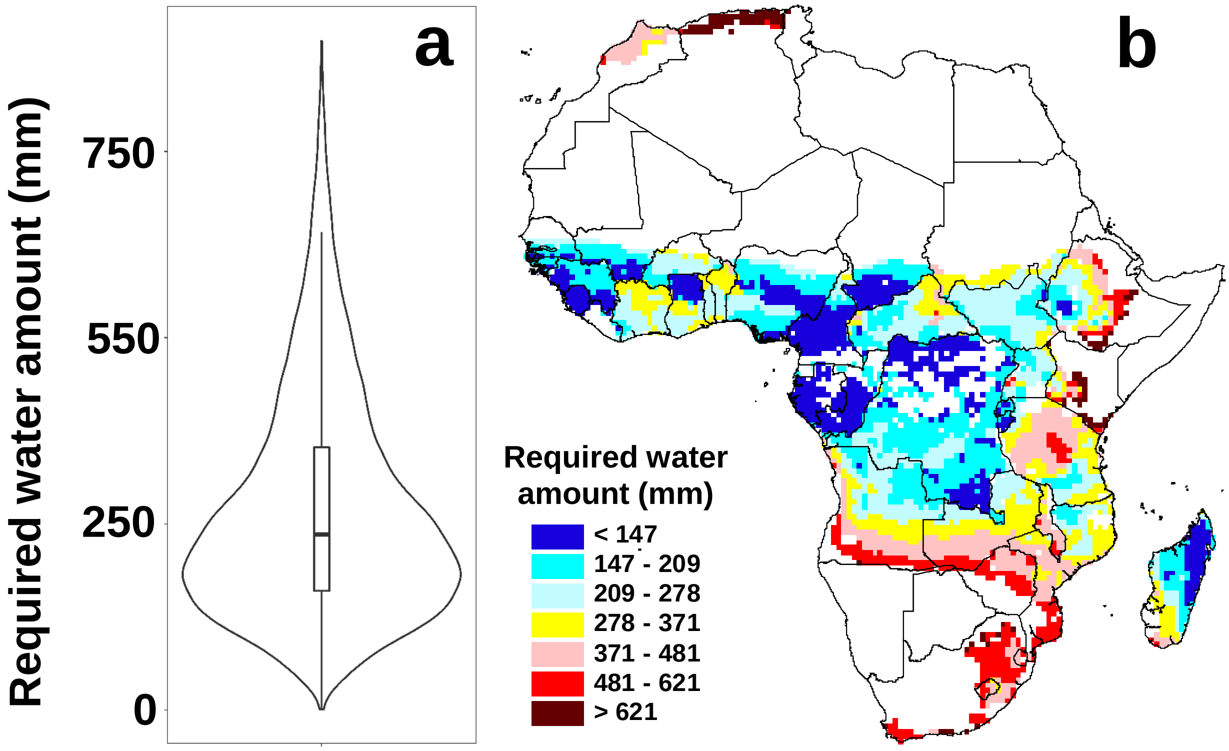

Figure 14. The probability distribution function (violin plot) and boxplot (a) and spatial pattern (b) of the estimated water requirements mm per growing season for supplementary irrigation in the period 1980-2010 across Africa.

4. Conclusion

We conclude that changes in management practices could be able to double the maize yield across Africa. However, the dominant yield limiting factors (water, nitrogen or a combination of both) varied over the African countries. The general influence of management factors on maize yield ranked as nitrogen fertilizer rate > supplementary irrigation > new cultivar based on our results. Nevertheless, a combination of change in fertilization, irrigation and cultivars showed the largest improvement in maize yield over the study period. Other management strategies such as change in either in phosphorus or manure application rate, or a change in sowing date need to be evaluated. At this point, a robust economic study is required to analyse the feasibility and cost benefit of such investments to change the management strategies. Focusing on increase in radiation use efficacy of maize cultivars was not an effective breeding strategy for yield improvement in Africa. Further research is required to identify crop characteristics for instance, change in dry matter remobilization rate after anthesis and define some site specific idiotypes of maize suitable for low-input systems in Sub-Saharan Africa to direct the breeding activities.

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