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Full Length Research Paper

Modeling the impact of water and nutrient management in African agriculture

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Africa has to adapt to the growing demand for agricultural commodities driven by growth in population, per capita income and new demands for biofuel. There is a wide agreement that African agriculture has enormous potential for growth and will shift towards a more productive farming. A systematic approach is needed to identify the main factors that explain observed yield gaps and to evaluate the impacts of a potential intensification on the environment. In this paper we presented a crop yield gap analysis for Africa using a newly developed tool linking a Geographic Information System and the biophysical model EPIC. We showed that in most African countries, the main limiting factor to crop production is nitrogen, while water limitation is more restricted to few countries. The predicted yield gap is much more marked in Sub-Saharan Africa than in North Africa. We predicted that a mining of soil resources, with nitrogen crop uptake exceeding the inputs through fertilization, is taking place in many countries in Africa. We also showed that even in water rich countries, appropriate water management including the development of irrigation infrastructure is needed to close the yield gap.

Key words: Water management, nitrogen requirements, irrigation requirements, yield gap, Africa, Epic.

INTRODUCTION

Nearly all Earth's population growth is expected to occur in the developing countries and all the projections suggest that demand for food will continue to augment in the next decades (FAO, 2009a; 2009b;Tilman et al., 2011; OECD/FAO, 2013). A general increase of food production by 70 % between 2005 and 2050 (FAO, 2009a; 2009b; Godfray et al., 2010) will be required to support population growth, higher standard of living, new diets, biofuels, etc. Furthermore, agriculture will have to adopt more efficient and sustainable cropping methods to adapt and face potential threats of negative climate change impacts (Müller et al., 2011). There is a wide agreement that African agriculture has enormous potential for growth thanks to its natural resources including land and water. For instance 400 million ha in the Guinean Savannah have been estimated suitable for commercial farming and only 10 % of this land is actually cropped (Morris et al., 2009).

In Africa, crop production is dominated by rainfed agriculture, representing about 94% of the cultivated area. Most of the irrigated area is concentrated in five countries (You et al., 2010). Increasing irrigation potential could boost agricultural production by at least 50% (You et al., 2010). The African Water Vision for 2025 and the related framework for action suggested a doubling of irrigated area in Africa as a requirement to achieve sufficient crop production goals. The Commission for Africa (2005) called for doubling the investments on irrigation infrastructure. NEPAD (2003) suggested a new irrigation strategy and water management in Africa as a major instrument of economic and agricultural development. Irrigation will also be a key component of mitigation to combat the potential effects of global warming on crop production.

Lack of fertilization is also a major obstacle to higher crop yield in Africa. About 75% of Africa's agricultural land is degraded and nutrient depletion is a major problem. The average fertilizer application rate is around 20 kgha^{-1}, which is extremely low when compared to the 73 kg ha^{-1} in South America, 135 kg ha^{-1}in East and South East Asia and 206 kg ha^{-1}in the industrialized countries (Fleshman, 2006; Kelly, 2006). This lack of water and nutrients has limited agricu-

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ltural production in Africa which is the lowest among all continents (FAOSTAT, 2009;Tittonell et al., 2013).

Many studies have focused on crop production at various scales making full use of faster computers, linking biophysical models and Geographical Information System (GIS). Biophysical models have proven to be useful tools to perform reliable investigations about the impacts of different management (and climatic) scenarios and strategies of agricultural production on the environment. GIS is a key component of the spatialization of biophysical crop growth models, despite limitations inherent to the issues of linking various scales: the scale of the biophysical processes simulated, of the available input datasets, of the required output data and that of validation data (Faivre et al., 2004; 2009). However, such integration provides the opportunity of using these biophysical models at regional and continental scale by handling a large amount of geographical data, allowing the assessment of the environmental impact of farming while taking into account soil, climate, and crop management spatial variability.

Different approaches are available in literature to estimate large scale crop production ranging from statistical regressions (Neumann et al., 2010) to biophysical (Liu, 2009) and terrestrial biosphere models allowing feedback interactions between crop growth and climate (Berg et al., 2011). GIS based biophysical models are powerful tools to evaluate crop production as impacted by a full range of drivers (Liu, 2009) and they are frequently used to estimate yield gaps at regional/global levels (Van Ittersum et al., 2013; Dzanku et al., 2015).

Different integrated systems of crop growth models and GIS have been developed and applied at global scale. Liu (2009) and Liu et al. (2007) used the EPIC model in a GIS environment to explore crop water productivity of wheat, maize and rice at global scale at a resolution of 30’ (approximately 55 km). Folberth et al. (2012) used the same model incorporating local management to predict maize yield in Sub-Saharan Africa. Tan and Shibasaki (2003) also used EPIC in a GIS framework (6’ grid cell) to simulate at global scale maize, rice, wheat and soybean. EPIC has also been used extensively to evaluate the impact of climate change on crop production (Wu et al., 2011). In all these applications the resolution of input datasets was generally not highly detailed (usually larger than 50 km x 50 km) or based on simplified management alternatives. In addition, these applications focused on food crop production, not considering major limiting factors such as water availability, and the potential environmental impacts.

However, agriculture has a major environmental impact at global scale and many studies have shown how agriculture may lead to air, water and soil pollution (Carpenter et al., 1998; Bennet et al., 2001;Vitouseket al., 2009;Burney et al., 2010), loss of biodiversity (Dirzo et al.,2003; Hulme et al., 2013), soil degradation and erosion (Pimentel et al., 1987; Hurni et al., 2008), and organic matter and water resources depletion, both at the local, regional and global scales. Understanding the potential environmental impacts of an intensification of crop production in Africa is critical in view of a sustainable growth and development. Therefore we think that it is of utmost importance to develop tools allowing a quick assessment of the response of crop production to higher levels of nutrients and water inputs and to evaluate the potential impact of this intensification on the environment.

The aim of this study was to develop a high resolution integrated GIS-biophysical model to estimate water and nutrient requirements of major crop production systems in Africa. We selected the biophysical model EPIC (Williams, 1995) because it simulates crop production under different farming practices and operations including fertilization and irrigation application rates and timing, and because it considers nutrient losses to the environment. In addition, it has been thoroughly evaluated and applied at scales ranging from local to continental (Gassman et al., 2005) and used in global assessments (Liu et al., 2008; Liu, 2009). The model has been applied for irrigation scheduling assessment (Rinaldi, 2001; Wriedt et al., 2009), climate change studies (Mearns et al., 1999), biofuels production (Velde et al., 2009). An integrated GIS-EPIC system was applied successfully at European scale (Bouraouiand Aloe, 2007), laying the grounds for extending it to Africa. The specific objectives of the study are therefore:

- Develop a high resolution biophysical database covering the entire African continent;
- Develop a GIS framework embedding the EPIC model to optimize model runs;
- Perform a yield gap analysis and evaluate the role of appropriate water and nutrient management for an optimal crop production in Africa;

The first part of the paper will detail the development of a continental spatial geo database and its linkage with the EPIC model. In the second part we describe the validation of the system in Africa and the major factors controlling crop production. Then we quantify irrigation and nutrient requirements to bring crop production to an optimal level while taking into account available water resources.

MATERIAL AND METHODS

GISEPIC-AFRICA is a GIS system integrating the biophysical continuous simulation model EPIC (Williams, 1995) with a spatial geo database to simulate nutrient and water cycling as affected by agriculture practices and crop growth at the African continental scale. The loose coupling approach (Huang and Jiang, 2002) was used to link the geodatabase and the EPIC model. The integration is based on the transfer of data between the GIS and the simulation model. This approach was preferred to a tight and full integration to avoid redundant programming and to facilitate the integration with new or other models. The data transfer between the geodatabase and the model is operated by means of a specific tool (dll component) and by the GIS interface. The system is composed of the following components: the EPIC model, the spatial geodatabase, the data transfer component (used for input-output transfer to the GIS) and the GIS interface (for selecting the spatial extent of the simulation). A more detailed and complete description of the system and methodology is given in Pastori et al. (2011).

The EPIC Model

EPIC is a biophysical, continuous, field scale agriculture management model. It simulates crop water requirements and the fate of nutrients and pesticides as affected by farming activities such as the timing of agrochemicals application, tillage, crop rotation, irrigation strategies, etc., while providing at the same time a basic farm economic account. The main components can be divided in the following items: hydrology, weather, erosion, nutrients, soil temperature, and plant growth.

EPIC maintains a daily water balance taking into account runoff, drainage, irrigation and evapo-transpiration. Potential crop growth is based on daily heat unit accumulation. The model adjusts the daily potential growth by constraints including the influence of the following limiting factors: nutrients, water, temperature, and aeration. These stresses can impact biomass production, root development and crop yield. A stress is estimated for each of the limiting factors and the actual stress is equal to the minimum stress value of all the factors.

EPIC simulates nitrogen and phosphorus cycles by considering different pools: active organic, stable organic, fresh organic, nitrate and ammonium pools for nitrogen, fresh organic P and stable organic P, labile P, active and inactive mineral pools for phosphorus. Dissolved nutrient losses are related to the processes of leaching, runoff and lateral subsurface flow and are calculated as a function of flow volumes and of dissolved nutrient concentrations. Crop uptake is a major pathway of nutrient losses and is estimated using a supply and demand approach. Daily nitrogen (N) demand is the product of biomass growth and optimal N concentration in the plant (related to crop stage) while soil supply of N is limited by mass flow of nitrates to the roots. For a detailed and complete description of these processes see Williams (1995).

Input Requirements

A geodatabase was developed to support the application of EPIC for the entire African continent. The geodatabase includes all the data required for EPIC modelling: meteorological daily data, soil profile data, crop distribution and management data, and scenario information. These attributes as well as the model setup are described below.

Spatial Discretization

Considering the resolution of available required datasets (soil, land use, climate and crop management) a reference spatial modelling unit grid of 15 km x 15 km covering the entire African continent was selected. This resolution is a balanced value between more detailed and coarser data sets. It accounts for land use-soil and climate variability which are key elements for nutrient and water dynamics. Entire Africa was thus discretized into 135000 different grid cells. Each grid cell (SITE) is characterized by uniform topography, soil and climate.

Soil Input

The Harmonized World Soil Database (HWSD; FAO et al., 2009) with a resolution of about 1 km (30 arc second) was used to characterize the soils of the SITE units. Over 6988 different mapping units are present in Africa. The original soil map is based on the concept of Soil Mapping Unit (SMU). For each spatial SMU a list of different soil types is described and characterized in the HWSD database. In order to consider all different soils, a weighted average was calculated at SITE level for each parameter required by EPIC considering the share of presence of the soil type in the SMU. The EPIC model requires information about soil textural composition, porosity, saturated hydraulic conductivity, along with the initial values of the various nitrogen and phosphorus pools.

DEM

A global digital elevation model (DEM) with a horizontal grid spacing of 30 arc seconds (FAO, 2009c) was processed to obtain elevation and slope for each grid cell.

Land Use

The SAGE crop maps were used (Monfreda et al., 2008) to derive a complete land use dataset for all African countries. SAGE is a detailed database of global land use describing the area (harvested) and yield of 175 distinct crops for the year 2000 on a 5 min by 5 min (approximately 10 km x 10 km) grid. The data were derived from agricultural surveys collected at the smallest political units available for all the countries (sub-national, usually one or two administrative levels below the national, and when not available data refer to FAO national statistics).

Meteorological Section

Two different datasets were used to derive the daily climate data required by EPIC. The Princeton University Global Meteorological Forcing Dataset for Land Surface Modeling (Sheffield et al., 2006) was constructed by combining a suite of global observation-based datasets with the NCEP/NCAR reanalysis. The dataset has a resolution of 1° covering the entire globe (360 x 180 Longitude/Latitude) and includes the time period extending from 1948 to 2006. The CRU monthly dataset covering the period 1961-2006 (New et al., 2002) with a resolution of 10´ latitude/longitude was used to downscale the Princeton daily data to a 10’ grid. To perform the downscaling a monthly weighting factor was calculated for each climatic parameter by calculating the long term monthly average at 10’resolution (CRU) divided by the long term average of all the CRU grid falling in the corresponding 1° Princeton grid cell. The 1°Princeton daily data were finally multiplied with the 10’weighting factors. The daily climate data includes precipitation, minimum and maximum temperature, wind speed, and solar radiation.

Crop Management section

Crop management is one of the most important sets of input required to run EPIC. It consists of detailed schedules and characteristics of the most common crop operations including sowing, harvesting, tillage, fertilization, and irrigation, for each of the crop used inthe EPIC simulations. It was not possible to obtain all management information at the relevant resolution (15 km) for Entire Africa. However, management practices (such as fertilization and irrigation practices) can be reasonably considered homogenous at sub national administrative units. For this reason administrative boundaries provided by FAO (Sub-National Administrative boundaries Level 2 and 3 (FAO, 2009d) were processed in order to obtain a homogeneous spatial representation of Africa. These administrative units were considered as the reference spatial scale for crop management. The 46 dominant crops in Africa were simulated, and management schemes for each of the crops were derived as described below.

Scheduling Dates

The definition of a sowing date is a key factor because it affects all other management operations (tillage, irrigation, harvest, etc.) and because it will impact crop growth. Planting dates are often estimated on the basis of climate datasets (Waha et al., 2012). This methodology is quite robust even in the case of rainfed agriculture because it allows taking into account the intra and inter-annual climatic variability and because the farmers generally base the timing of their sowing on experience driven by past precipitation and temperature conditions. In this study two approaches were used to define the sowing dates according to the geographic location of the site. The potential heat units (PHU) methodology is more appropriate in regions where temperature is the main limiting factor during the growing period and, consequently, it was used in the area above the tropics. This method considers the total number of heat units required to bring a plant to maturity. Heat units are calculated using long term minimum/maximum temperatures, optimum and minimum plant growing temperatures and the average number of days for the plant to reach maturity. The crop property database provided by Williams (1995) and the long term climate statistics were used to calculate the heat units for each crop.

In the tropical - subtropical regions usually the main limiting factor governing crop sowing is precipitation and consequently, the PHU approach is no longer valid. A different approach based on rain limitation was selected. This approach was originally developed by the Agriculture Hydrology Regional Centre in Niamey and applied in different studies (Genovese et al., 2001; Rojas et al., 2005). The sowing decade (a calendar year is divided into 36 decades) is calculated as the first decade with at least “x” mm of rain followed by 2 decades with at least “x” mm of rainfall. In our study 3 distinct thresholds (x) were used according to different annual average rainfall (P_{year}):

- x =10 mm for regions with $P_{year} < 400$ mm;
- x=20 mm for regions with $400 \leq P_{year} < 800$ mm;
- x=30 mm for regions with $P_{year} \geq 800$ mm.

All crop management schedules were compared and checked with reported data including crop calendar provided by FAO (FAO, 2012), USDA – FAS Crop Explorer service and EARS (EARS, 2009; USDA, 2009). The limited rain method is less precise than PHU approach because it doesn’t consider crop specific parameters. However a check of the estimated with reported sowing periods suggests that it can be considered a sufficient approximation for the application of the model at continental scale.

Other relevant crop operation schedules were then evaluated by relating them to the estimated sowing dates. The crop harvesting date was calculated by adding to the sowing date the climatic region specific time to maturity derived from the calculated length of growing period (FAO and IIASA, 2006). A tillage operation was performed three days prior to sowing.

Fertilizer Management

Fertilization input data were derived from the FAO FERTISTAT database (FAO, 2009f) and complemented by other total fertilizer consumption datasets when required (IFA, 2009). Fertilization data are available at country level and consequently it was not possible to differentiate fertilization strategies at the sub-national level. The following methodology was thus adopted to derive a spatially detailed fertilization database. First, average annual nitrogen fertilizer consumption data were collected for all countries. Then annual yields and harvested areas were collected for each crop, for each country and for each administrative management unit. This regional crop yield data was then converted into nitrogen yield using crop specific nitrogen content (Neitsch et al., 2010). Finally, the reported national use of nitrogen was redistributed at administrative level for each crop based on the regional nitrogen yield. EPIC was then set to run under automatic fertilization with the maximum amount applied for each crop set according to the calculations detailed previously.

Water Management

The FAO global map of irrigated areas (Siebert et al., 2005; 2005; 2006; 2007) was used as the main reference to identify areas where irrigation was considered in the EPIC simulations. This map was selected because it has a resolution of 5 min that is compatible with the EPIC SITE dimension, and because it is based on FAO statistics that are the main data source for crop area and distribution. Irrigation reports from FAO were used to identify crops or groups of crops that are irrigated in different countries (FAO, 2005; FAO, 2009e). A table was designed in the database to store all required information: presence of irrigation in the simulation unit (yes if more than 50% of the cropland area is originally mapped as irrigated), the relative percentage of irrigated area, and crop type irrigated. When some discrepancies were observed (rice cultivation in Madagascar not falling in an irrigated area), the Global Irrigated Area Map of the World (Thenkabail et al., 2009) was used to complete the missing information.

The Global Irrigated Area Map of the World was developed for year 1999 using multiple satellite sensors and secondary data such as rainfall series, land use data DEM, and others (see Thenkabail et al., (2009) for details). The final product is a 10 km resolution map with 28 rainfed and irrigated crop classes covering the entire globe. EPIC was set to run using the auto-irrigation option. EPIC schedules automatically the irrigation and the amount applied is calculated according to daily plant water stress.

Model Validation

The goodness of fit of the validation was assessed using the coefficient of efficiency (Nash and Sutcliffe, 1970), and the coefficient of determination (R^2), and the root mean square error (RMSE). The coefficient of efficiency takes values from $-\infty$ to 1, where 1 indicates a perfect fit between the measured and the predicted values.

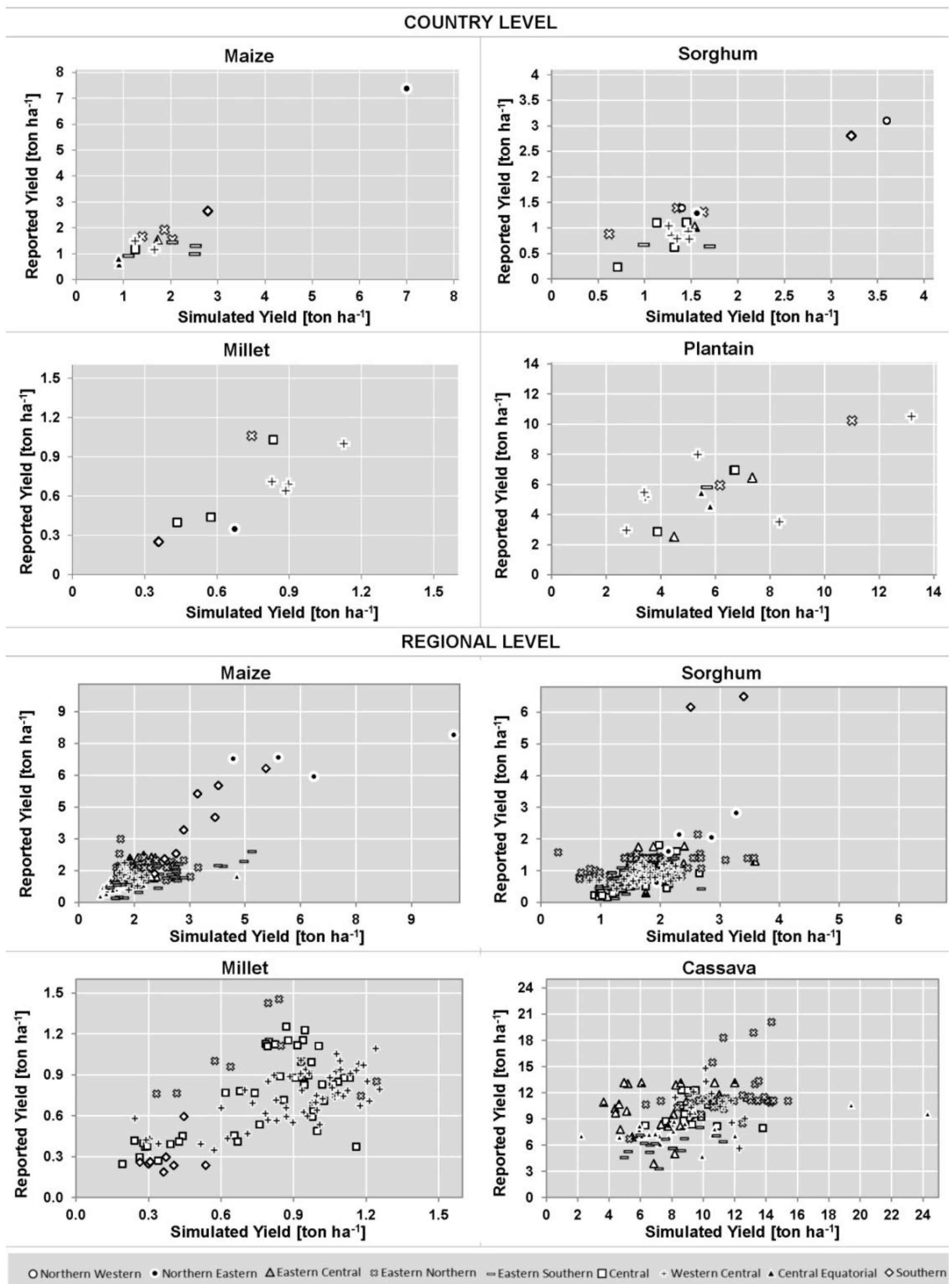
Model Results and Analysis

EPIC was applied for the five most dominant crops of each SITE cell (15 km x 15 km) for the time period extending from 1980 to 2006. For clarity purposes, we focused our discussion on specific crops critical for food production in Africa. These crops include maize, sorghum, and millet for cereals, cassava for tubers, and banana group for fruits. Cereals are the most important group accounting for the 49% of the total cropped area (FAOSTAT, 2009).The most cropped cereals in Africa are maize, sorghum and millet (37% of total area). Root crops and pulses occupy a significant share of the arable land, and the most important crops are cassava and beans. Fruits are less dominant at continental scale, and the most used is banana (plantain).

Validation

The validation was not performed at the site level as no high-resolution measured data was available. The validation focused mostly on crop yield as it is the only reported data readily available for the entire African continent. Therefore, the validation was performed at the regional level making full use of the available spatial crop yield data. Indeed, it is important to stress that most continental scale studies usually limit the validation exercise at the country level (Liu, 2009; Priya et al., 2001; Tan and Shibasaki, 2003). The SAGE raster grids derived by combining national, sub-national census statistics and land use data (Monfreda et al., 2008) were used as the reference for the regional model validation. Original SAGE grids available at a resolution of 5 minutes were re-aggregated at the administrative level (Monfreda et al., 2008; Ramankutty et al., 2008). The EPIC model was used with no calibration and all default parameters were kept unchanged. The comparisons between the predicted and reported yields for the various crops at national and regional level are shown in Figure 1. The statistical evaluation of the model results is given in Table 1. The simulated and the reported yields compare well, in particular for cereal. Most crops are well simulated at country level with a coefficient of determination (R^2) around 0.90, 0.66, 0.51, 0.67, and 0.57 for maize, millet, sorghum, cassava and plantain, respectively. For cassava, the R^2 is about 0.3. However the results are much better when considering only the countries where cassava is one of the dominant crops (Angola, Democratic Republic of Congo, and Mozambique). Indeed when a crop is marginal in a specific country, the yield reported by the FAO might not reflect the national yield, but would be more specific to the location where cassava is grown. At sub-national level, the coefficients of determination are high, indicating that EPIC captured also the regional variations of crop yield (Table 1). The R^2values are also higher for cereals and lower for cassa-

Figure 1. Comparison between simulated and reported yields at national and regional level for major crops in Africa.



va at regional level. Root mean square errors (RMSE) are low both at national and sub-national level for all crops but for wheat. The robustness of the EPIC prediction is also shown by comparing the measured and predicted average yield for most major crops. A significant over-prediction can be noted for sorghum and wheat.

However in this study no attempt was done to calibrate the yield. As regards sorghum two outliers located in South Africa are affecting negatively model performance. This over prediction is probably due to some of the simplification in the management practices and also in part to the accuracy of the reported yield (estimated regional yield). Indeed, as mentioned previously we used the SAGE data (Monfreda et al., 2008) as a basis for validating the model at regional scale. However, the regional data in the SAGE database don't always come from reported value but are in many cases estimated.

Table 1. Statistical evaluation of the EPIC model performance for the major simulated crops.

CROP	R^2 coefficient		Nash–Sutcliffe efficiency		RMSE tons ha^{-1}		Av. Yield tons ha^{-1} Country	
	Country	Regional.	Country	Regional	Country	Regional	Obs	Sim
Maize	0.90	0.61	0.92	0.58	0.47	0.80	1.9	2.1
Sorghum	0.51	0.44	-0.01	-1.3	0.64	0.26	0.9	1.4
Millet	0.66	0.28	0.53	-0.21	0.21	0.29	0.6	0.7
Wheat	0.86	0.67	0.60	0.83	1.26	1.14	0.9	1.5
Cassava	0.67	0.16	0.65	-0.35	1.18	2.19	9.0	8.7
Plantains	0.57	0.37 (0.49*)	0.37	-0.27	1.81	3.02	5.8	6.2

*excluding Ivory Coast

Consequently, there is not always in SAGE a “true” reported regional yield, therefore affecting the regional validation. We performed an additional validation of the reported yields by comparing the calculated irrigation volume applied with the reported national value. At country level the amount of simulated irrigation is in general in very good agreement with reported water abstraction for agriculture (FAO, 2009e; FAO, 2009f). The correlation coefficient between estimated and reported annual water abstraction is around 0.9 (0.05 level of significance). However, EPIC generally tends to under-predict the abstracted water. This is explained by the fact that we only calculated crop water requirements without considering irrigation efficiencies and conveyance losses which are included in the statistics reported by FAO (FAO, 2009e; FAO, 2009f).

An important element to consider when evaluating the model is the assessment of its ability to represent the importance of climate parameters and their influence on crop yield and in general on water and nutrient processes and cycles. We analyzed specifically the impact of precipitation on maize yield. In some African countries (Central and Eastern Africa) there is a significant positive correlation between precipitation and the maize yield. For other regions including Egypt and North Africa no linear relation can be found indicating that extra water inputs (irrigation) are controlling maize yield. In southern countries, maize yield tends to exhibit a linear relation with precipitation while in central equatorial countries; the yield does not seem to be linked with precipitation. For Africa in general yield seems less correlated with precipitation and other climate variables than it is in Europe (Velde et al., 2009) and this can be partially explained by the fact that in many countries the actual agriculture is characterized by low intensity where the main limiting factor is fertilization.

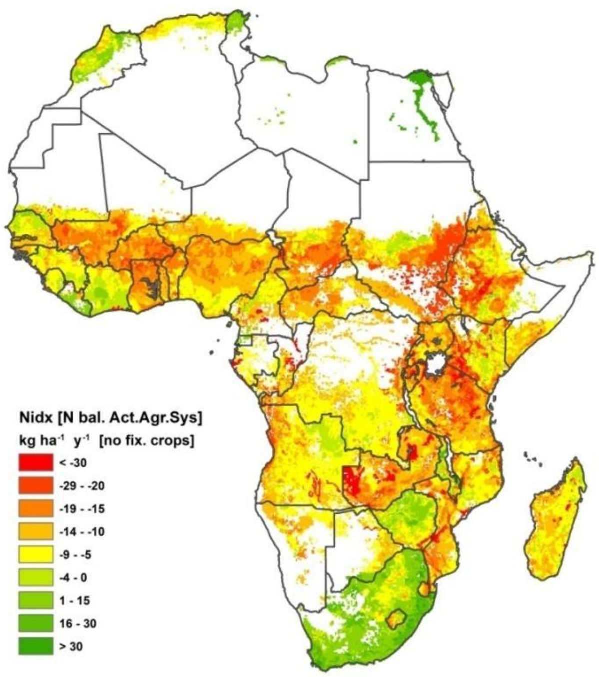
Indeed, the actual fertilizer applications are generally very low in Africa (20 kg ha^{-1}average for all crops) and this low input practice is reflected in the crop production that is the lowest compared with all other continents for all major crops. Insufficient nutrient fertilizers inputs have been identified as a major cause for the extremely low crop production in Africa (Brams, 1971; Payne, 2010; Folberth, 2012). Agro-ecosystems with long term low fertilization input can lead to soil nutrient depletion (Wheight and Kelly, 1998) and to a loss of soil organic matter and subsequently to a loss of soil functionalities. Cultivation with minimum or no input can introduce a 30% loss of soil organic matter after 12 years and 66% after 46 years (Weight and Kelly, 1999). To assess the sustainability of current practices, we calculated a nitrogen index defined as the difference between the nitrogen input through fertilization and the nitrogen uptake of the 5 dominant crops (excluding N fixing crops):

$$N_{index} = FERTN_{modelinput} - N_{modelcropuptake}$$

The index was estimated for each EPIC site and the results are displayed in Figure 2. Under current fertilization practices, we predict that only 8 countries have a positive or null nitrogen balance. Egypt is the country where the nitrogen index value (calculated for the 5 dominant crops and including non-fertilized crops) is the highest with an average nitrogen positive excess around 70kg N ha^{-1}.However, many countries exhibit a negative balance (Figure 2). This N deficit indicates a depletion of nitrogen in the soil that will lead in the medium to long term to a decrease of soil fertility.

These negative values of N_{index} reflect an unbalanced crop production and in general a non efficient management of soil fertility. A consequence of this situation is that many African farmers overcome this problem by abandoning land after few years deforesting new areas, causing a loss of soil fertility, loss of biodi-

Figure 2. Nitrogen index at grid cell level under actual fertilization practices for 5 dominant crops.



versity, deforestation and losses of ecosystem services (Carpenter et al., 1998; Benayas et al., 2010; Achard et al., 2002).

N_{index} estimates show negative values in many Sub Saharan Countries with values ranging between -20 to -10kg N ha^{-1}, values similar to the estimates of nutrient balances (inflows / outflows) in other studies. Weight and Kelly (1998) reported for 38 SSA countries an annual depletion (kg/ha) for the period 1980-1990 of nitrogen (22 kg), phosphorus (2.5 kg) and potassium (15 kg). Stoorvogel and Smaling (1998) calculated an annual average nutrient loss for Sub Saharan Countries of 26 kg ha^{-1} for the year 2000, while according to other estimates by Van den Bosch et al. (1998) and De Jager et al. (1998) typical value of N balance in central African farms is -70 kg N ha^{-1} y^{-1}. We estimated that more than 80% of the total cropland is characterized by nitrogen crop uptake exceeding the fertilization rate. Similarly, Henao and Baanante (2006) estimated that about 85% of the total cropland in Africa is characterized by high nutrient mining rates.

This index can be considered an efficient indicator of potential soil N mining even though other important aspects were not considered (such as crop residues management, long fallow periods, and other N inputs sources from legume intercropping systems). This indicator clearly shows that actual N fertilizer application rates should be increased to meet crop demand and to allow closing the yield gap without depleting soil fertility. Further it allows targeting areas where it is possible to close yield gaps avoiding agricultural expansion into natural ecosystems and clearing more land, thus following to a more sustainable path to reach food security (Ray et al., 2013; Foley et al., 2011).

Irrigation and Nutrient Requirements for Optimal Crop Production

As highlighted previously, crop production in Africa is limited regionally by the lack of water, and at larger scale by the low input of fertilizers. We propose in the following section to perform a yield gap analysis and to identify for each country the major limiting factor of crop growth and calculate nutrient and water requirements to bring production at the optimum level. Yield gap is defined in our study as the difference between potential crop yield under no water and nutrient constraints (Lobell et al., 2009)and the actual yield. Our analysis focuses primarily on the impact of management practices on crop yield. To this purpose we setup EPIC to run under two alternative scenarios. The first scenario (SC1) is conservative with respect to water use and is characterized by a maximum (not limited) fertilization strategy. In this scenario the GISEPIC-AFRICA system was set to free auto-fertilization, while irrigation was identical to the baseline. With this configuration the model will apply fertilizer in order to maximize the yield according to crop nitrogen requirements. This scenario is focused on the nitrogen fertilization that has been identified as the main limitation

Table 2. Relative impact of the fertilization and irrigation scenarios on average yields for dominant crops.

COUNTRY	Yield gap (%)		(SC2-SC1) / SC2	Main crop limitation	
	SC1-Act.	SC2-Act.		Nitrogen limited	Water limited
Algeria	75	385	4.1		●
Angola	195	372	0.9	●	●
Benin	219	265	0.2	●	
Botswana	97	695	6.2		●
Burkina Faso	284	361	0.3	●	
Burundi	79	314	3.0		●
Cameroon	272	368	0.4	●	
Central African Rep.	179	275	0.5	●	
Chad	195	295	0.5	●	
Congo	49	108	1.2	●	●
Cote d'Ivoire	400	533	0.3	●	
Dem. Rep. of Congo	193	268	0.4	●	
Djibouti	1	1775	1774.0		●
Egypt	0	97	106.8		●
Equatorial Guinea	206	241	0.2	●	
Eritrea	47	385	7.2		●
Ethiopia	149	235	0.6	●	
Gabon	169	229	0.4	●	
Gambia	71	83	0.2	●	
Ghana	308	418	0.4	●	
Guinea	169	250	0.5	●	
Kenya	74	384	4.2		●
Lesotho	88	156	0.8	●	
Liberia	126	167	0.3	●	
Libyan Arab Jam.	58	502	7.7		●
Madagascar	264	356	0.3	●	
Malawi	141	164	0.2	●	
Mali	223	363	0.6	●	
Mauritania	68	454	5.7		●
Morocco	34	451	12.3		●
Mozambique	268	402	0.5	●	
Namibia	153	1021	5.7		●
Niger	170	497	1.9	●	●

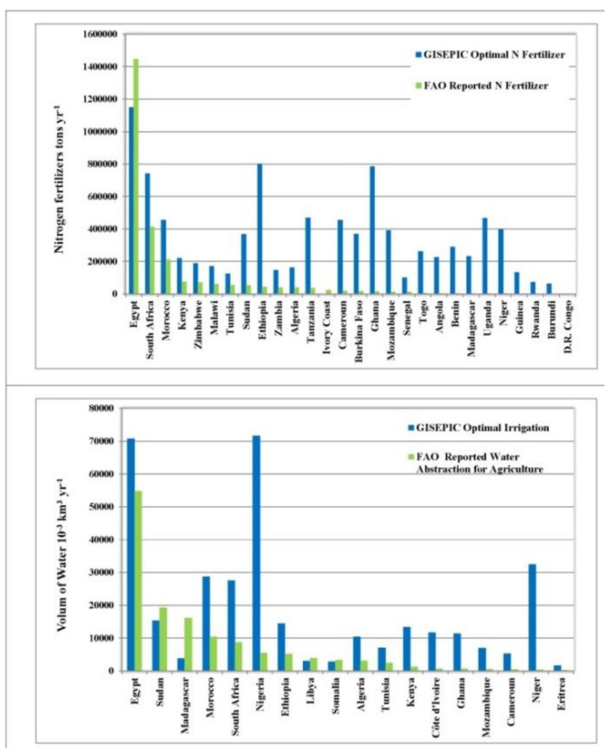
in restricting yields production, usually more than water availability (Breman et al., 2001).This results in a water-limited potential yield that is a good benchmark for rainfed agriculture (Van Ittersum et al., 2013). The second scenario (SC2) is the “high production potential” with no limitation for both fertilizers and irrigation. This scenario aims at simulating the higher range of potential production of agriculture in Africa under actual land use. Under these conditions crops can always obtain sufficient water and nitrogen when stress occurs. The scenarios were compared with the base scenario representative of current irrigation and fertilization management practices.

The results for both scenarios are given in Table 2. For instance for Algeria, unlimited fertilization will result in an increase of crop yield by about 75%, while unlimited fertilizer and water application results in an increase of the yield by 385%. Clearly in Algeria, water is the main limiting factor to higher production. The comparison be-

Table 2. Cont.

Nigeria	256	325	0.3	●	
Rwanda	87	186	1.1	●	●
Senegal	134	219	0.6	●	
Sierra Leone	166	207	0.2	●	
Somalia	190	1023	4.4		●
South Africa	45	229	4.1		●
Sudan	19	75	2.9		●
Swaziland	364	574	0.6	●	
Togo	334	364	0.1	●	
Tunisia	40	183	3.6		●
Uganda	147	436	2.0	●	●
United Rep. of Tanz.	251	391	0.6	●	
Zambia	175	227	0.3	●	
Zimbabwe	76	231	2.0	●	●

Figure 3. Calculated and estimated nitrogen consumption (top graph) and calculated crop water requirements and water abstraction (bottom graph).



tween actual scenario and the "free fertilization" scenario (SC1) highlights that the main limiting factor for agriculture production in Africa can be identified as the nutrient fertilization. About 20 countries have their crop production mainly limited by water availability while 32 countries exhibit a nutrient limitation.

The ratio between the optimal and actual nitrogen fertilizer use ranges usually from 1.8 in South Africa to more than 100 in Niger and Uganda (Figure 3). The worst ratio is found in the Democratic Republic of Congo where the actual nitrogen fertilizer use is less than 0.06 kgha^{-1} while the optimal use is around 60 kg ha^{-1} (ratio of more

Table 3. Required nitrogen and water application rates to bring major crops to optimal yield.

		Average Yield [tons ha^{-1}]		N applied [kg ha^{-1} y^{-1}]		Water applied [mm ha^{-1} y^{-1}]	
		ACTUAL SCENARIO	OPTIMAL SCENARIO	ACTUAL SCENARIO	OPTIMAL SCENARIO	ACTUAL SCENARIO	OPTIMAL SCENARIO
MAIZE	North Africa	6.5	10.4	145.8	267.5	596	915
	Sub-Saharan Africa	1.7	9.6	13.7	335	2	206
WHEAT	North Africa	1.5	5.4	65.8	264.7	163	473
	Sub-Saharan Africa	1.2	5.2	27.4	249.3	28	376
SORGHUM	North Africa	1.4	6.4	17.5	225.3	31	294
	Sub-Saharan Africa	1.3	7.6	9.9	258.8	2	202
CASSAVA	Sub-Saharan Africa	8.7	20.5	3.0	102.4	2.8	582
MILLET	Sub-Saharan Africa	0.5	2.0	2.4	89	1	307

than 1000). In Egypt the ratio is around 0.8, meaning that the reported data by FAO is larger than that calculated by EPIC under the optimal scenario indicating an over-fertilization (only case in Africa). The countries that showed the highest potential to increase crop yield, included Ivory Coast, Swaziland, Togo, Ghana, Burkina Faso, Cameroon, Mozambique, Madagascar, Nigeria, United Republic of Tanzania, and Mali. They are usually located in rainy regions and characterized by very low fertilizer inputs under actual management.

For water, the ratio between the optimal and actual irrigation volume ranges usually between 0.8 for Sudan and 17 in Ghana, indicating that the volume actually applied is below what is needed for optimal crop growth.

Niger had the highest ratio (around 79) mostly due to the extremely low precipitation (around150 mmyr^{-1}) and the absence of irrigation. Egypt, Djibouti, Sudan, Morocco, Tunisia, South Africa, Libya, Mauritania and Eritrea, are characterized by an agriculture production that seems mainly limited by water input.

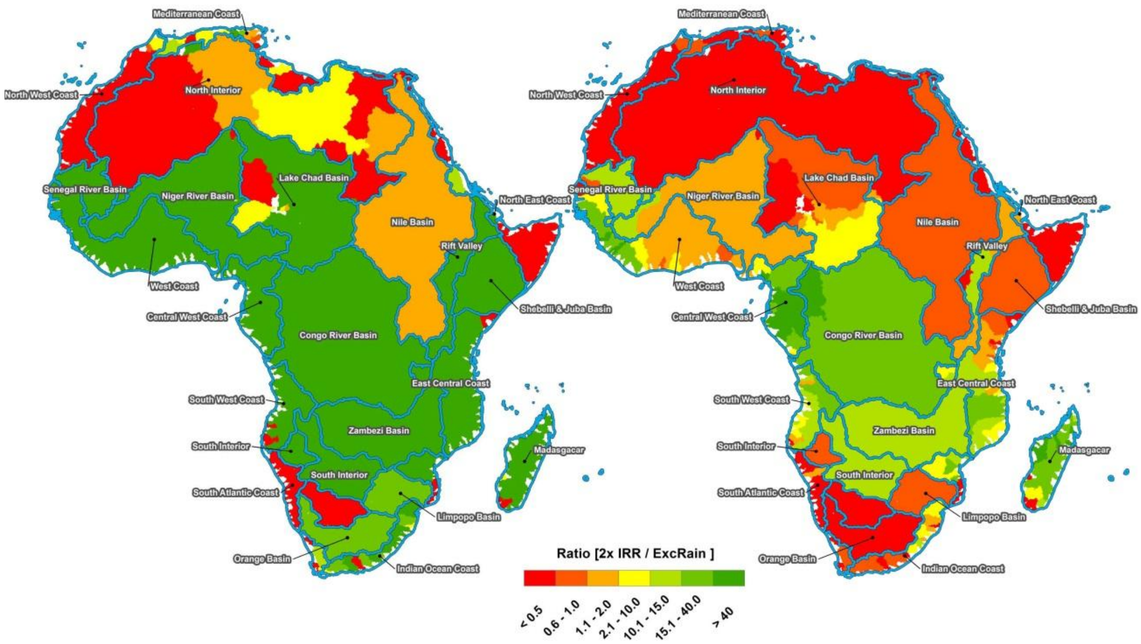
The potential yield and the calculated nitrogen and water requirements for some major crops are shown in Table 3. Maize yield can significantly increase both in North Africa and Sub-Saharan Africa, however with a significant increase of nitrogen application and water application, in particular in Sub-Saharan Africa. A similar outcome is predicted for all the other major crops (Table 3). Yield gap for maize is significantly larger in Sub-Saharan Africa than in North Africa.

Increasing crop production is feasible in Africa but clearly with increased economic costs associated with the purchase of nitrogen fertilizers, price of pumping, irrigation infrastructure, roads, etc. (Mueller et el., 2012) but also increased environmental costs such as additional water abstraction for irrigation. To evaluate the sustainability of the high production scenario (SC2), we calculated at river basin level (Jenness et al., 2007) the ratio between the river discharge at the outlet and twice the estimated amount of irrigation water. We used twice the crop water requirements to consider water required for salt leaching. River discharge was retrieved from Fekete et al. (2002).The ratio gives an indication about the availability of water to satisfy the irrigation requirements at the river basin level. A ratio lower than one indicates that more water than available at the watershed outlet is required to achieve the yield potential, leading to a depletion of water resources. The results for the baseline and the high production scenario are displayed in Figure 4.

Under current conditions, only a limited number of watersheds are under stress, mostly concentrated in North Africa, Ethiopia, South Africa and Namibia. The Nile River Basin has the highest volume of water use for irrigation and is characterized by a ratio of less than two, indicating some small potential to increase irrigation.

In the high production potential scenario the number of river basins with a ratio less than one increases considerably. The areas under water stress include all North Africa, the Nile river Basin, South Africa (South West Coast, Orange and Limpopo basins). Most of the basins in Central and South East

Figure 4. Ratio between the river discharge and irrigation water at river basin level for baseline scenario (left side) and high production scenario (right side).



part of Africa can meet the full potential production water requirements without depleting water resources. The Niger River Basin and the West Coast of Africa are characterized by ratios less than 2 and larger than 1 indicating that irrigation requirements can also be met. However, we did not include in our analysis other water requirements needed to sustain improved access to water, environmental flow, etc.

Consequently these basins might be at risk of water stress. In addition, under the high production scenario, increased nutrient losses to the environment can be expected. Indeed, we predict that in the high production scenario nitrate leaching to the aquifer will double, and losses of nitrate in surface runoff will be multiplied by 7, causing additional stress to the environment. A sustainable intensification of agriculture balancing the quality and quantity of water resources is feasible in Africa, without depleting soil resources while avoiding expansion of agriculture in natural ecosystems.

CONCLUSION

African agriculture is one of the least productive in the world because of the small extent of irrigated agriculture and in particular because of the low fertilizer use that is one-tenth of the world average. Consequently, the productivity gap between Africa and the rest of the world is continuing to rise. In this context African agriculture needs to shift towards a more productive but efficient and sustainable farming. Increasing crop production without agricultural expansion is suggested by many studies and authors as the most sustainable solution (Godfrey et al., 2010; Foley et al., 2011; Phalan et al., 2011; Hulme et al., 2013). However this requires the adoption of strategies and solutions that will not lead to environmental degradation. Using a newly developed and validated tool linking a GIS and the EPIC model we show that Africa has high potential to increase crop production in order to cope with the increasing demand. We show that in most African countries, the main limiting factor to crop production is nitrogen, while water limitation is more restricted to few countries. We also show that a mining of soil resources is taking place in many countries in Africa, with the uptake of nitrogen exceeding the inputs. We confirm that irrigation can substantially increase yield in water rich regions, and the lack of infrastructure does not allow countries such as those located along the Gulf of Guinea to reach high production levels. Access to fertilizer may not be enough to close yields gaps even in water rich regions and the adoption of water management strategies is required. On the other hand countries such as Northern African countries are mining water resources in many regions and an improved sustainable use of water resources will be needed, in particular to cope with climate change (drier and hotter climate). Clearly, these countries will be more vulnerable under climate change with reduced precipitation and increased temperature. We show that yield gap can be reduced through appropriate nutrient and water management, in particular in Sub-Saharan Africa where the yield gap is larger than in North Africa. However, optimized management strategies considering water availability and water quality are needed in view of a sustainable development. The link with tools such as GIS-EPIC with multi-criteria optimization approaches will play a key role in identifying optimal solutions considering several constraints including social, economic, and environmental factors. It can be expected that the growth in demand for agricultural commodities, driven by growth in population, per capita income and new demands for biofuel could be met in Africa through sustainable management.

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