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Modeling maize yield responses to improvement in nutrient, water and cultivar inputs in sub-Saharan Africa

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ABSTRACT

Maize yields in sub-Saharan Africa (SSA) are at the lower end of the global range of yields since decades. This study used the large-scale agricultural crop growth model GEPIC to simulate maize yield responses to different management scenarios concerning: (a) level of nutrient supply; (b) extent of irrigated areas; and (c) low- or high-yielding cultivars. The results show that extending irrigation or planting an improved cultivar produced little effect on maize yield at the current level of nitrogen (N) and phosphorus (P) application rates. Increasing nutrient supply to the level commonly applied in high-input regions would allow for a tripling of maize yields from the current 1.4–4.5 Mg ha^{-1} and could increase yields even to 7 Mg ha^{-1} in combination with an improved cultivar. Irrigation was found to be especially effective for lifting very low yields concomitant to improved nutrient supply and cultivar. The highest yields when combining all the three improved management practices were predicted for East and Southern Africa with mostly 8–10 Mg ha^{-1}, and West Africa with 7–9 Mg ha^{-1}. The lowest yield potentials were found for the Western parts of Central Africa where they often reached only about 4–6 Mg ha^{-1}, due to low solar radiation and low nutrient availability on highly weathered soils. The inputs required for reaching these high yield levels would be very costly. Nevertheless, the simulation shows that with a supply of only 50 kg N ha^{-1} and 18 kg P ha^{-1}, which is less than one third of the current level in high-input countries, the maize yield could be doubled for most areas in SSA. The resulting increase in maize production would be about 10 times of the amount currently imported to the sub-continent including food aid.

1. Introduction

Maize is an important staple food crop in Sub-Saharan Africa (SSA), covering about 20% of the calorie intake and 13% of the total cultivated land (FAO, 2010). Yet, SSA is the region with the lowest maize yields in the world. Maize yields are mostly in the range of 0.5–2.5 Mg ha^{-1} compared to the global average of 6–7 Mg ha^{-1} and high-yield regions like the Corn Belt in the USA with 10–12 Mg ha^{-1} (Monfreda et al., 2008). To meet the growing demand – mainly due to population growth – cultivation areas have been expanded, the duration of fallows has been shortened, and imports have been increased. Still many regions depend on foreign food aid (Rosegrant et al., 2005).

It has been widely recognized that the main reasons for the persistent low yields are soil degradation and nutrient depletion. Continuous removal of crop residues from cultivated land and insufficient nutrient replenishment have led to serious soil nutrient depletion in most parts of SSA (Saïdou et al., 2004; Bationo et al., 2006; Liu et al., 2010). Nitrogen fertilizer application rates for maize are currently at about 3–5 kg ha^{-1} in SSA, with most areas not being fertilized at all due to lack of local fertilizer production facilities, transport infrastructure, and financial means for investment. In contrast, the world average lies at 134 kg N ha^{-1}, up to 180 kg ha^{-1} are applied in some states of the USA, and some countries such as Spain even report application rates of up to 220 kg N ha^{-1} (FAO, 2007).

Besides nutrients, low water availability has been recognized as a yield limiting factor in arid regions. Erratic rainfalls and inter-annual rainfall variability pose high risk of yield losses in semi-arid and tropical regions (Barron et al., 2003; Faurès and Santini, 2008). This has led to severe famines due to droughts in the past (Faurès and Santini, 2008). The current extent of irrigated areas for maize production in SSA is only about 3% of the total maize cultivation area, of which nearly 90% are located in the five countries South Africa, Somalia, Ethiopia, Sudan, and Tanzania (Portmann et al., 2010).

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A third concern in sub-Saharan maize cultivation is the use of low-yielding cultivars. Local varieties are prevalent. Physiological as well as social research have been focusing on the development and adoption of high-yielding cultivars (Gabre-Madhin and Haggblade, 2004). These are mainly bred for providing a higher yield fraction (harvest index), and for drought and heat tolerance, specific times until maturity, and specific nutritional characteristics. But the usage of high-yielding cultivars is still rare in most parts of SSA.

These issues lead to questions as to how maize yields will respond to different levels of improvement in inputs concerning fertilizer, irrigation, and high-yielding cultivar in SSA, what combinations of inputs would provide the optimum effect, and where the potentials for increasing maize yields are high for a given level of improved inputs. Recently, various studies have been published dealing with different aspects of maize yield gaps at the global scale (Licker et al., 2010; Neumann et al., 2010) or at the (multi-)site scale in SSA (Breman et al., 2001; Verdoodt et al., 2003; Sileshi et al., 2010). The former used statistical and climatic data for estimating potential yields, which are estimated to be at up to 8–9 Mg ha^{-1} in tropical regions. The latter used data from field trials to assess effects of different agronomic measures for increasing maize yields. As there are diverse concepts of crop yield gaps (Lobell et al., 2009), the definition of obtainable or potential yields does often differ. Statistical approaches for example assume usually that potential yields are already achieved in certain places of the study region, which may not be the case in SSA, while experimental approaches may not address all yield limiting factors at the same time. This renders the application of a process-based crop growth model suitable, which allows for quantifying the potential effects of different levels of inputs on maize yields based on biophysical algorithms. Such an approach is particular useful for countries in which no or little agricultural research is currently taking place. Coupled with a GIS, crop models can assess yield responses and identify variations in the returns to the inputs over large geographical areas with high spatial resolution.

It is worth noting that the agricultural ministers of the African Union have vowed to increase the average N fertilizer application rates for all crops in SSA to 50 kg N ha^{-1} by 2015 (African Union, 2006) in order to lift the very low productivity. The experience from Malawi has suggested a very positive outcome. Maize yields have doubled in Malawi with the implementation of a program subsidizing fertilizers and improved cultivars. This has allowed the country to become a net exporter of maize, after being dependent on maize imports for years (Denning et al., 2009).

The aim of this study was to assess the maize yield responses to the improvement of inputs on the SSA scale and with high spatial resolution. Agricultural inputs taken into account were N and P fertilizers, irrigation, and cultivars. In addition to projecting the yield potential under high supply of nutrients, water and usage of high-yielding cultivars, yield responses to different levels of fertilizer inputs were also assessed.

We used the Environmental Productivity Integrated Climate (EPIC) crop growth model, which had been linked to a GIS (Liu et al., 2007; Liu, 2009) and is hereafter referred to as GEPIC (GIS-based EPIC). The EPIC model has been used globally for more than 20 years in a wide range of (agricultural) studies (Gassman et al., 2004). Also for the present study region, EPIC, GEPIC and other GIS-based EPIC frameworks have been applied at different scales, e.g., field scale in Nigeria (Adejuwon, 2006), (sub-)national scale in Benin (Gaiser et al., 2010a,b; Kuhn et al., 2010), regional and continental scale (Liu et al., 2008; Gaiser et al., 2011; Folberth et al., 2012), as well as the global scale (e.g. Liu, 2009; Liu and Yang, 2010). The model has shown satisfactory reproduction of reported crop yields and crop water use. The good performance of the model in the previous studies renders EPIC highly suitable for the purpose of the present study. We have further evaluated the model performance for different input management strategies based on literature from the Malawian fertilizer and seed subsidy program and field studies. The results of this assessment are presented in the Supplementary Information S1 of this paper.

2. Methods and data

2.1. Model description and setup

EPIC is a bio-physical model that estimates plant growth and crop yield at a daily time step using a set of empirically based algorithms (Williams et al., 1989). For each day, the model first estimates potential plant growth and then reduces it according to the limitation due to the most dominant stress (N and P deficit, water, temperature, aeration, salinity) by a factor between 0 and 1. Yield is estimated using an actual harvest index (HI), which is calculated by the model within the range of a defined potential HI and a minimum HI depending on water stress. Potential evapotranspiration (ET) was calculated using the Hargreaves method (Hargreaves and Samani, 1985) and actual ET according to Ritchie (1972). In this study, we used the recently released version EPIC v0810.

GEPIC runs the EPIC model at the grid cell level (Liu et al., 2007; Liu, 2009) with a resolution of 0.5° × 0.5°. Depending on the employed scenario (see Section 2.3 and Table 1), each grid cell is treated as a homogenous area that is either rain-fed or irrigated or partially irrigated and partially rain-fed. In the latter case, irrigated and rain-fed yields are modeled separately for each grid cell and the mean yield is calculated as a weighted average:

$$Y_W = \frac{Y_I \times A_I + Y_R \times A_R}{A_T} \tag{1}$$

Table 1
Scenarios used in the study. Each scenario represents a combination of fertilizer application rates, extent of irrigated areas, and cultivar.

No.	Description	Abbreviation[a]
I	Fertilizer as "around 2000" Current extent of irrigated areas Low-yielding cultivar (baseline)	FcIcCc
II	Fertilizer as "around 2000" Irrigation on all harvested land Low-yielding cultivar	FcIsCc
III	Fertilizer as "around 2000" Current extent of irrigated areas High-yielding cultivar	FcIcCh
IV	Fertilizer as "around 2000" Irrigation on all harvested land High-yielding cultivar	FcIsCh
V	Sufficient fertilizer supply Current extent of irrigated areas Low-yielding cultivar	FsIcCc
VI	Sufficient fertilizer supply Irrigation on all harvested land Low-yielding cultivar	FsIsCc
VII	Sufficient fertilizer supply Current extent of irrigated areas High-yielding cultivar	FsIcCh
VIII	Sufficient fertilizer supply Irrigation on all harvested land High-yielding cultivar	FsIsCh
IX	Fertilizer supply at different levels x[b] Current extent of irrigated areas Low-yielding cultivar	FxIcCc
X	Fertilizer supply at different levels x Irrigation on all harvested land High-yielding cultivar	FxIsCh

This scenario was mostly evaluated for a level of 50 kg N ha^{-1}.

[a] F: fertilizer supply (c = current|s = sufficient), I: irrigated (c = current|s = all area), C: cultivar (c = low-yielding|h = high yielding).

[b] This scenario was mostly evaluated for a level of 50 kg N ha^{-1}.