Tropentag 2010
ETH Zurich, September 14 - 16, 2010
Conference on International Research on Food Security, Natural Resource Management and Rural Development

Modeling the impact of climate change on agricultural food production in Sub-Saharan Africa and measures of mitigation

Christian Folberth[a], Karim Abbaspour[a], Rainer Schulin[b], Hong Yang[a]

a EAWAG, Swiss Federal Institute of Aquatic Science and Technology, Ueberlandstr. 133, 8600 Dübendorf, Switzerland
b ETH Zürich, Institute of Terrestrial Ecosystems, Universitätsstr. 16, 8092 Zürich, Switzerland

Introduction

Several recently published studies have shown that climate change will very likely have a big impact on the global agricultural production. While an increase in agricultural yields is expected in temperate zones, crop yields are supposed to decrease even further from already low levels in (sub-)tropic and (semi-)arid regions of Sub-Saharan Africa. Our study makes use of a regionalized large-scale crop growth model based on the Environmental Productivity Integrated Climate (EPIC) model. In contrast to former, global modeling studies that mostly make use of a general parameter set or scaling factors for certain regions, we implement here results from regional studies in order to adjust the model. For this preliminary study only maize is investigated as it is the most widely planted crop on the sub-continent and can also be considered representative for other cereals. Starting from the regionalization of the model, the study investigates the impact of climate change on the crop yield and we present modeling results for a few options in agricultural practice to increase maize yields now and under changing climate.

Material and Methods

We used CRU's (Climate Research Unit) CRU TS 2.1 monthly climate statistics (min. temperature, max. temperature, precipitation, and frequency of wet days) for the years 1901-2002 as well as the GCM data for the ECHAM4 and CGCM2 models (Mitchell and Jones, 2005). Out of the climate change scenarios, only ECHAM4 A2 and B2 and CGCM2 A1FI were applied in this study. Rain-fed and irrigated harvested areas for maize were obtained from the MIRCA2000 Version 1.1 dataset (Portmann et al., 2010). Datasets for soil parameters and spatial distribution of soils as well as fertilizer use on a national scale have been described earlier in Liu (2009).
The GEPIC software has been described extensively by Liu (2009). It is a combination of the well-established crop growth model EPIC (Williams et al., 1989) and an ArcGIS VBA program. The ArcGIS component is used for the compilation of input raster datasets and the setting of parameters. Subsequently it writes a command-line script file that executes the EPIC model for each grid cell of a defined region using the submitted input parameters and site data.
The regionalization was carried out by adjusting model parameters and soil conditions. Plant growth parameters for maize were adopted from Gaiser et al. (2010) who calibrated EPIC for local growth conditions and plant varieties in Benin. Adjusted parameters are harvest index, water stress harvest index, critical aeration factor, and plant density among others. The soil degradation was simulated by continuous maize cultivation with 99% biomass removal for 20

years and the results evaluated. For further simulations the soil status after 10 years was chosen, as soil degradation – measured as OC depletion – was quite advanced at this point, but not yet saturated. By choosing this time period we took into account that most but not all agricultural soils are heavily degraded in Sub-Saharan Africa (Sanchez, 2002) and that the continuous cultivation with the same crop is only one of many cultivation systems.

Results and discussion

Regionalization of the model

The impact of the regionalization on crop yields is shown in Fig. 1. The first step – adjustment of plant growth factors – leads to a decrease of average simulated yields from about 5.3 t ha^{-1} to about 3.8 t ha^{-1}. Soil degradation lowers yields by another 1.7 t ha^{-1} resulting in a final 2.1 t ha^{-1} average. For the time being, the remaining yield gap to reported yields from Monfreda et al. (2008) is attributed to factors that cannot be represented by a bio-physical plant growth model on a large scale, like wide-spread epidemic health problems among farmers, political conflicts, as well as insect pests and weeds for which no data is available on the observed scale (e.g. Stocking, 2003). Also errors in data reporting can be a source of uncertainty here, as it is known that farmers who practice intercropping often report yields for the whole field instead of the fraction that was actually planted with the respective crop.

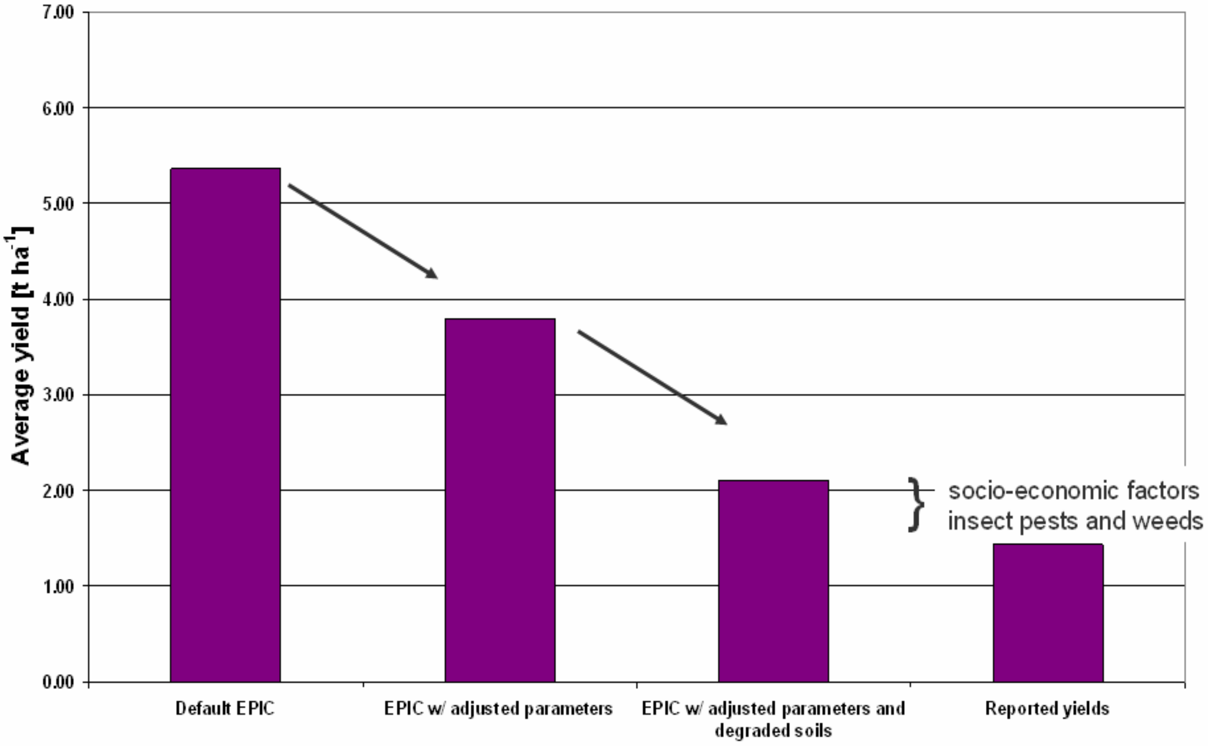

Fig. 1: Yield decrease within steps of model adjustment.

Impact of climate change on maize yields

Due to increases in the atmospheric CO_2 concentration, local increases in precipitation, and the heat tolerance of maize an over-all increase in yields can be expected until the 2040s (Fig. 2) under current practice. Until the 2080s this will decrease, though, as the temperature is expected to keep rising above the tolerable threshold in many areas. Specific regions, among them Southern Africa, Ethiopia, Sudan, and Chad will most likely suffer from yield decreases on both time-scales.

In addition, the comparison of climate change impacts on maize yields with and without soil degradation (data not shown) highlights the importance of taking the soil status into account. Without prior degradation of the soils, the expected over-all increase in yields until the 2040s is higher, while also the decrease until the 2080s is more distinct and leads here to lower yields than under current climate. In addition to the aforementioned regions, also countries of the West-African coast would be affected severely by yield decreases. This stronger impact of climate change on agricultural production can be attributed to changes in the plant stress simulation. As there is barely nutrient stress on the native soils of the ISRIC database, the model becomes more sensitive for temperature and water stress.

Impact of different cultivation practices on current and future maize yields

Figure 2 shows the results of simulations with different agricultural practices. It can be seen that for current climate, there is barely any effect of rain water harvesting and also irrigation increases yields only marginally on the average. As it could be expected, a dramatic increase in yields by a factor > 2 can be observed when sufficient nitrogen fertilizer is applied. Water harvesting has also with sufficient nitrogen only a small effect, while additional sufficient irrigation leads to further increase to finally three times the initial value.

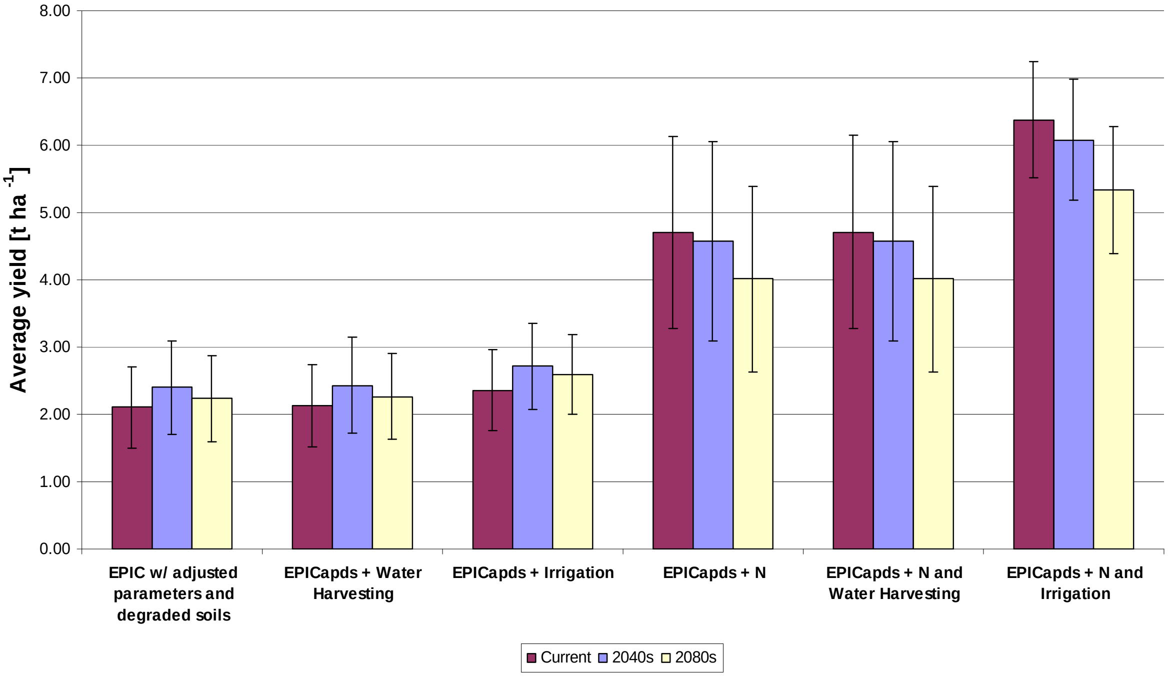

Fig. 2: Efficiency of methods for increasing agricultural outputs under current and future climate. EPICapds = EPIC with adjusted parameters and degraded soils.

When climate change is brought into the simulations there is a steady decrease in yields across the three time periods for all scenarios with sufficient nitrogen. Yields in the future time periods are still higher than under current practice, but this means that in the future the return on investment for the inputs will decrease. In the scenarios without nutrient input, there is an increase in yields until the 2040s that will then slightly decrease whereas the decrease is lower in the irrigation scenario compared to water harvesting and current practice. The poor results for the water harvesting technique might be an issue of the model setup and the coarse resolution as there is strong evidence from field experiments about the positive effects of rain-water harvesting (e.g. Sekar and Randhir, 2007). The implementation of the method might therefore have to be revised.

Conclusions and outlook

In this preliminary study of an on-going project we have shown that there are big differences in crop yield estimates for current and future climate on a large scale depending on the model parameterization and implementation of actual agricultural practice (here leading to soil degradation). Detailed setup and regionalization of large-scale crop growth models seems therefore necessary in order to retrieve reliable estimates. For future studies solar radiation estimates, based on the cloud cover, and historic wind speed records will be implemented as a further refinement. The number of GCMs and emission scenarios will be expanded to a total of 18 GCM/scenario combinations. As climate data is currently the limiting factor for increasing the resolution of the simulations, climate down-scaling methods will be applied if feasible. The soil status will be estimated more accurately as detailed data about soil degradation is expected to become available from the Africa Soil Information System (africasoils.net) in the near future. Out of the herein applied agricultural practice scenarios, the implementation of high inputs is the most promising in order to increase yields now and in the future. But it seems that this is economically not a sustainable solution as yields will continuously decrease in the future under this system. We will therefore test more options, including agro-forestry, inter-cropping, crop choice optimization, conservation agriculture, and green manure among others. Additional staple food crops to be included in future studies are sorghum, millet, cassava, rice, and wheat.

References

Gaiser, T., de Barros, I., Sereke, F., and Lange, F.-M., 2010. Validation and reliability of the EPIC model to simulate maize production in small-holder farming systems in tropical sub-humid West Africa and semi-arid Brazil. Agricult. Ecosys. Environ. 135, 318-327.

Liu, J., 2009. A GIS-based tool for modelling large-scale crop-water relations. Environ. Modell. Software 24, 411-422.

Mitchell, T.D. and Jones, P.D., 2005 . An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int. J. Climatol. 25, 693-712.

Monfreda, C., Ramankutty, N., and Foley, J.A., 2008. Farming the planet. Part 2: Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochem. Cycles 22, GB1022, doi:10.1029/2007GB002947.

Portmann, F. T., Siebert, S., Döll, P., 2010. MIRCA2000 - Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution dataset for agricultural and hydrological modeling, Global Biogeochem. Cycles 24, GB 1011, doi:10.1029/2008GB003435.

Sanchez, P.A., 2002. Soil fertility and hunger in Africa. Science 295, 2019–2020.

Sekar, I. and Randhir, T.O., 2007. Spatial assessment of conjunctive water harvesting potential in watershed systems. J. Hydrol. 334, 39– 52.

Stocking, M.A., 2003. Tropical soils and food security: the next 50 years. Science 302, 1356-1359.

Williams, J.R., Jones, C.A., Kiniry, J.R., and Spanel, D.A., 1989. The EPIC crop growth model. Trans. ASAE, 32, 497-511.