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Yield effects of selected agronomic innovation packages in maize cropping systems of six countries in Sub-Saharan Africa

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Abstract

Implementation of suitable innovation packages into cropping systems is required to address the issues of food security and improvement of the crop yield in Sub-Saharan Africa. However, quantification of the effects of innovation packages such as increase in fertilizer application rates, introduction of high yielding cultivars or change in farming practices such as sowing date and irrigation, generally requires substantial investments, in particular the quantification at large scales. Crop models are widely employed to estimate the impacts of agronomic decisions on cropping systems and to detect the most suitable areas for their implementation. The main goal of the study is to quantify the effects of a) change in nitrogen fertilization rate, b) adjustment of sowing date, c) implementation of new cultivars, and d) supplementary irrigation on maize cropping systems across six African countries including Ghana, Nigeria, Kenya, Malawi, Ethiopia and Burkina Faso. For this purpose, 30 years (1980-2010) of climate data are used as well as soil and management information obtained from global datasets at 0.5° x 0.5° spatial resolution. The nitrogen and cultivar packages were tested for all six countries whereas the changes in sowing dates (Ghana and Malawi) and the irrigation (Ethiopia) package were used in specific countries only. The crop modelling framework SIMPLACE was used to test the effects of innovation packages at the country level. The model results indicated that the agronomic innovation packages could improve maize yield by 1 t ha^{-1} to 2.3 t ha^{-1} in the studied countries. The magnitude of the yield improvement is country and package specific. The largest maize yield improvements across the packages were obtained by increase in nitrogen application rate, assuming that other nutrients like phosphorus and potassium are not limiting crop growth and yield. However, in some cases a combination of the agronomic innovation packages showed the highest maize yield. We conclude that it is vital to combine the agronomic packages to fill the gap between potential and current yields of maize in Africa. This will require appropriate incentives and investments in extension services, fertilizer distribution networks, and farmer capacity building.

Keywords: Grain maize, sowing date, nitrogen, supplementary irrigation, cultivar, Sub-Saharan Africa, PARI

JEL codes: O30, O33, Q10, Q16

1. Introduction

The yield gap is commonly defined as differences between theoretical yield levels and actual farmers' yields (Van Ittersum et al., 2013). Globally, the production of cereals has amplified dramatically during the past 50 years, partly owed to the extension of crop growing areas and the development of new varieties but mainly as a result of intensified land management and introduction of new technologies (Neumann et al., 2010). However, based on the FAO statistics, the yield of six major cereal crops including maize, wheat, millet, sorghum, rice, and barley in Africa is persistently less than 50% of the global yield average (FAO, 2014). Maize and wheat yields in Africa are reaching only 20% of the attainable yield (Hoffmann et al., 2017). This means that low crop yields in Africa are not only driven by climatic and soil conditions but mainly by poor crop management (Rockström, 2003; Rockström and Falkenmark, 2000).

The global crop yield variability is largely controlled by fertilizer application, irrigation, and climate (Mueller et al., 2013). Nutrient limitations are the major yield limiting factor of maize productivity in West Africa; however, maize yield is co-limited by drought stress and nutrient deficiency in East Africa (Mueller et al., 2013). 50% of the crop yield gap in Africa could be closed by targeting the nitrogen and phosphorus limitations and farmers could reach 75% of the attainable yield by expanding irrigated areas on top of reducing nutrient deficiencies in Sub-Saharan Africa (Mueller et al., 2013). Merely introducing new high yielding cultivars without improving the fertilizer management and establishing new irrigation strategies will not contribute to yield improvement (Sánchez, 2010). Nevertheless, in the last decades, there were huge investments in the development of new cultivars without giving proper attention on soil fertility issues in Africa (Sánchez, 2010).

Nitrogen is the element that is essential for growth and development of crops as it is the most important nutrient in terms of quantity (Erley et al., 2007). In the early 2000s, the average fertilizer application rate (mainly nitrogen) in Africa was limited to 8 kg/ha (less than 1% of the global fertilizer consumption), compared with 96 kg/ha in East and Southeast Asia and 101 kg/ha in South Asia (Morris et al., 2007). Overcoming nitrogen deficiency could double the crop yield in East Africa (Sanchez, 2002).The maize yield in Malawi more than doubled at the country scale after the implementation of a nitrogen subsidiary program in 2006 compared to the maize yield in the previous year (Denning et al., 2009). Increasing the nitrogen application rate from 30 kg N ha^{-1} to 60 kg N 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). Optimizing the fertilizer application rate raised the maize yield from 2 t ha^{-1} to 4 t ha^{-1} in Kenya (Vanlauwe et al., 2014).

The main aim of the crop modeling activities within the PARI project (http://research4agrinnovation.org/) was to assess the effects of new agronomic innovations on yield rates of selected crops across 12 African countries. In addition, outputs of crop model simulations will be supplied as an input to economic models run by IFPRI to evaluate the cost-benefit relations of the agronomic innovations on food security and welfare at the country scale. The following stepwise procedure was developed to perform the crop modeling experiments (Figure 1).

At the first step, the crop model inputs were prepared including daily climate data (minimum and maximum temperature, precipitation, radiation, and wind speed), soil information (physical and chemical properties), and management data (sowing date, crop properties, and fertilizer application rate) from global and national datasets. At the next step, we defined the potential agronomic innovations (Figure 2) based on a literature review and expert knowledge on cropping systems in Africa. Next, the crop model was calibrated by using recent studies on maize production in Africa and tested against FAO statistics providing long term yield statistics at the national scale.

The simulations were performed for maize cropping systems of six African countries including Ghana, Nigeria, Kenya, Malawi, Ethiopia and Burkina Faso as these are the focus countries of PARI. The number and the type of the innovation scenarios were selected based on the climatic, current management and yield limiting factors in the specific countries. Finally, a limited number of innovation combinations was selected based on the cost of the innovation and their impact on crop productivity was assessed with the crop model. The results of the simulations were then sent out to the economic modeling group at IFPRI.

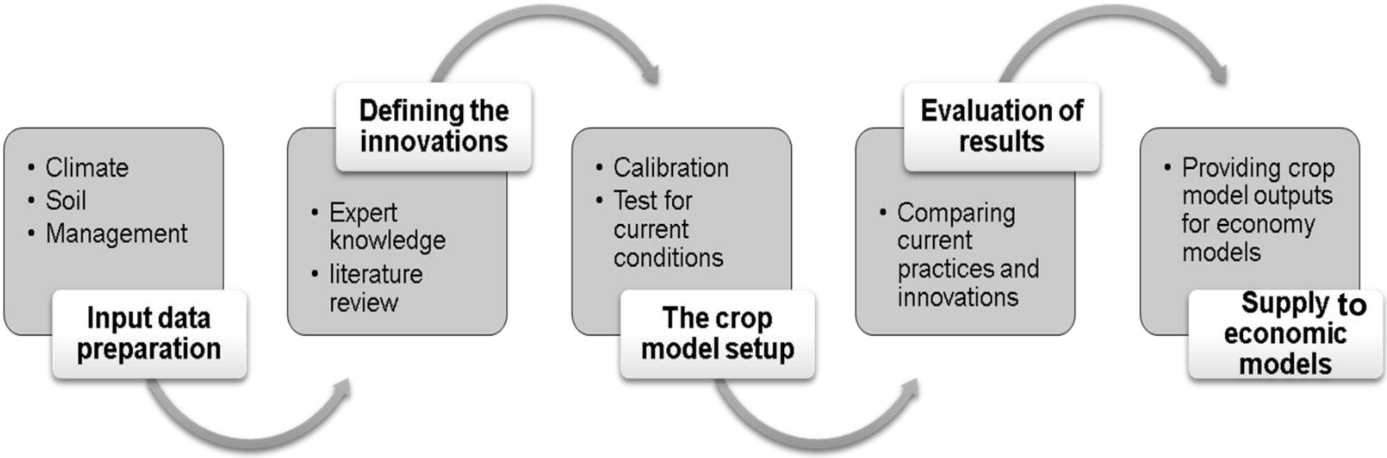

Figure 1. Schematic overview of the PARI work plan

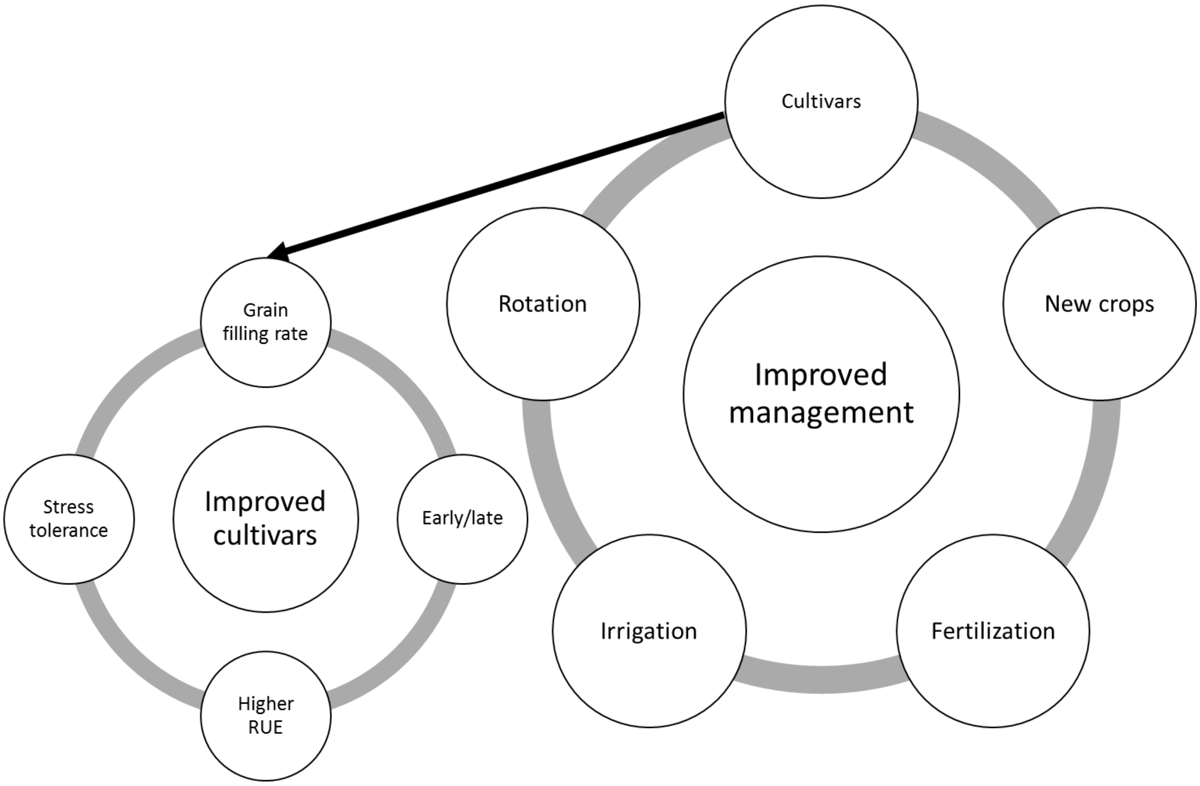

Figure 2. List of the potential agronomic innovations (for Africa) to be implemented in the crop models.

2. Materials and methods

2.1. Input data preparation

2.1.1. Climate data

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

2.1.2. Soil data

The physical (field capacity, wilting point and profile of 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 4).

2.1.3. 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 1998-2002 at the country level (Figure 5 a and b). The sowing date of maize in Ghana and Malawi was adjusted based on the Global Agro-Ecological Zoning (LGP) (Figure 5 c).The nitrogen fertilizer application rate of the African countries for maize was obtained from a number 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 accounts 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 for maize 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) (van Bussel et al., 2015).

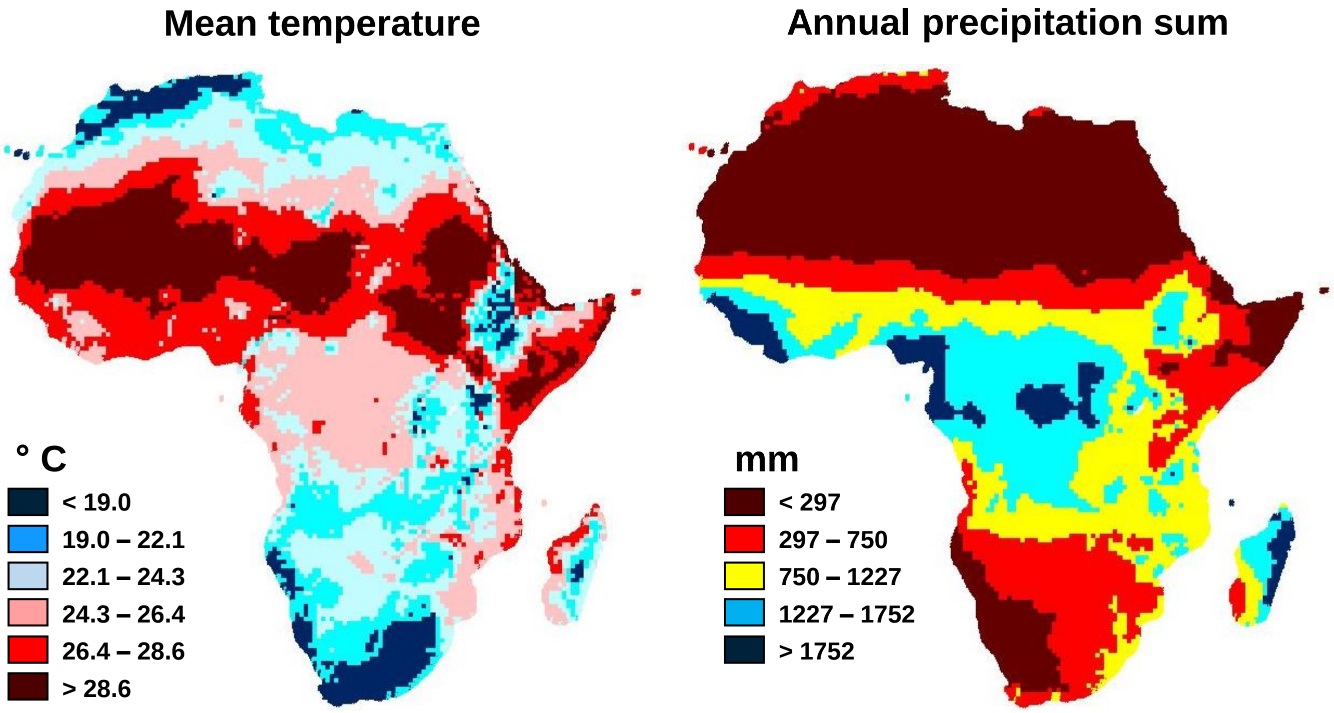

Figure 3. The mean annual temperature and annual precipitation sum in Africa in the period 1980-2010 were obtained from AgMERRA dataset (Ruane et al., 2015).

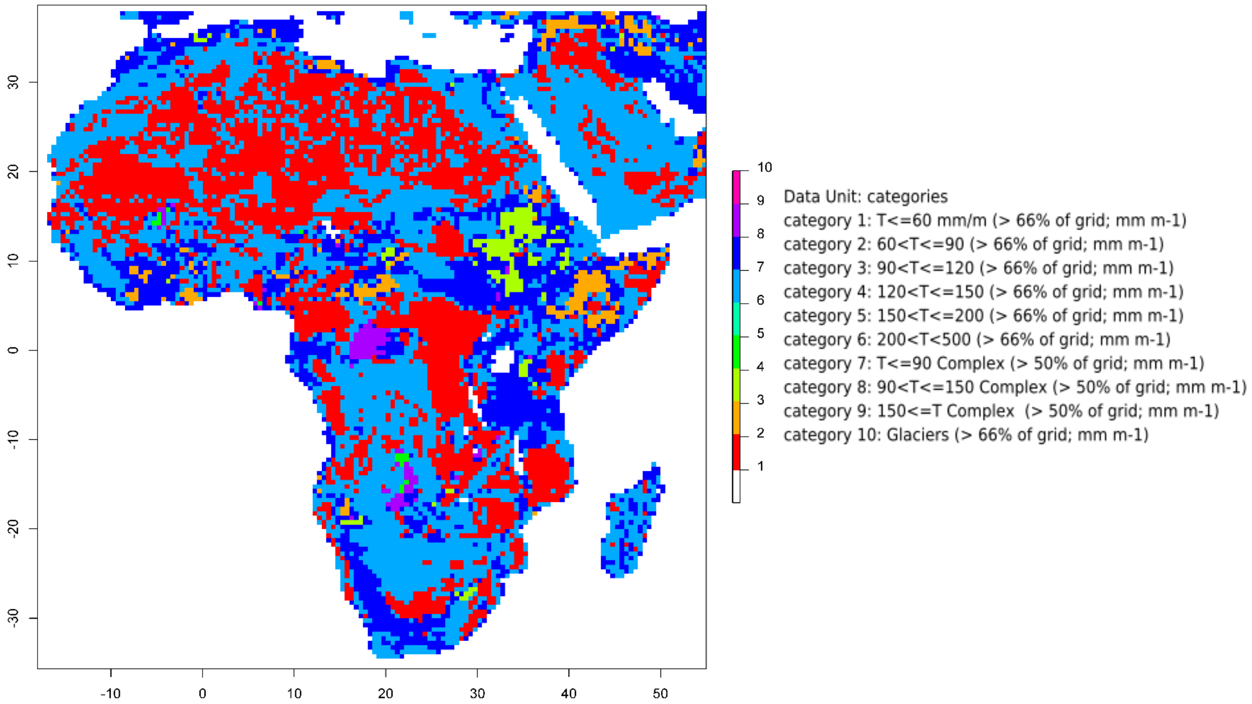

Figure 4. The total available water capacity at 1 m soil depth in Africa obtained from ISRIC-WISE global dataset (Batjes, 2012).

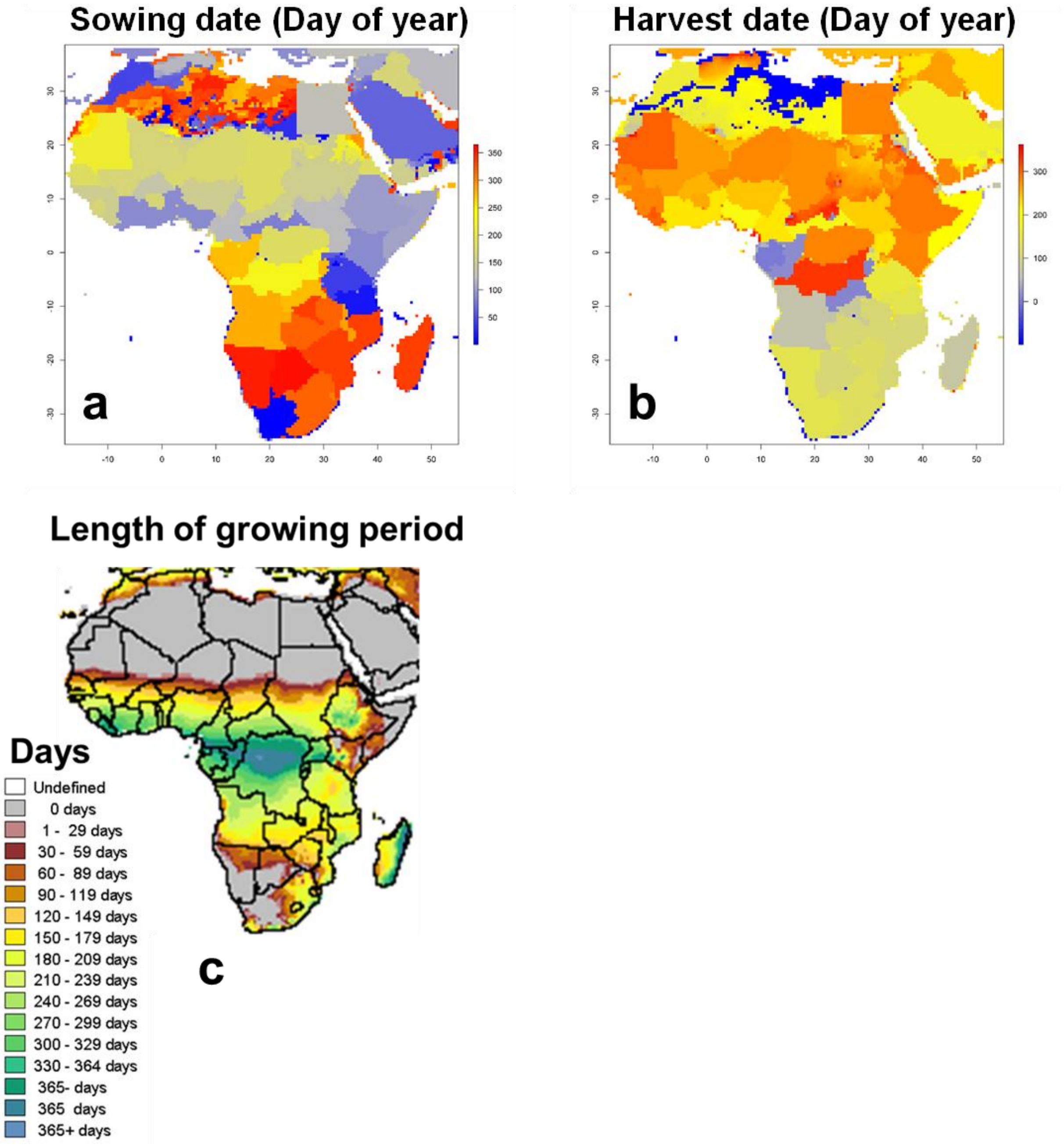

Figure 5. The sowing (a) and harvest (b) dates of the rainfed maize at the African scale obtained from the MIRCA2000 dataset (Portmann et al., 2010) and the map of the length of growing period (c) (https://goo.gl/FzPz1y).

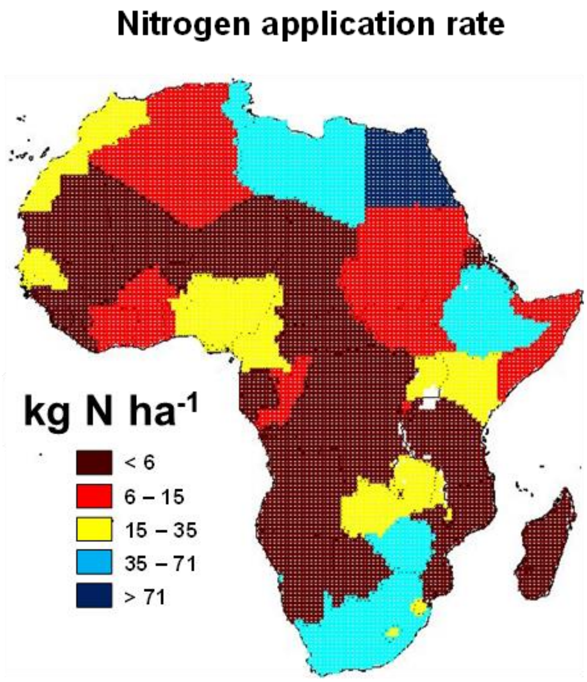

Figure 6. Average nitrogen application rates (kg N ha^{-1}) per country for major cereals such as maize at the Pan-African scale (Potter et al., 2010).

2.2. The spatial aggregation of simulation results

The crop model outputs in each country were aggregated to district level by using Global Agro-Ecological Zoning (LGP) provided by FAO and IIASA (https://goo.gl/FzPz1y) in 0.5° × 0.5° resolution to adapt the crop model outputs to a spatial aggregation level which is suitable for the economy models.

2.3. The model setup

SIMPLACE (Scientific Impact assessment and Modeling Platform for Advanced Crop and Ecosystem management) 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 framework is called a model solution (Gaiser et al., 2013).

All Sim-Components except phenology, biomass translocation, and heat stress on grain yield followed the approach given in the crop model LINTUL5 (Wolf, 2012). The final model solution is called SIMPLACE<LINTUL5,HEAT,RE-TRANSLOCATION>. 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 performance of the model was tested against ten years (2000-2010) of FAO yield statistics at national scale (Eyshi Rezaei and Gaiser, 2017).

2.4. Identification of agronomic innovations for maize production systems in Africa

Agronomic innovation scenarios for the study countries were limited to change in nitrogen application rate, sowing date, introduction of new cultivars, and implementation of supplementary irrigation (Table 1). The change in nitrogen application rate and introducing new cultivars are the basic scenarios for all study countries. The sowing date scenarios were tested for Malawi and Ghana and the supplementary irrigation scenario was implemented in Ethiopia. All possible combinations of management scenarios were implemented in the crop model and simulated for each grid cell for the period 1980-2010 at the country scale. For instance, we had 3 × 3 × 3 combinations of nitrogen application rate and timing, sowing date, and new cultivars in Ghana.

The nitrogen application scenarios were selected based on a meta-analysis of fertilization studies in Africa. We reviewed 32 peer reviewed journal articles which conducted field experiments across 12 African countries and extracted the maize yield improvement due to increase in nitrogen application rate. We reviewed nitrogen application rates ranging from 20 kg N ha^{-1} to 140 kg N ha^{-1} and found a large variability in yield response at a similar level of nitrogen application due to the climatic and cultivar differences over the years and locations (Figure 7a). The response of maize yields to nitrogen fertilizer was tested by the piecewise linear regression method (Eyshi Rezaei et al., 2017) to find the break point of yield changes. The maize yields showed an increasing trend (240 kg ha^{-1} per increase of 10 kg N ha^{-1}) with increasing nitrogen application rate from 20 to 90 kg N ha^{-1} compared to control (Figure 7b). However, there was a reducing trend (-120 kg ha^{-1} per increase of 10 kg N ha^{-1}) in yield change in response to increase in nitrogen fertilizer rate from 90 to 140 kg N ha^{-1} compared to control which refers to the treatment without nitrogen application (Figure 7b).

The sowing date of maize in Ghana is controlled by onset of precipitation and labor availability. We did a sensitivity analysis (in the realistic range of sowing date) and picked up the most reliable sowing date in Ghana and Malawi. The cultivar scenarios for Ghana and Nigeria were established on suggested recommendations by the AgMIP project (http://www.agmip.org/) based on the breeders advices to solve the real world problems. Deficit and supplementary irrigation is a well-established strategy to avoid drought stress (Fereres and Soriano, 2007).

A well-structured supplementary irrigation plan can optimize water use for regions where full irrigation is not possible such as in Africa. A small amount of water during the sensitive growth phases could avoid a significant yield loss in cereal crops. The supplementary irrigation scenario (automatically applied in the crop model) water was applied to the crop whenever the actual soil water content dropped below 50% of the field capacity in Ethiopia.

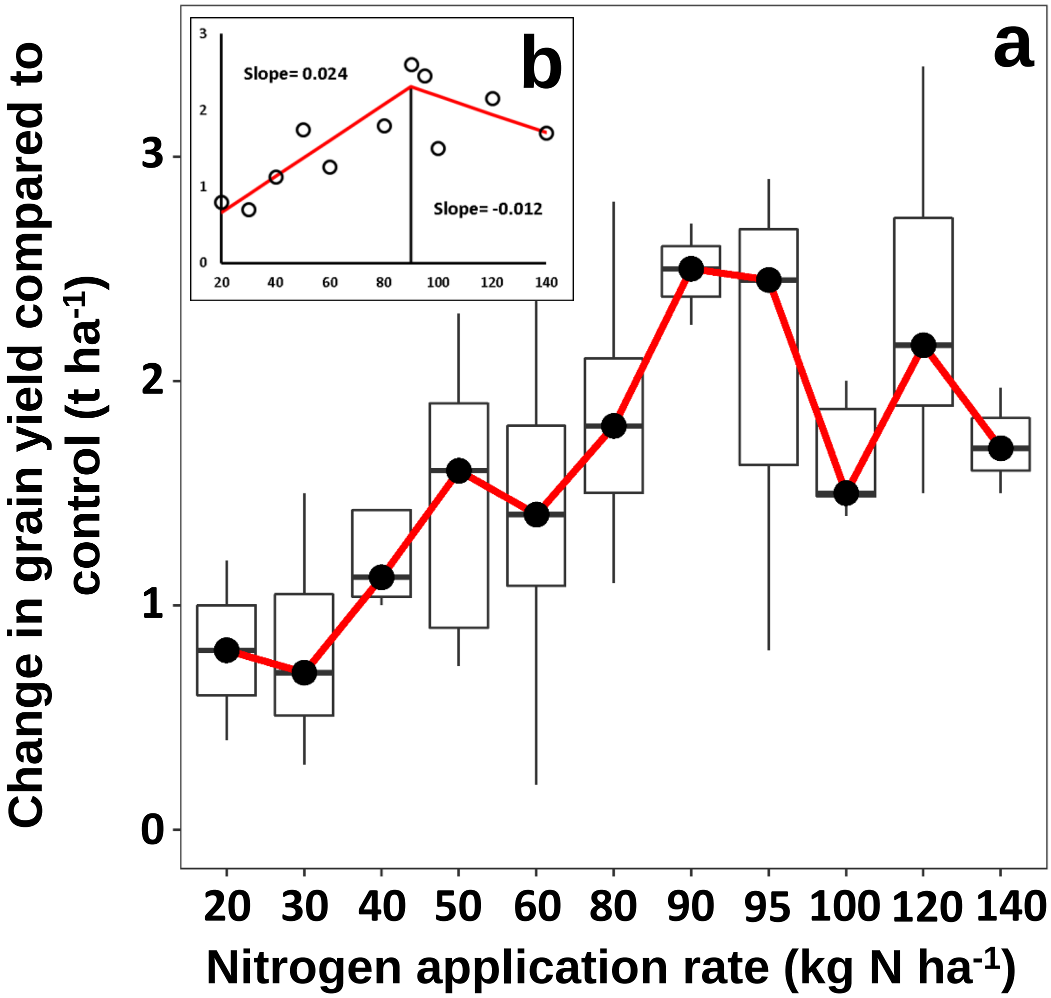

Figure 7. Boxplot of (a) the change in grain yield of maize under different levels of mineral nitrogen fertilization in Africa extracted from 32 peer reviewed journal articles and (b) piecewise, linear trends in change of the grain yield under different levels of nitrogen fertilization. Each point represented the median of the yield response to specific nitrogen application rates over the reviewed studies.

Table 1. The agronomic innovation scenarios for maize production in Ghana, Nigeria, Malawi, Kenya, Ethiopia and Burkina Faso.

Scenarios/Country	Ghana	Nigeria	Malawi	Kenya	Ethiopia	Burkina Faso
Nitrogen scenarios	N1: 20 kg N ha^{-1} N2: 40 kg N ha^{-1} N3: 60 kg N ha^{-1}	N1: Current conditions (17 kg N ha^{-1}) N2: 30 kg N ha^{-1} N3: 60 kg N ha^{-1}	N1: Current conditions (17 kg N ha^{-1}) N2: 60 kg N ha^{-1}	N1: Current conditions (17-34 kg N ha^{-1}) N2: 60 kg N ha^{-1}	N1: Current conditions (3-43 kg N ha^{-1}) N2: 60 kg N ha^{-1}	N1: Current conditions (5 kg N ha^{-1}) N2: 60 kg N ha^{-1}
Cultivar scenarios	C1: 20% increase in grain filling rate C2: 20% increase in radiation use efficiency C3: C1 + C2	C1: Current cultivar C2: 20% increase in grain filling rate and radiation use efficiency	C1: Current cultivar C2: 20% increase in grain filling rate and radiation use efficiency	C1: Current cultivar C2: 20% increase in grain filling rate	C1: Current cultivar C2: 20% increase in grain filling rate	C1: Current cultivar C2: 20% increase in grain filling rate
Sowing scenarios	S1: TSD – 15 days S2: Typical Sowing Date (TSD) S3: TSD + 15 days	Typical Sowing Date (TSD)	S1: Typical Sowing Date (TSD) S2: TSD – 25 days	Typical Sowing Date (TSD)	Typical Sowing Date (TSD)	Typical Sowing Date (TSD)
Irrigation scenarios	Rainfed	Rainfed	Rainfed	Rainfed	IR1: Rainfed IR2: Supplementary irrigation	Rainfed

3. Results

3.1. Maize yield in Ghana

Implementation of different scenarios in Ghana showed that new cultivars with increased amount of nitrogen (60 kg ha^{-1}) and earlier sowing dates may be an option to improve the average maize yield (1.5 t ha^{-1} to 3.8 t ha^{-1}) in Ghana (Figure 8). The baseline (8 kg N ha^{-1}) nitrogen application rate is currently one of the most limiting factors of maize yield in Ghana. Results of other simulation studies also showed that increasing 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} over Sub-Saharan Africa (Folberth et al., 2013). Our results also showed that earlier sowing dates in combination with new cultivars and highest nitrogen application rates were able to double the maize yield and showed the best performance with respect to maize yield in our simulations (Figure 8).

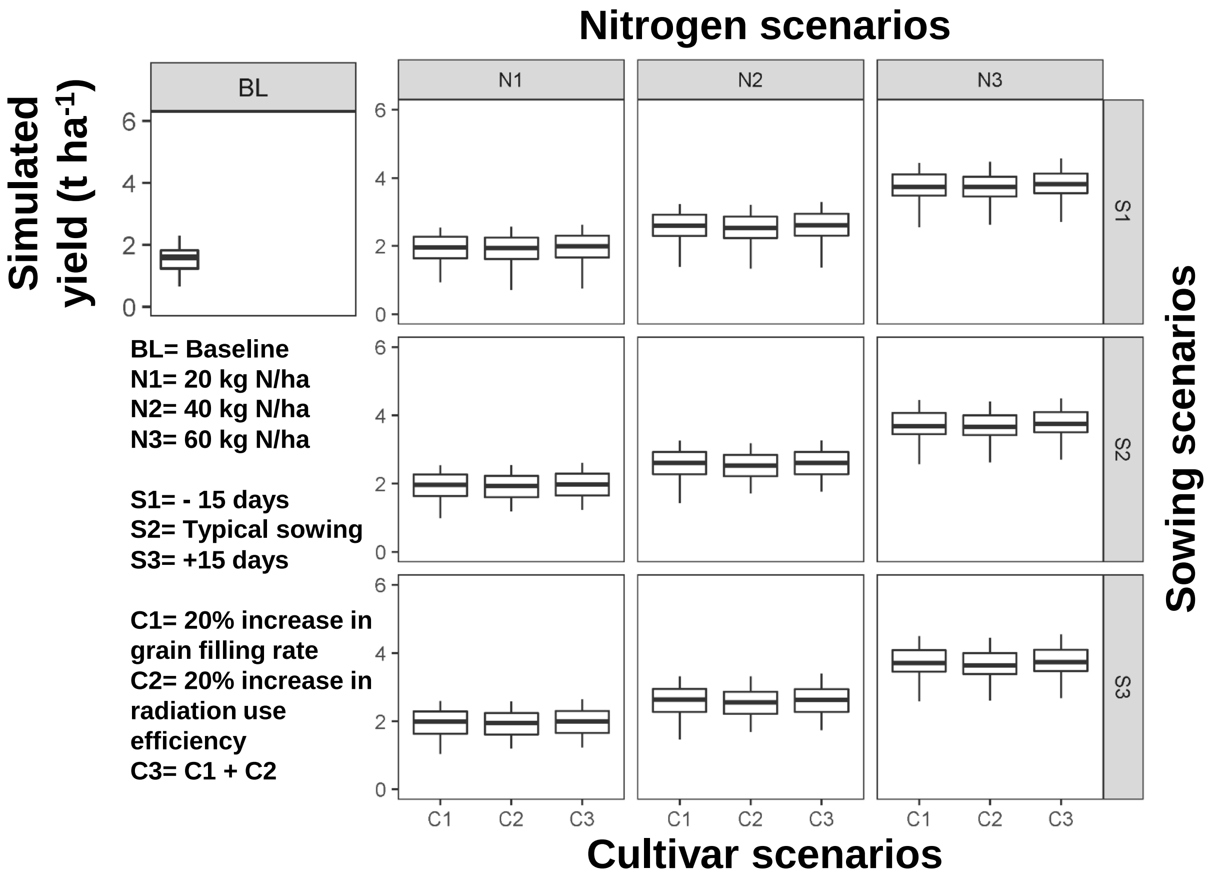

Figure 8. The boxplots of simulated maize yield under different scenario combinations across Ghana.

3.2. Maize yield in Nigeria

The simulations of maize yield under different scenario combinations in Nigeria were restricted to the grid cells which were classified as length of growing season > 90 days based on the LGP zoning system (Figure 5c).The results of maize production simulations in Nigeria showed that increasing the nitrogen application rate from 17 kg ha^{-1} (as baseline condition) to 60 kg ha^{-1} can substantially increase (2.2 t ha^{-1} to 3.7 t ha^{-1}) the average yield of maize in Nigeria in the period 1980-2010 (Figure 9). However, introduction of the new cultivar showed a smaller impact (+5%) on simulated yield (Figure 9).

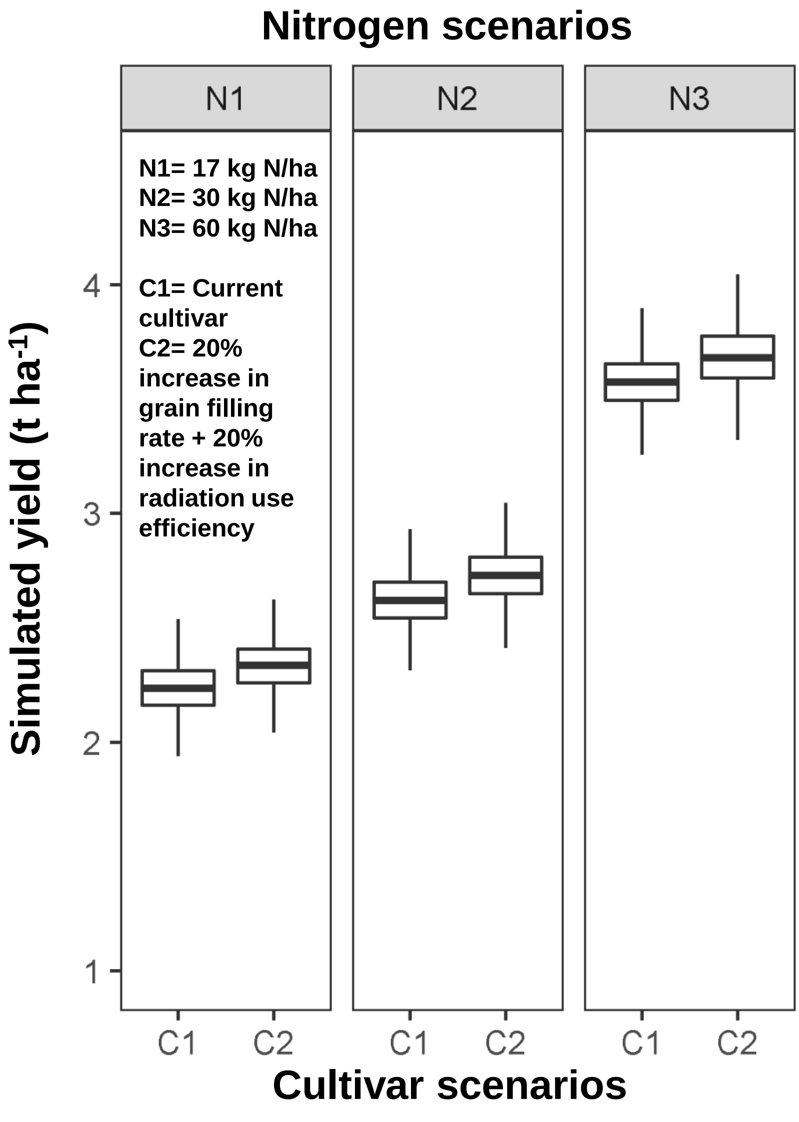

Figure 9. The boxplots of simulated maize yield under different scenario combinations across Nigeria.

3.3. Maize yield in Kenya

The simulations of maize yield under different scenario combinations in Kenya were limited to the grid cells which were classified as length of growing season > 90 days based on the LGP zoning information (Figure 5c). The current maize yield (2.3 t ha^{-1}) could increase to 3.4 t ha^{-1} under improved an nitrogen application rate (60 kg N ha^{-1}) and through the introduction of new cultivars in Kenya (Figure 10a).The increase in nitrogen application rate (+28%) and the introduction of the new cultivars (+24%) showed a relatively similar impact on yield improvement in Kenya (Figure 10a). The highest yield improvement of maize under the implemented scenarios was obtained in the Southwest of Kenya (Figure 10b). However, there was a marginal change in simulated yield for central and Southern parts of Kenya mainly due to the large extension of the drought prone areas, thus indicating that water stress is the most important yield limiting factor in these parts of the country (Figure 10b).

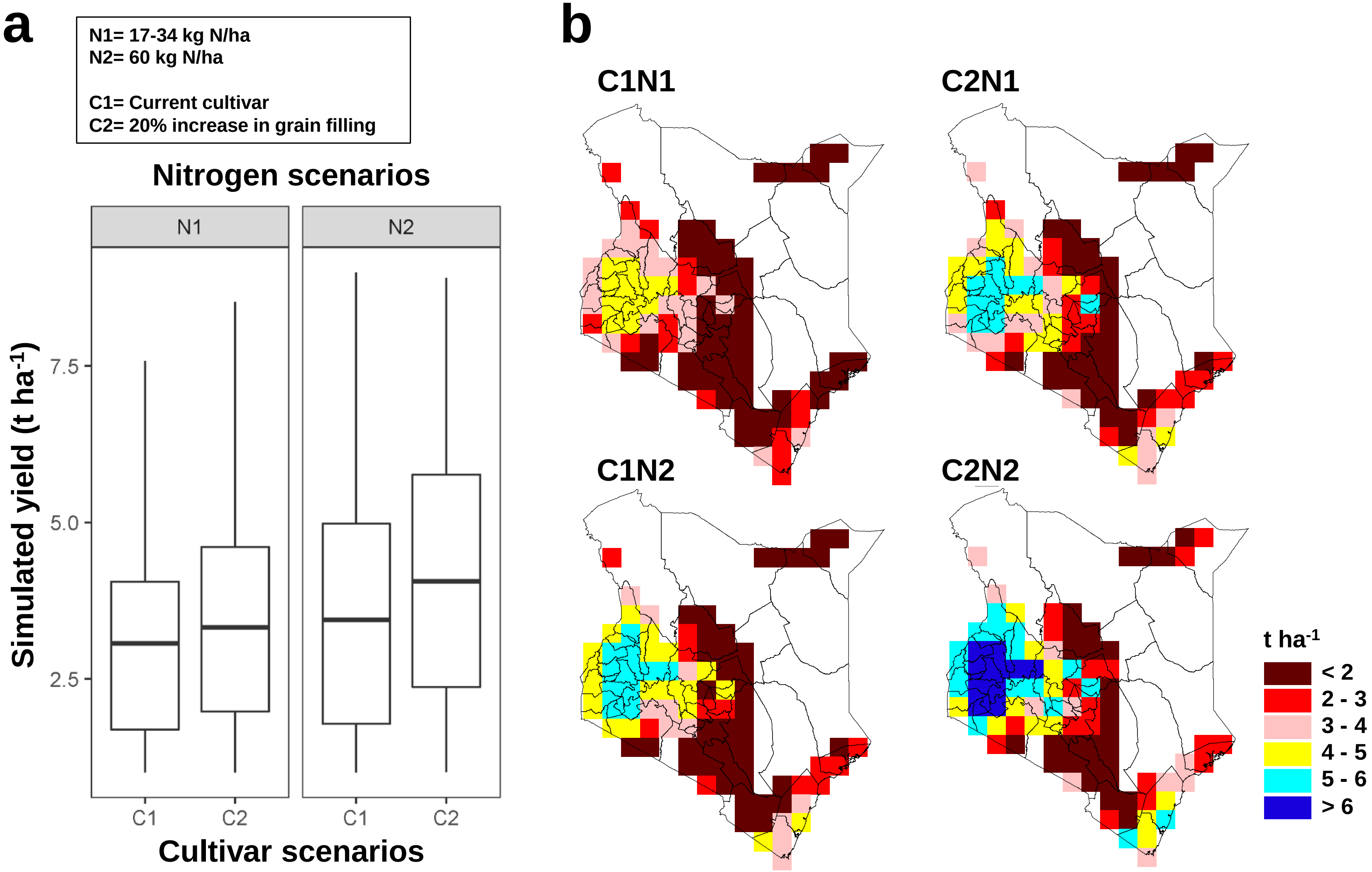

Figure 10. Boxplots (a) and spatial pattern (b) for simulated maize yield under different scenario combinations across Kenya.

3.4. Maize yield in Ethiopia

At the first step of this set of simulations the study grid cells were limited to the cells which are categorized as LGP > 90 days considered as potential maize growing areas in Ethiopia (Figure 5c). Implementation of different scenarios in Ethiopia showed that the new cultivars with an increased amount of nitrogen to 60 kg N/ha and supplementary irrigation could be an option to improve the average maize yield (+0.3 t ha^{-1} to +2.3 t ha^{-1}) in the country (Figure 11). The low fertilizer application rate and drought stress are currently the most important limiting factors of maize yield in Ethiopia. The potential of new cultivars can be maximized by an increased nitrogen application rate and by supplementary irrigation. Implementation of the supplementary irrigation reduced the variability of maize yields (explained as coefficient of variation) from 57% to 24% over the study period (Figure 12).

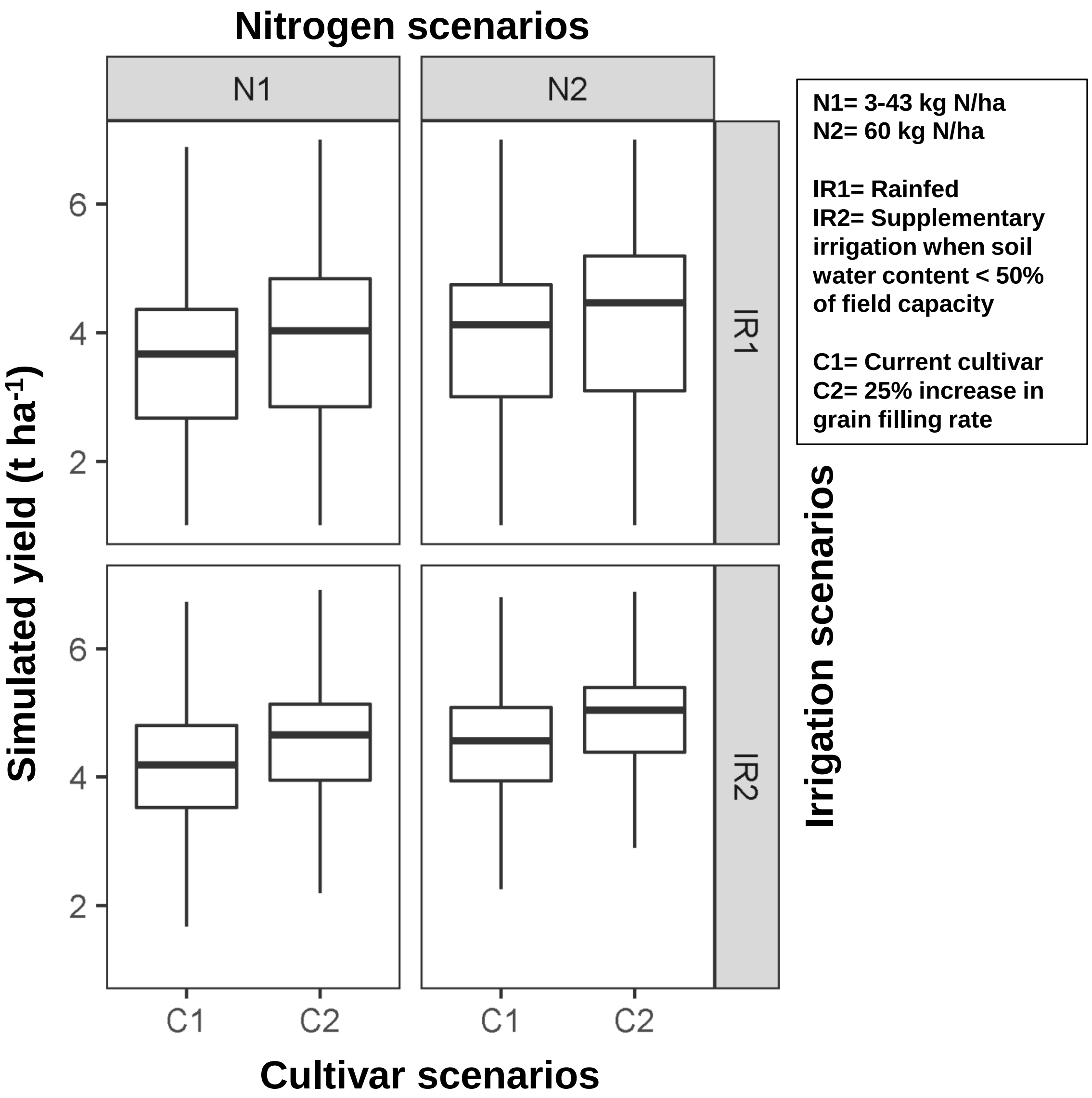

Figure 11. Boxplots of simulated maize yield under different scenario combinations across Ethiopia.

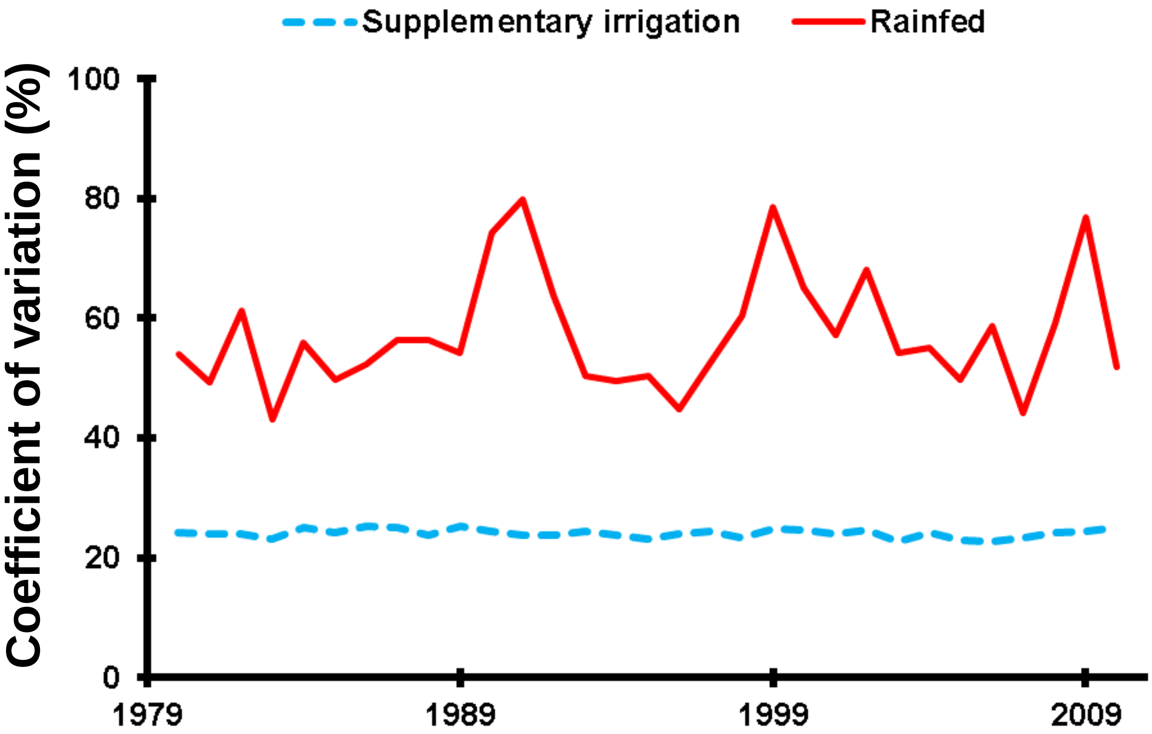

Figure 12. The time series (1980-2010) of simulated maize yield for the option of combining new cultivars with a nitrogen application of 60 kg N ha^{-1} under rainfed and supplementary irrigation conditions across Ethiopia.

3.5. Maize yield in Malawi

We tested the effect of eight scenario combinations on the maize cropping systems of Malawi. The simulated maize yield could increase from 2.7 t ha^{-1} to 4.3 t ha^{-1} through combining an increase in nitrogen application rate (60kgN/ha^{-1}), new cultivars, and an early sowing data compared to the baseline in the period 1980-2010 (Figure 13). Most of the yield improvement of maize was related to the increase in the nitrogen application rate (+1.2 t ha^{-1}). Introducing new cultivars contributed to 0.3 t ha^{-1} at the country scale (Figure 13). The change in sowing date indicated a marginal improvement on simulated maize yield in Malawi (Figure 13).

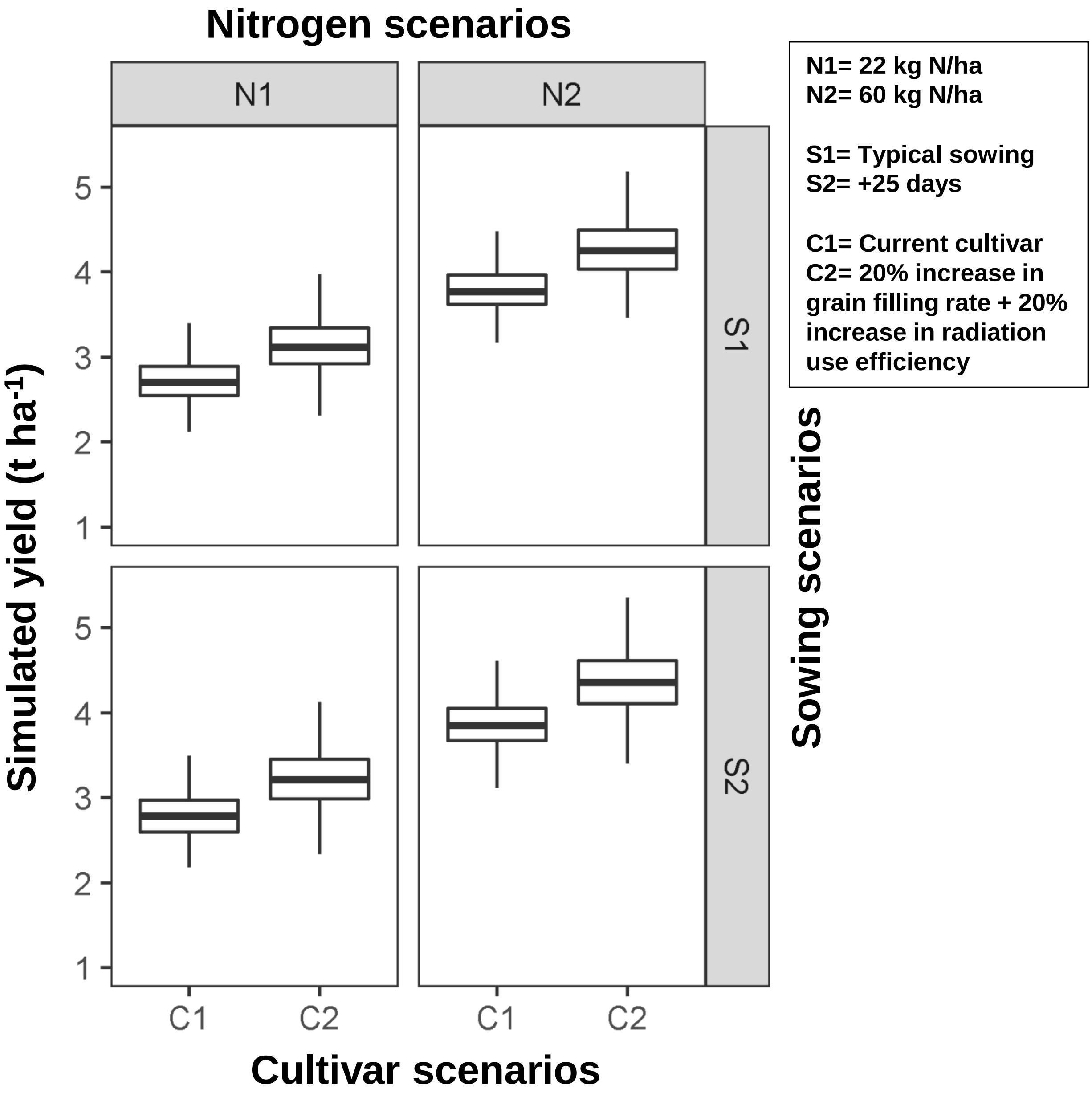

Figure 13. Boxplots of simulated maize yield under different scenario combinations across Malawi.

3.6. Maize yield in Burkina Faso

The simulations of maize yield under various scenario combinations in Burkina Faso were restricted to the grid cells classified as length of growing season > 90 days based on the LGP zoning approach (Figure 5c). Combining an increased nitrogen application rate and new cultivars could improve maize yield from 1.4 t ha^{-1} to 3.0 t ha^{-1} compared to baseline in Burkina Faso (Figure 14).

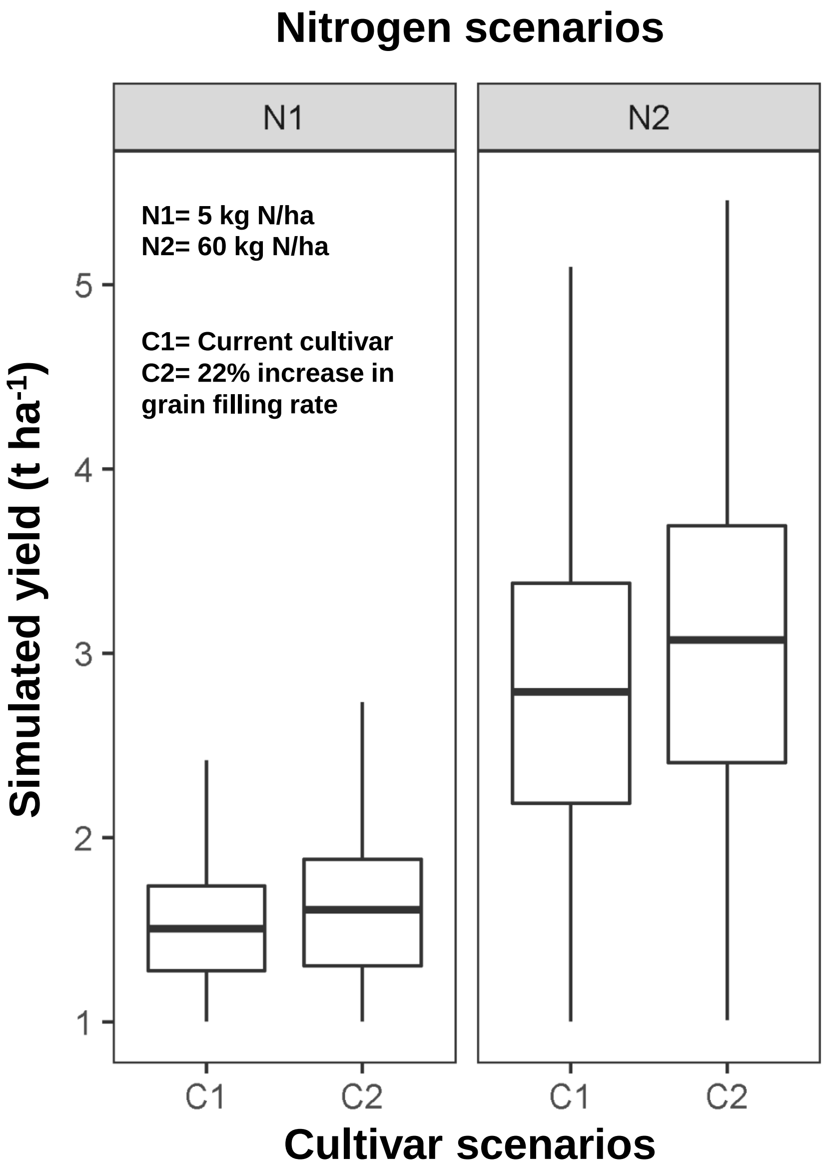

Figure 14. Boxplots of simulated maize yield under different scenario combinations across Burkina Faso.

4. Conclusion

The results of modeling experiments indicated that the proposed management scenarios on maize production in Ghana, Nigeria, Kenya, Malawi, Ethiopia, and Burkina Faso could not only double the maize yield but also increase stability of yield against climate variability in particular for the irrigation scenario. However, impact of the nitrogen scenarios on yield stability is country specific. The magnitude of maize yield improvement is related to the initial management conditions within the countries. In addition, supplementary irrigation can decrease the variability of maize yield due to climate conditions and thus support food security for climate sensible cropping systems in Africa. Further investigations are required to assess the impacts of combined changes in nitrogen and phosphorus fertilizers and manure application rate on maize cropping systems in Africa. In addition, access to high resolution climate, soil and management data would also improve the consistency of the simulations at the country scale.

References

Batjes, N.H., 2012. ISRIC-WISE derived soil properties on a 5 by 5 arc-minutes global grid (ver. 1.2). ISRIC Rep. 56.

Batjes, N.H., 1997. A world dataset of derived soil properties by FAO-UNESCO soil unit for global modelling. Soil Use Manag. 13, 9–16. https://doi.org/10.1111/j.1475-2743.1997.tb00550.x

Batjes, N.H., 1995. A Homogenized Soil Data File for Global Environmental Research: A Subset of FAO, ISRIC, and NRCS profiles (Version 1.0). Work. Pap. Prepring 95/10b, Int. Soil Ref. Inf. Center, Wageningen.

Carsky, R.J., Oyewole, B., Tian, G., 1999. Integrated soil management for the savanna zone of W. Africa: legume rotation and fertilizer N. Nutr. Cycl. Agroecosystems 55, 95–105. https://doi.org/10.1023/A:1009856032418

Denning, G., Kabambe, P., Sanchez, P., Malik, A., Flor, R., Harawa, R., Nkhoma, P., Zamba, C., Banda, C., Magombo, C., Keating, M., Wangila, J., Sachs, J., 2009. Input Subsidies to Improve Smallholder Maize Productivity in Malawi: Toward an African Green Revolution. PLOS Biol. 7, e1000023.

Enders, A., Diekkrüger, B., Laudien, R., Gaiser, T., Bareth, G., 2010. The IMPETUS Spatial Decision Support Systems, in: Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 360–393. https://doi.org/10.1007/978-3-642-12957-5_11

Erley, G.S.A. m., Begum, N., Worku, M., Bänziger, M., Horst, W.J., 2007. Leaf senescence induced by nitrogen deficiency as indicator of genotypic differences in nitrogen efficiency in tropical maize. J. Plant Nutr. Soil Sci. 170, 106–114. https://doi.org/10.1002/jpln.200625147

Eyshi Rezaei, E., Gaiser, T., 2017. Change in crop management strategies could double the maize yield in Africa, Dicussion Paper on Developmenet Policy, No. 239.

Eyshi Rezaei, E., Siebert, S., Ewert, F., 2017. Climate and management interaction cause diverse crop phenology trends. Agric. For. Meteorol. 233, 55–70. https://doi.org/10.1016/j.agrformet.2016.11.003

FAO, 2014. FAO Statistics [WWW Document]. Food Agric. Organ. United Nations. URL http://www.fao.org/faostat/en/

Fereres, E., Soriano, M.A., 2007. Deficit irrigation for reducing agricultural water use. J. Exp. Bot. 58, 147–159. https://doi.org/10.1093/jxb/erl165

Folberth, C., Yang, H., Gaiser, T., Abbaspour, K.C., Schulin, R., 2013. Modeling maize yield responses to improvement in nutrient, water and cultivar inputs in sub-Saharan Africa. Agric. Syst. 119, 22–34. https://doi.org/10.1016/j.agsy.2013.04.002

Gaiser, T., Perkons, U., Küpper, P.M., Kautz, T., Uteau-Puschmann, D., Ewert, F., Enders, A., Krauss, G., 2013. Modeling biopore effects on root growth and biomass production on soils with pronounced sub-soil clay accumulation. Ecol. Modell. 256, 6–15. https://doi.org/10.1016/j.ecolmodel.2013.02.016

Hoffmann, M.P., Haakana, M., Asseng, S., Höhn, J.G., Palosuo, T., Ruiz-Ramos, M., Fronzek, S., Ewert, F., Gaiser, T., Kassie, B.T., Paff, K., Rezaei, E.E., Rodríguez, A., Semenov, M., Srivastava, A.K., Stratonovitch, P., Tao, F., Chen, Y., Rötter, R.P., 2017. How does inter-annual variability of attainable yield affect the magnitude of yield gaps for wheat and maize? An analysis at ten sites. Agric. Syst. https://doi.org/10.1016/j.agsy.2017.03.012

Liu, J., You, L., Amini, M., Obersteiner, M., Herrero, M., Zehnder, A.J.B., Yang, H., 2010. A high-resolution assessment on global nitrogen flows in cropland. Proc. Natl. Acad. Sci. U. S. A. 107, 8035–8040. https://doi.org/10.1073/pnas.0913658107

Morris, M., Kelly, V.A., Kopicki, R.J., Byerlee, D., 2007. Fertilizer Use in African Agriculture. Lessons Learned and Good Practice Guidelines, Experimental Agriculture. https://doi.org/10.1017/S0014479707005777

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2013. Closing yield gaps through nutrient and water management. Nature 494, 390–390. https://doi.org/10.1038/nature11907

Neumann, K., Verburg, P.H., Stehfest, E., Müller, C., 2010. The yield gap of global grain production: A spatial analysis. Agric. Syst. 103, 316–326. https://doi.org/10.1016/j.agsy.2010.02.004

Portmann, F.T., Siebert, S., Döll, P., 2010. MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling. Global Biogeochem. Cycles 24, 1–24. https://doi.org/10.1029/2008GB003435

Potter, P., Ramankutty, N., Bennett, E.M., Donner, S.D., 2010. Characterizing the spatial patterns of global fertilizer application and manure production. Earth Interact. 14. https://doi.org/10.1175/2009EI288.1

Rienecker, M.M., Suarez, M.J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M.G., Schubert, S.D., Takacs, L., Kim, G.K., Bloom, S., Chen, J., Collins, D., Conaty, A., Da Silva, A., Gu, W., Joiner, J., Koster, R.D., Lucchesi, R., Molod, A., Owens, T., Pawson, S., Pegion, P., Redder, C.R., Reichle, R., Robertson, F.R., Ruddick, A.G., Sienkiewicz, M., Woollen, J., 2011. MERRA: NASA's modern-era retrospective analysis for research and applications. J. Clim. 24, 3624–3648. https://doi.org/10.1175/JCLI-D-11-00015.1

Rockström, J., 2003. Resilience building and water demand management for drought mitigation. Phys. Chem. Earth, Parts A/B/C 28, 869–877. https://doi.org/10.1016/j.pce.2003.08.009

Rockström, J., Falkenmark, M., 2000. Semiarid Crop Production from a Hydrological Perspective: Gap between Potential and Actual Yields. CRC. Crit. Rev. Plant Sci. 19, 319–346. https://doi.org/10.1080/07352680091139259

Ruane, A.C., Goldberg, R., Chryssanthacopoulos, J., 2015. Climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation. Agric. For. Meteorol. 200, 233–248. https://doi.org/10.1016/j.agrformet.2014.09.016

Sanchez, P.A., 2002. Soil fertility and hunger in Africa. Science. https://doi.org/10.1126/science.1065256

Sánchez, P.A., 2010. Tripling crop yields in tropical Africa. Nat. Geosci. 3, 299.

van Bussel, L.G.J., Stehfest, E., Siebert, S., Müller, C., Ewert, F., 2015. Simulation of the phenological development of wheat and maize at the global scale. Glob. Ecol. Biogeogr. 24, 1018–1029. https://doi.org/10.1111/geb.12351

Van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance-A review. F. Crop. Res. 143, 4–17. https://doi.org/10.1016/j.fcr.2012.09.009

Vanlauwe, B., Wendt, J., Giller, K.E., Corbeels, M., Gerard, B., Nolte, C., 2014. A fourth principle is required to define Conservation Agriculture in sub-Saharan Africa: The appropriate use of fertilizer to enhance crop productivity. F. Crop. Res. 155, 10–13. https://doi.org/10.1016/j.fcr.2013.10.002

Wolf, J., 2012. User guide for LINTUL5: Simple generic model for simulation of crop growth under potential, water limited and nitrogen, phosphorus and potassium limited conditions.