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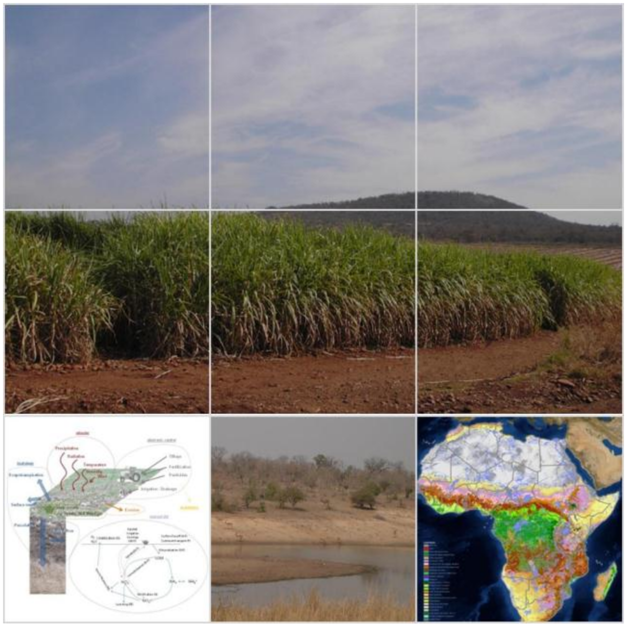
GISEPIC AFRICA: A modeling tool for assessing impacts of nutrient and water use in African agriculture

Database, Model and GIS System development
and testing

Marco Pastori, Fayçal Bouraoui, Alberto Aloe, Giovanni Bidoglio



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Contact information
Address:Faycal Bouraoui, JRC, TP 460, Via Fermi 2749, 21027 Ispra (VA), Italy
E-mail: faycal.bouraoui@jrc.ec.europa.eu
Tel.: 00 39 0332 785173
Fax: 00 39 0332 785601

http://ies.jrc.ec.europa.eu/
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1 Introduction

Nearly all of the population growth is expected to occur in the developing countries and all the projections suggest that market demand for food will continue to grow (population growth, higher standard of living, biofuels, etc.), requiring a general increase of food production by 70 % between 2005 and 2050 (FAO, 2009a). In this context food crop production in developing countries will have to almost double to adapt to the new needs. Furthermore, agriculture will have to adopt more efficient sustainable cropping methods to adapt to climate change. There is a wide agreement that African agriculture has enormous potential for growth thanks to its natural resources, i.e. land (for instance, 400 million ha of land in the Guinean Savannah have been estimated suitable for commercial farming and only 10 % of this land is actually cropped; Morris et al., 2009) and water. Indeed, food production is dominated by rain fed agriculture with only 6% of the cultivated area being irrigated, area mostly concentrated in five countries (You et al., 2010) Increasing irrigation potential could increase agricultural production by at least 50% (You et al., 2010). Lack of fertilization is a major obstacle to higher yield crop production. About 75% of Africa’s agricultural land is degraded and nutrient depletion is a major problem. The application rate of fertilizer is around 20 kg/ha, low compared to the 73 kg/h in South America, 135 kg/ha in East and South East Asia and 206 kg/ha in the industrialized countries (Fleshman, 2006). Clearly, supplying right water and nutrients amount can bring crop yield to higher level in Africa, however possibly affecting the environment including drinking water, soil degradation, deforestation, biodiversity.

In this context, it is of utmost importance to have tools allowing to quickly assess the impact of these potential future agricultural development scenarios on the environment, and more specifically on water availability and water quality degradation. Biophysical models allow to perform reliable investigations on different management (and climatic) scenarios and strategies. However, they are mainly developed to be applied at point scale or site specific conditions. Spatialization of crop models is very powerful, but it needs to link different scales: the scale of the biophysical process simulated, the scale of available input datasets, the scale of required output data and the scale of validation data (Faivre et al., 2004; 2009). However, output aggregation can lead to errors in temporal and spatial scales (Hansen and Jones, 2000) and policy decisions and socio economic drivers not considered in the large scale data aggregation can locally influence farm management resulting in different yields and water-nutrient dynamics (Faivre et al., 2003, 2009). It is thus of critical importance to have tools that allow analysis at larger scale, while maintaining a high spatial and temporal resolution to take into account management options which are usually taken at local/regional scales.

Large efforts have been dedicated to link biophysical models and Geographic Information Systems (GIS). Such integration provides the opportunity to use these biophysical models at regional and continental scale, managing a large amount of geographical data allowing the assessment of the environmental impact of agriculture taking into account the soil, climate, and crop management spatial variability.

Different systems integrating crop growth models and GIS have been developed and applied at national and global scale with different purposes (Liu, 2009; Liu et al., 2007; Tan and Shibasaki, 2003; Stockle et al., 2003; Priya and Shibasaki, 2001 Ghile et al., 2008). In the case of African continent specific applications and studies were mainly developed focusing in the Sub-Saharan Area and on the food security issue in particular the latter is illustrated by the FOODSEC (EC-JRC MARS, 2011) project in which a crop yield forecasting system aiming at providing accurate and timely crop yield forecasts and crop production biomass was developed and applied in Eastern Africa. Applications available at continental scale are in general limited in the resolution of input datasets usually not highly detailed (larger than 50 km x 50 km) while more detailed applications are local and limited to specific regions or countries focusing on crop production and not considering the environment.

The aim of our study was to develop a high resolution GIS tool integrated with a biophysical model able of simulating impacts of nutrient and water limitation on crop production. We selected the biophysical model EPIC (Willians 1995) accounting for farming practices and operations, and for application rates and timing of fertilization and irrigation. EPIC has been thoroughly evaluated and applied from local to continental scale (Gassman et al., 2005) and used in global assessment (Liu et al., 2008; Liu, 2009). The model has been applied for irrigation scheduling assessment (Rinaldi, 2001; Wriedt et al. 2009), climate changes studies (Mearns et al., 1999), biofuels production and assessment (van der Velde et al., 2009). Such an integrated system was also applied successfully at European scale (Bouraoui and Aloe, 2007, Wriedt et al., 2009), laying the grounds for extending it to Africa.

The first part of the report will detail the development of a continental spatial geodatabase and its linkage with the EPIC model. In the second part we describe a validation of the system in a northern region in Africa. Then we illustrate an application of the integrated GIS system to assess environmental impact both in terms of water requirements and nutrient leaching of different crop management scenarios.

2 Material and methods

GISEPIC AFRICA is a GIS system integrating the biophysical continuous simulation model EPIC (Williams et al., 1995) with a SQL Server 2008 database that allows simulating nutrient and water cycling as affected by agriculture practices and crop growth at the African continental scale. The system is mainly composed by the following components: the EPIC model, the spatial geodatabase, the dll component and the GIS interface (Figure 1).

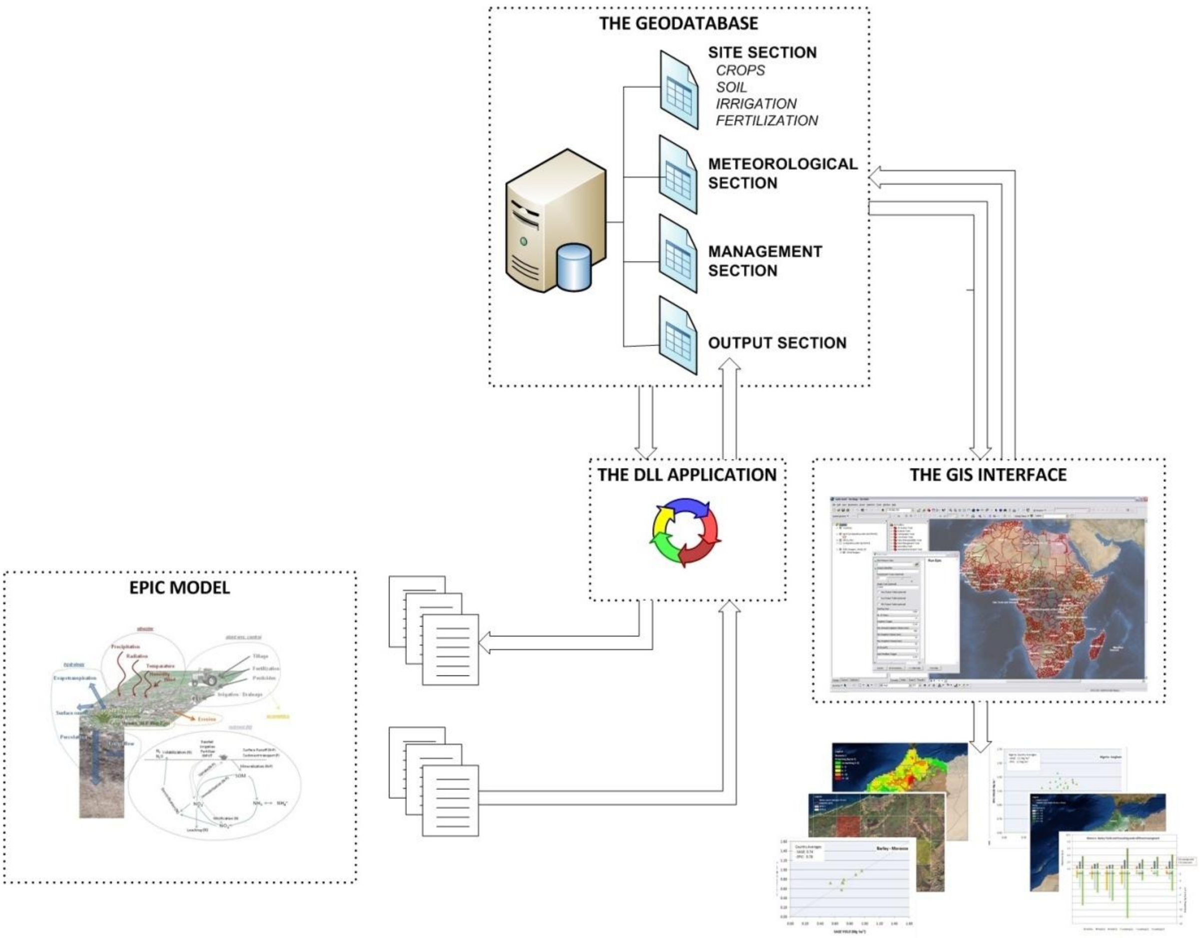


Figure 1.Structure of the GISEPIC AFRICA system.

2.1 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 timing of agrochemicals application, different tillage, crop types and varieties, 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, plant growth, tillage, plant environment control and economics. Complete and detailed information and description of each component are given by Williams et al. (1995), while in this paper only a brief description of crop growth and nutrients components is given.

2.1.1 Crop growth

A single model is used in EPIC for simulating all crops, both annual and perennial. Annual crops grow from planting to harvest or maturity date, while perennial crops maintain their root systems throughout the year. EPIC uses a daily time step to calculate crop potential growth. Maximum crop yield is based on the radiation use efficiency. The daily potential biomass increase is calculated as:

$$\Delta B_p = 0.001\ BEPAR \ [1]$$

where B_p is the potential biomass production (t/ha), BE is energy to biomass conversion parameter (kg/ha/MJ/m^2) function of atmospheric CO2 level, and PAR is the intercepted photosynthetic active radiation (MJ/m^2) estimated based on Beer's law as:

$$PAR = 0.5\ RA\ (1 - \ EXP^{-0.65\ LAI}) \ \ [2]$$

where RA is the solar radiation (MJ/m^2), and LAI is the leaf area index. LAI is calculated daily based on heat units. Heat units (HU) on a particular day are calculated during the phenological development of the crop as the average daily temperature in excess of the crop base temperature, and the heat unit index (HUI) estimated as the ratio of the cumulative heat unit divided by the potential heat units:

$$HU_i \ = \max(0, T_{av} - \ T_b); HUI_i = \ \frac{\sum_{k=1}^{i} HU_i}{PHU_j} \ \ [3]$$

Where T_{av} is the average daily temperature (°C), T_b is the base crop growth temperature (°C), *i* is the day, PHU is the potential heat unit for crop *j* (obtained as the sum of heat units from normal planting to maturity). The yield is calculated as the product of the harvest index and above ground biomass. The harvest index can however be reduced by water stress, or a shortened growing season and it is thus adjusted accordingly.

EPIC adjusts the daily potential growth by constraints including the influence of the following limiting factors: nutrients, water, temperature, aeration and radiation. These stresses can impact not only biomass production, but also root development and yield. A stress is estimated for each of the limiting factor and the actual stress is taken equal to the minimum stress calculated for each of the constraints (see Williams (1995) for more details).

2.1.2 Nutrients

EPIC takes into account nitrogen and phosphorus cycles. Five nitrogen pools are considered: active organic, stable organic, fresh organic, nitrate and ammonium pools.

Nitrate losses are related to the processes of leaching, runoff and lateral subsurface and are calculated as a function of flow volumes and nitrate average water concentration. All three process are calculated only for the first top layer, while for the lower layers only leaching and later flow are considered.

Denitrification is considered by the model as an exponential function of temperature, organic carbon, nitrate concentration and soil water content. Denitrification occurs only when the soil water content is 90% of saturation or greater.

The mineralization (transformation from organic to ammonia) is simulated with a modification of the PAPRAN mineralization model (Seligman and van Keulen, 1981): mineralization can be from fresh organic pool (associated with crop residue and microbial biomass) and from stable organic pool (associated with soil humus). Fresh organic mineralization is mainly governed by C:N and C:P ratios, soil water, temperature and the stage of residue decomposition. For the soil humus pool one stable and one active sub pools are considered and mineralization can occurs only from the active one as a function of organic N mass, soil water and temperature.

Like mineralization, immobilization is calculated with a modification of the PAPRAN model by subtracting the amount of N contained in the crop residue from the amount assimilated by the microorganisms.

Nitrification, the conversion of ammonia to nitrate is estimated with a first order kinetic rate (Reddy et al., 1979) and is a function of temperature, soil water content and soil pH. Volatilization, the loss of ammonia to the atmosphere, is simulated simultaneously with nitrification as a function of temperature and wind speed, while below surface volatilization is a function of cation exchange capacity and soil temperature.

Crop uptake is a very important process and is estimated using a supply and demand approach. Daily 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.

Fixation of N is important for leguminous crops and is estimated as a fraction of daily plant uptake. It is a function of soil nitrate and water contents and plant growth stage. It decreases linearly below 85% of field capacity to zero at wilting point. EPIC also consider the N contribution from rainfall, as a function of an average N concentration in the rain.

The cycling of organic P is similar to that described for nitrogen with mineralisation occurring from the fresh organic P and organic P associated with humus. Mineral P is divided into a labile P pool, an active mineral pool, and an inactive mineral pool. Fertiliser P is labile at application and then is transferred rapidly to the active mineral pool. The active and stable inorganic P pools are dynamic, and at equilibrium, the stable mineral P pool is assumed to be four times larger than the active mineral P pool (Sharpley and Williams, 1990).

2.2 The GEODATABASE

The geodatabase was developed to support the application of EPIC for the whole African Continent.

The most relevant characteristics of the geodatabase should be the following:

- it should collect all the data required for EPIC modelling (meteorological daily data, soil profile data, land use data with crop distribution and agriculture management data) and all necessary set of attributes required to simulate different strategies, management and scenarios;
- it should be based on a data model that stores geographic data (spatial database), allowing to reasonably represent different agro-ecosystems;
- it should have a wide geographic scope in order to allow EPIC simulations for Africa;
- it should be integrated with a tool allowing to access data, to modify the data, and to store the output of the model simulations.

Considering the available data resolution of required datasets (soil, land use and crop management were the most limiting factors) a reference spatial unit grid of 15 km x 15 km covering all the African territory was selected. The whole Africa was thus discretized into 135000 different grid cells. Each grid cell, representing the unit for simulation, is characterized by uniform topographic, soil and climate data.

This conceptual model is very useful because it allows performing EPIC simulations based on the mentioned subunits re-aggregating back the results to run unit level: the output in term of environmental and/or economic indicators can be aggregated and weighted in a single value taking into account crop area. All data were implemented into an object relational data model within the context of the ESRI ArcGIS geodatabase and in a Microsoft SQL Server 2008 environment.

2.2.1 SITE section

This is the core part of the data model as it contains the EPIC spatial simulation run units. These units were created in ArcGIS 9.3 using “Fishnet Tool”: the final vector grid is based on a projected space in Lambert Azimuthal Equal Area Projection and has a resolution of 15 km.

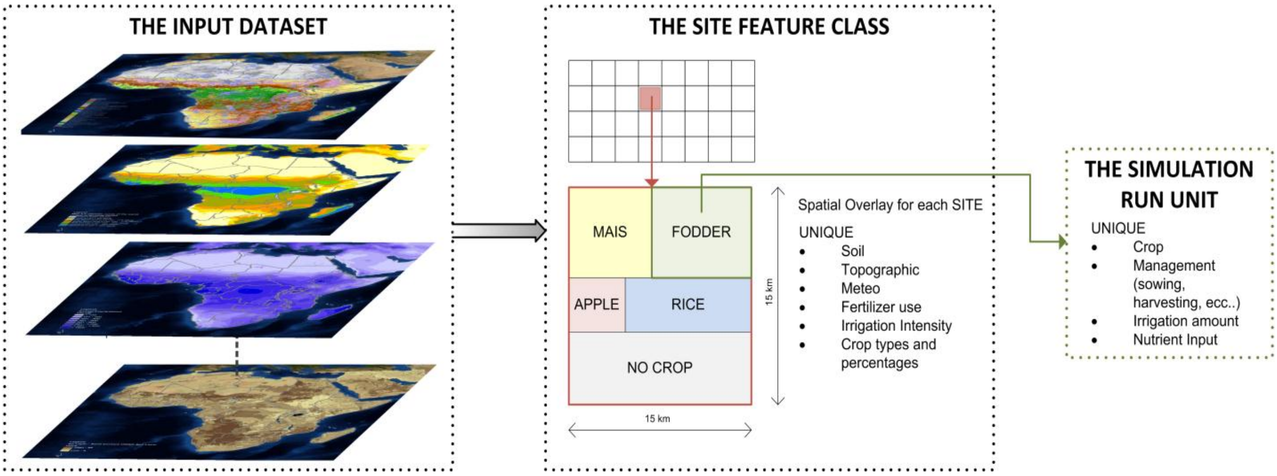


Figure 2. SITE and simulation unit definition

SITE spatial units are characterized by uniform soil, meteorological and topographic data and for each crop available in the SITE, the management (crop scheduling, soil tillage operations, irrigation practices, fertilization amounts) is also defined.

Soil and topographic data were aggregated to the SITE feature with a spatial analysis as described in the following sections while meteorological data were spatially linked to each site. Finally information on land use and crop distribution were aggregated to each site to obtain agriculture area and crop specific areas.

2.2.1.1 Soil Input

The Harmonized World Soil Database (HWSD) v.11 March 2009 (FAOc, 2009) was used to characterize the soils of the SITE units. The original datasets consists of an Access database and a GIS GRID layer with a resolution of about 1 km (30 arcsec). Over different 6988 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 soil a weighted average was calculated for each parameter required by EPIC considering the share of presence of the soil type in the SMU. For each parameter (Table 1) required by EPIC a weighted value was calculated by multiplying the value for the share of the unit and divided by the total share of the soil unit. The average values were finally aggregated to EPIC spatial unit SITE calculating the mean value using ESRI Spatial Analyst tool "Zonal Statistic as Table"resulting in a final soil attribute table with data aggregated at SITE level.

Table 1. Soil data required by GISEPIC Africa for both top and sub layers

FIELD NAME	DESCRIPTION	UNIT	SOURCE
Silt	Silt content	$\%_w$	HWSD v.11
Sand	Sand content	$\%_w$	HWSD v.11
Clay	Clay content	$\%_w$	HWSD v.11
pH	pH	-	HWSD v.11
OC	Organic carbon	$\%_w$	HWSD v.11
OM	Organic matter	$\%_w$	Calculated; [OM = OC * 1.714]
Gravel	Gravel content	$\%_{vol}$	HWSD v.11
CEC	Cation exchange capacity	cmol kg^{-1}	HWSD v.11
$CaCO_3$	Carbonate content	$\%_w$	HWSD v.11
Bd	Bulk density	kg dm^{-3}	HWSD v.11
Ks	Saturated conductivity	mm h^{-1}	Calculated; [$Ks = Exp(7.755 + 0.0352*Silt + 0.93– 0.967*Bd^2 – 0.000484*Clay^2 – 0.000322*Silt^2 + 0.001/Silt –0.0748/0M – 0.643*Ln(Silt) - 0.01398*Bd*Clay –0.1673*Bd*OM + 0.02986*Clay – 0.03305*Silt)$ (Wösten et al. (1999))]

2.2.1.2 DEM

A global digital elevation model (DEM) with a horizontal grid spacing of 30 arc seconds (FAOd, 2009) was processed to obtain elevation and slope within SITE units.

2.2.1.3 Crop input

The SAGE crop dataset was selected (Monfreda et al., 2008) in order to derive a complete land use dataset for all African countries. SAGE dataset 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 grid data, stored in Netcdf format, were derived from agricultural and survey information on the areas and yields collected at the smallest political units available for all the countries (sub-national data are generally one or two administrative levels below the national and when not available data are referred to FAO national statistics).

Input land use Netcdf layers were imported into ArcGIS and spatially overlayed and tabulated against SITE units feature class to obtain area of each crop as a SITE (15 km) attribute. A Pyton Script was developed to facilitate the procedure of overlay of the 175 crops layers, ad to derive a unique table with grid code and a list of all crops with areas and yield data. Finally the resulting attribute table was processed into SQL Server to simplify the high number of crops grouping them into a list of 46 crops already available in default EPIC database.

2.2.2 Meteorological section

EPIC retrieves the required weather information from a dedicated meteorological global dataset storing global daily resolution data and required monthly statistics.

Two different datasets were used to derive the data:

- The Princeton University (Department of Civil and Environmental Engineering) Global Meteorological Forcing Dataset for Land Surface Modeling (Sheffield. et al., 2006). This is a global, 50-year, dataset of meteorological forcings, that can be used to drive models of land surface hydrology. The dataset is constructed by combining a suite of global observation-based datasets with the NCEP/NCAR reanalysis. The dataset has a grid format with a resolution of 1° and covering the entire globe (360 x 180 Longitude/Latitude). The temporal range is between 1-1-1948 to 31-12-2006;
- CRU monthly dataset for the period 1961-2006 (New et al., 2002). This is a global dataset in a GRID format with a resolution of 10´ latitude/longitude of mean monthly variation in climate. It includes 8 climate variables (precipitation, wet-day frequency, temperature, diurnal temperature range, relative humidity, sunshine duration, ground frost frequency and wind

speed). This dataset has been used to downscale the daily data collected in the Princeton University to a 10' grid.

The original climatic data were pre-processed in order to satisfy EPIC modelling needs. All data were imported in a specific SQL SERVER 2008 database system. Daily meteorological datasets were then derived downscaling the original 1 degree resolution daily data to a 10 minutes daily dataset by means of the more detailed monthly statistics from the CRU dataset. The final table stores all daily series starting from 1965 to 2006 with all parameters required by EPIC. Meteorological monthly statistics are then directly calculated with specific functions in the SQL server 2008 and dynamically saved for EPIC runs.

2.2.3 Crop Management section

Crop management practices data are one of the most important input required for EPIC modelling. They consist of detailed schedules and characteristics of the most common crop operations (sowing, harvesting, tillage, fertilisation, irrigation, etc.) for each crop used for EPIC simulations. It was not possible to obtain all management detailed information at a relevant resolution (15km) for the entire African territory. However, management practices can be reasonably considered homogenous at sub national administrative units. For this reason polygons provided by FAO (SubNational Administrative linear boundaries Level 2 and 3, FAOd 2009) were processed and aggregated in order to have a more uniform area extension of each polygon for all African continent and were considered as the reference level for crop management when no detailed data was available at the SITE level. The final polygonal data was stored into a feature class (NUT – National Uniform Unit Territories), containing 1061 polygons (mean area is 7100km^2) covering Africa.

Water management was defined at SITE level because of the availability of high resolution data as described in the following section, while fertilization data and scheduling dates were defined at NUT level. A flowchart of the crop management section is illustrated in Figure 3.

Figure 3.Geodatabase management section data model.

2.2.3.1 Water Management

The latest version of the global map of irrigated areas from FAO (Siebert et al., 2005, 2006 and 2007) was used as the main reference to identify the area where irrigation has to be considered in the EPIC simulations. This map was used because it has a resolution of 5´ that is compatible with the SITE units dimension and it is related with FAO data statistics that are the main source data also for crop area and distribution. Irrigation reports from FAO were used to identify crops or groups of crops that are irrigated in different countries (FAOe, 2009). When some discrepancies with reported data from FAO map were observed, the Global Irrigated Area Map of the World map (Thenkabail et al., 2008) was used to provide missing data. The Global Irrigated Area Map of the World is a map 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., 2008 for details). The final product is a 10 km resolution map with 28 classes covering the entire globe. Finally, irrigation reports from FAO (FAOf, 2009) were mainly used to identify crops or groups of crops that are irrigated in different countries. Other information was available from other FAO statistic database (FAOf, 2009).

A table was designed in the database to store all the required information: presence or not of irrigation, which crops are actually irrigated, the relative percentage of irrigated area (crop selective irrigation) and the maximum amount of water that can be applied.

2.2.3.2 Fertilizer management

Fertilization input data were derived from the FAO FERTISTAT database and integrated with other fertilizer total consumption datasets when required (IFA, 2009). Fertilization data are available at country level and and for this reason it was not possible to differentiate the various NUTS. Available nutrient statistics differentiate nitrogen and other nutrient use for main crops in each country: nitrogen is normally expressed in kg ha^{-1} of cropped area.

For each country it was defined which crops are fertilized and which is the maximum fertilizer (only for nitrogen) amount by year. In many cases fertilization data are not available for all the crops used in a country and in some isolated case the data are not available at all. Furthermore, all these data are reported annually at country level thus do not allow differentiating fertilization at more detailed level. For this reason the following methodology was adopted to derive a complete and more detailed fertilization database:

1. Average annual nitrogen fertilizer consumption data were collected for all countries
2. Annual yields and harvested areas were collected for each crop, for each country and for each NUTS
3. Total reported use of nitrogen was divided for each country and for each NUT considering crop yields, harvested areas and nitrogen content in the crops (see Figure 4)

The total nitrogen amount (total nitrogen consumption in the country derived from FAO resources statistic data and IFA statistics) was divided and weighted for each country and for each NUT considering reported crop yields, crop harvested areas and reference nitrogen content in the crop (Table 2). With this approach we were thus able to evaluate which crops were fertilized and the amount of applied fertilizer per crop.

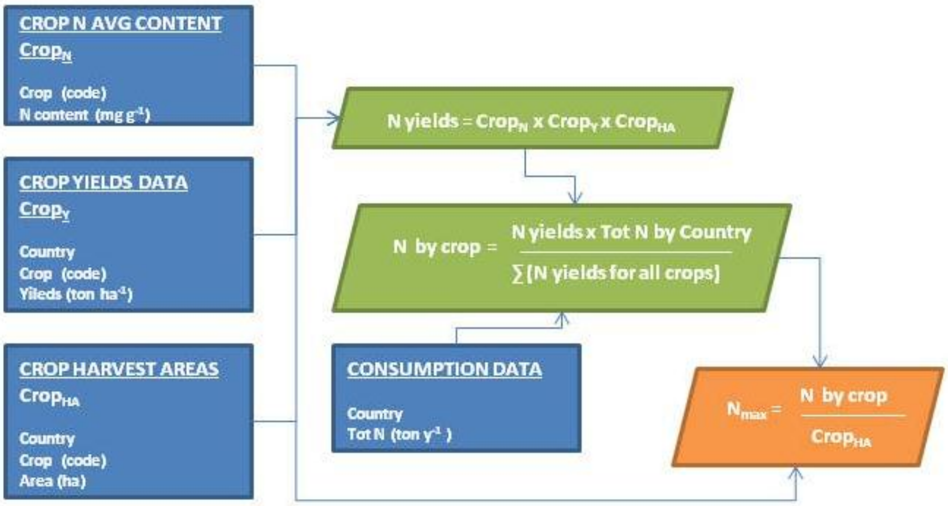


Figure 4. Scheme of methodology to derive missing data for fertilizer input by crop for each country

EPIC CROP	NAME	Harvest N content ($g\ kg^{-1}$)	EPIC CROP	NAME	Harvest N content ($g\ kg^{-1}$)
ALFA	Alfaalfa	22	PEPR	Pepper	4
ALMD	Almond	1	PMIL	Millet	15
APPL	Apple	1	PNUT	Peanuts	2.2
BANA	Banana	2	POTA	Potato	4
BARL	Barley	17	RICE	Rice	13
CANA	Oil plants	33	RYE	Rye	19
CASS	Cassava	2	SGBT	Sugarbeet	2
CHKP	ChickPeas	35	SGHY	Sorghum	15
CITR	Citrus	1	SGUM	Gum tree	1
CLVR	Clover	15	SOYB	Soybeen	35
COFF	Coffee	24	SPOT	Sweet potato	3
CORN	Mazie	14	SUGC	Sugar cane	1.2
COTS	Cotton	24	SUNF	Sunflower	34
COWP	Cowpea	35	SWHT	Soft Wheat	16
CSIL	Mazie for silage	4	TOBC	Tobacco	13
CUCM	Cucumbers	2	TOMA	Tomato	3
FLAX	Flax	30	WMEL	Watermelon	2
GRAP	Grape	1	WWHT	Winter wheat	19
GRBN	Greenbeen	35	YAM	Yam	3
LENT	Lentils	35			
LETT	Lettuce	2.3			
OATS	Oats	16			
OILP	Oilpalms	15			
OLIV	Olive	1			
ONIO	Onion	2			
OOIL	Other oils	30			
OTHR	Other crops	8			

Table 2. Values of N content in the crop harvest use for N fertilizer repartition.

2.2.3.3 *Crop management scheduling dates*

It was not possible to obtain scheduling detailed information at a relevant resolution (15 km) for the entire Africa. For this reason a specific methodology was adopted to model management practices for all the 46 crops considered in the GISEPIC African database. Input data used to build crop management schedules include:

- polygons provided by FAO (SubNational Administrative linear boundaries Level 2 and 3, FAOd 2009),
- crop parameters and management data included in the model EPIC (Williams, 1995).

- crop scheduling information from different sources (USDA, 2009; FAOh, 2009; FAST Crop Yield Forecast, 2009; SAGE, 2009)

The first step in the methodology was the definition of the sowing dates, for each crop and site, based on the available information on crop growing period, typical harvesting time, meteorological factors and crop specific growth parameters. The definition of sowing date is a key factor because it affects all other management operations (tillage, irrigation, harvest, etc..). Two approaches were used to define sowing date:

- the potential heat units approach
- the rain limiting factor approach

The first approach considers the total number of heat units required to bring a plant to maturity using long term minimum/maximum temperatures, optimum and minimum plant growing temperatures and the average number of days for the plant to reach maturity. This approach is more functional in regions were temperature is the main limiting factor during the growing period

The specific tool "Potential Heat Units" program (PHU), developed at Texas Agricultural Experiment Station, was used. The heat unit theory states that plants have specific heat requirements that can be linked to the time to maturity. The portion of the average daily temperature that exceeds the plant's base temperature is the one contributing to plant growth. The heat unit (HU) for a given day can be expressed as follows:

$$PHU = \sum_{d}^{m}\left(T_{avg} - T_{b}\right) \; ; when\, T_{avg} > T_{b} [4]$$

where T_{avg} and T_b have been defined previously, and *d* and *m* identify the known time interval for the plant to reach maturity (sowing to harvesting period). It has to be noted that, for perennial crops, time to maturity interval is identified by using seasonal crop growing stages like budding and leaf senescence.

For each crop the following information was used as input for the PHU program:

- crop growing season (winter versus spring crop),
- base growing temperature (°C),
- optimum growing temperature (°C),
- dry down fraction,
- time to maturity (days) which corresponds to the number of days between planting and harvesting. This attribute is related to 5 climatic zones. Different growing time intervals are provided for each climatic zone.

The crop growing season, the base and optimum growing temperatures, and the dry down fraction were taken from the default values provided by the PHU and EPIC crop databases. Specific crop time to maturity intervals were estimated for each climatic region comparing different data sources [FAO website, National Country Reports, PECAD (USDA, 2009)]. Such information was then processed against each running unit (NUTS administrative units) where long term minimum/maximum temperatures are known. A Visual Basic program was used to batch process management units with the PHU program and write outputs to a database table. The program manages the entire process from PHU input preparation and PHU execution (via shell) to writing outputs (sowing dates and heat units) to a database table.

The original PHU program is mainly designed to work in the Northern Hemisphere because it starts to work (checking daily T_{avg}) from the 1st of January. This approach is not valid in Southern Africa because seasons occur in different times then in the Northern hemisphere. For this reason the PHU program application for the units belonging to the Southern Hemisphere was modified in order to start counting PHU from the 1st (Figure 5).

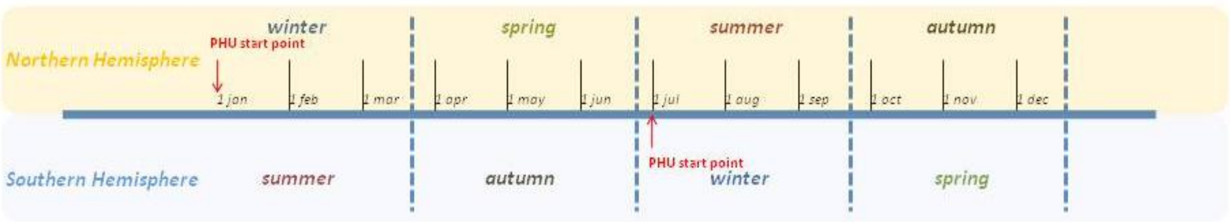


Figure 5. Different starting points for PHU calculation for sowing date estimation.

However, in the tropical - subtropical regions usually the main limiting factor governing crop sowing is the precipitation and consequently, the PHU approach is no longer valid. In these regions a rain limiting factor based approach was followed. This approach was originally developed at the Agriculture Hydrology Regional Centre in Niamey and applied in different studies (Rojas, 2005; Genovese, 2001). The sowing decade 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 this study 3 distinct thresholds were used according to different annual average rainfall (P_{year}):

- 10 mm for region with $P_{year}< 400$ mm
- 20 mm for region with $400 < P_{year}< 800$ mm
- 30 mm for region with $P_{year}> 800$ mm

An algorithm was developed to apply the method on a table stored in a SQL SERVER database.

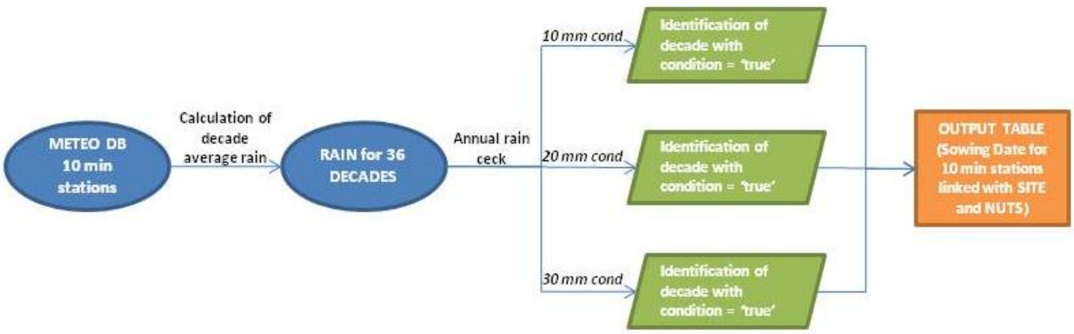


Figure 6.Scheme of Rain method application.

The method was applied using the 10´downscaled meteorological data (average for a single year). The function starts to cumulate the decade rain from the 1st decade (January) for the Northern Hemisphere and from the 19th decade for the Southern Hemisphere, stores the number of the first decade that satisfies the imposed condition into a temporary table and finally creates a new table with the right decade for each meteorological station. The meteorological station is linked with SITE Epic run unit and it was thus possible to estimate the sowing date for each national management unit.

This method is less precise then the PHU approach, because it does not take into consideration crop specific parameters (for example the PHU approach considers the reference base temperature that is different for each crop). Consequently, the sowing day is the same for each crop even though it does not correspond to reality. However, it can be considered a sufficient approximation for the application of the model a continental scale.

All derived data were compared with reported data (including crop calendar provided from FAO and USDA – FAS Crop Explorer service). These are general data in the format of monthly scheduling for different crops in the country; with in some case a differentiation within the country (for example for climatic reasons or for altitude constraints). In the following figure (Figure 7) some examples are reported for different countries where the different approaches were used (PHU and RAIN).

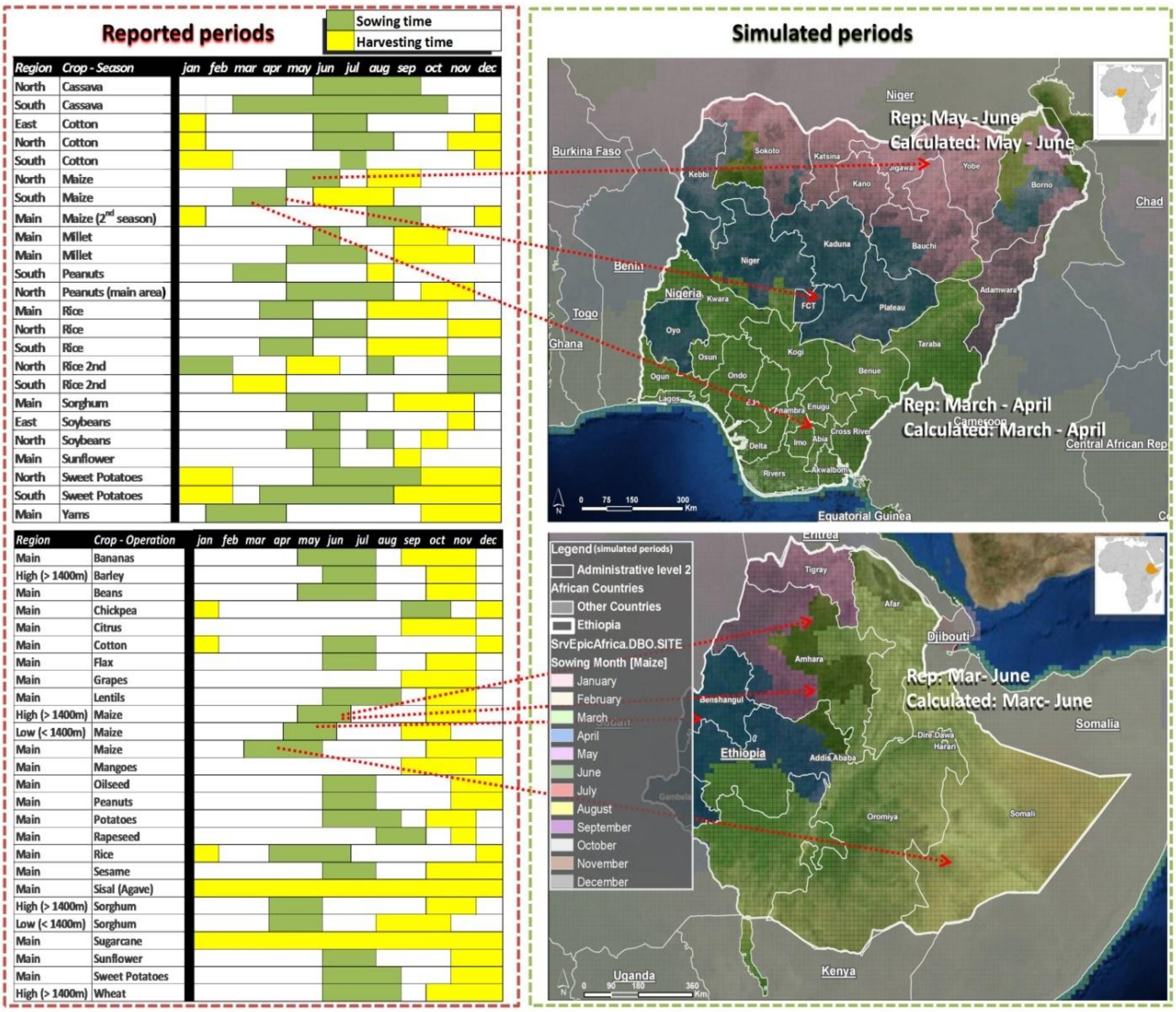


Figure 7. Comparison between maize sowing periods reported in FAO data and calculated (rain method).

Other relevant crop operation schedules were then evaluated by relating them to the known sowing/planting dates. The following simple schema was adopted:

- crop harvesting date: calculated by adding the climatic region specific time to maturity to the sowing date,
- crop killing date: calculated as harvesting date + 1 day. This is the physical removal of the crop from the field,
- crop tillage date: applied on sowing date -3 days,
- irrigation date: when irrigation is active the automatic scheduling EPIC option is used. This model schedules automatically the irrigation and the amount applied is calculated according to daily plant water stress. Different parameters can be used to control the irrigation scheduling and to parameterize the irrigation according to regional and local practices. In our application the maximum total volume by year and also the type of irrigation (furrow or sprinkler) and the time between different water applications are defined for each SITE and for each crop as already described in the previous section.
- crop fertilisation: automatic EPIC fertilization scheduling is used: the model calculates the fertilization scheduling according to plant nitrogen stress level. The maximum nitrogen fertilizer is defined annually (expressed as kg N ha^{-1}) for each SITE and for each crop and also the minimum time between single applications is defined at SITE level.

2.2.4 Ouput section

The purpose of this section is to store results of EPIC modelling for a particular study area. It includes a summary output table (EPICSUM table) and a table storing occurred error logs (EPICLOG table) and optionally (following user needs) more detailed output tables at annual, monthly scale (Table 3). More specifically four options are available:

- Standard output: with only summary data;

- Annual output: with summary files and single years summary data;
- Crop annual yields: with the previous plus a specific yearly output for crop yields;
- Monthly output: with all the previous plus monthly summary data.

Table 3.Subset of output parameters available for modelling results analysis.

OUT_CODE	***FIELD DESCRIPTION***	***UNIT***	***SUM***	***ANN***	***CROP***	***MONTHLY***
PRCP	Rainfall	mm	☑	☑		
PET	Potential ET	mm	☑	☑		☑
Q	Runoff	mm	☑	☑		
SSF	Subsurface flow	mm	☑	☑		
PRK	Percolation	mm	☑	☑		☑
NMN	Net Mineralization	kg ha^{-1}	☑			
NFIX	Nitrogen fixation	kg ha^{-1}	☑			
NITR	Nitrification	kg ha^{-1}	☑			
AVOL	N Volatilization	kg ha^{-1}	☑			
DN	Denitrification	kg ha^{-1}	☑			
MNP	P mineralization	kg ha^{-1}	☑			
YON / YP / YOC	N_{loss}/ P_{loss}/ OC_{loss} Sediment	t ha^{-1}	☑	☑		☑
QNO3	$NO_{3\ loss}$ in Runoff	kg ha^{-1}	☑			☑
SSFN	$NO_{3\ loss}$ in Subs. Flow	kg ha^{-1}	☑			☑
PRKN / PRKP	$NO_{3\ loss}$/ P_{loss} in Leaching	kg ha^{-1}	☑	☑		☑
YLDG/YLDF	Yield Grain/Forgae	t ha^{-1}	☑		☑	
BIOM	Biomass	t ha^{-1}	☑		☑	
YLN/P	Yield Nitrogen/ Phosphorus	kg ha^{-1}	☑		☑	
FTN/P	N/P Applied	kg ha^{-1}	☑		☑	
IRGA	Irrigation	mm	☑		☑	☑
FNO / FNO3 / FNH3	Fertilizer organic / nitrate / ammonia	kg ha^{-1}		☑		
FPO / FPL	Fertilizer organic / labile P	kg ha^{-1}		☑		
TS	Temp stress	days	☑		☑	
WS	Water stress	days	☑		☑	

OUT_CODE	*FIELD DESCRIPTION*	*UNIT*	*SUM*	*ANN*	*CROP*	*MONTHLY*
NS	N stress	days	☑		☑	
PS	P stress	days			☑	
KS	K stress	days			☑	
TMP	Soil t	°C				☑
USLE	USLE erosion	t ha^{-1}		☑		☑
MUSS	MUSS erosion	t ha^{-1}		☑		
MUST	MUST erosion	t ha^{-1}		☑		
MUSL	MUSLE erosion	t ha^{-1}				☑
MUSS	MUSS erosion	t ha^{-1}	☑	☑		

2.3 The GIS interface

The GIS interface developed allows running the model spatially with the African geodatabase in 3 different ways:

- standard configuration control working as an ArcGIS toolbar
- as a specific toolbox that allows to configure the model setting directly inside ArcGIS environment
- externally of ArcGIS by means of scripts written in the Python scripting language (Python 2010) that allow simulation customizing and batch operations.

Inside ArcGIS system it is possible to select specific regions, areas and single or groups of sites to perform specific simulations. It is then possible both inside the ArcGIS environment and externally to configure the simulations in order to change input / output data to build up and analyze different scenarios (Figure 8).

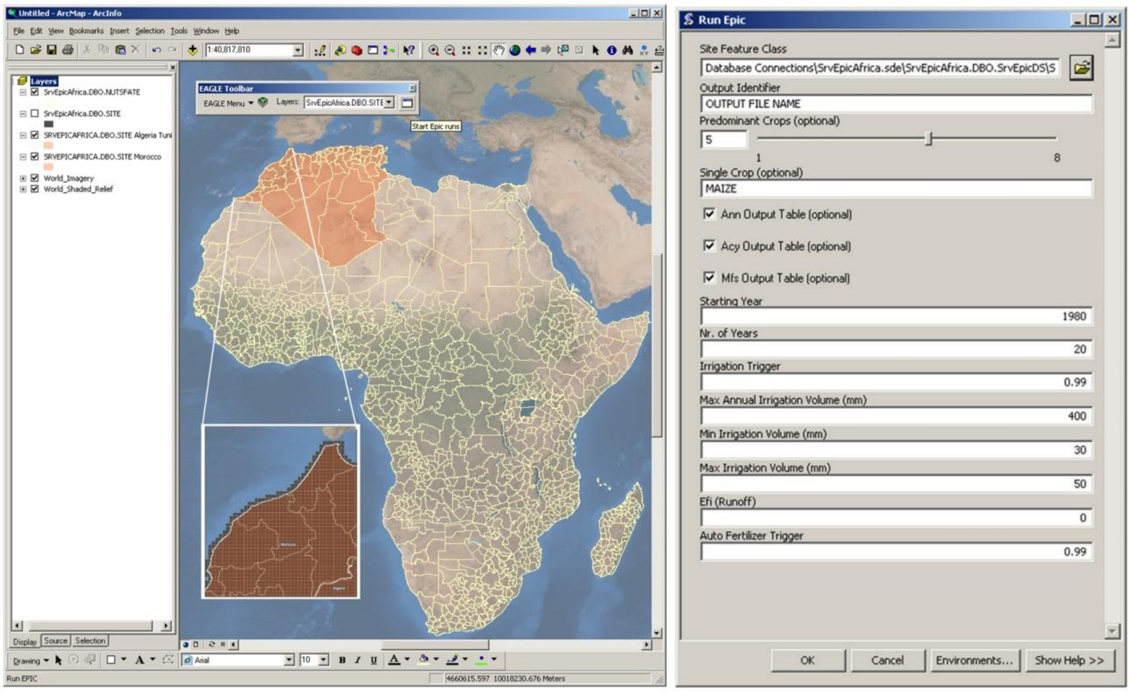


Figure 8. The GIS Interface

3 Applying GISEPIC AFRICA

3.1 Northern Africa case study

In this case study the GISEPIC AFRICA was applied with the main objective of assessing water and nutrient requirements in Morocco, Tunisia and Algeria, which, all together, account for more than 80 % of agriculture land in the Northern Africa. Wheat, barley olive and maize were considered in the application as they account for about 80% of the total harvested area in these countries in the year 2000 (Table 4)

Table 4.Main crops cultivated in Algeria, Morocco and Tunisia (FAOSTAT – 2000)

Main Group	***Cereals***		***Oilcrops***		***Pulses***		***Fruits***		***Others***	
	ha	***%***	***ha***	***%***	***ha***	***%***	***ha***	***%***	***ha***	***%***
Tot Area harvest	7642820	62	2200177	18	520870	4	774357	6	1174163	10
Main crops	***crop***	***%***	***crop***	***%***	***crop***	***%***	***crop***	***%***		
Tot Area harvest	*Wheat*	36.0	*Olive*	17	*Beans*	1.9	Citrus	1.4		
	Barley	23.0								
	Maize	2.3								

The validation was rather difficult since there are not high-resolution measured data comparable with the high-resolution output results units of our study. Furthermore, the only measured data readily available for all the African continent is crop yield, while detailed data on nutrient balance are scarcely available. The comparison at the level of EPIC run units (15 km x 15 km) was then not possible. For this reason the system was validated at the regional level using statistical average yields from FAO statistics (crop uptake is one the main component of water and nutrient cycles). This provides a good level of validation considering that the aim of the system is to be a support tool at policy and decision making level. It is further important to stress that most continental scale studies usually limit the validation exercise at the country level. 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 model validation because of their better resolution (sub-national) respect to Country data. Original SAGE grids are available at a resolution of 5 minutes but they result from a spatial disaggregation based on a crop land use map (Ramankutty et al., 2008) of national and sub-national statistics (see Monfreda et al., 2008 for the methodological details).

3.1.1 Results

The model was used with no calibration and the default parameters were kept unchanged. The comparison between the predicted and reported yield for the crops considered in the study is shown in Figure 9. The simulated and the reported yields compare well, even if the results tend to be better for some crops respect to others. In particular barley, wheat and maize are quite well simulated (R2 value is around 0.6 for barley and 0.5 for wheat and 0.8 for maize). For the olive there are some discrepancies mainly in Tunisia (the R2 value is about 0.4, but considering only Algeria and Morocco the value is around 0.7). These coefficients of correlation are rather high considering that no calibration was performed and the model was run using the defaults parameters and settings. It should be also considered that the reported sub-regional yields are referred to a specific year (2000) while the model was run for a period of 20 years starting from 1980 to 2000 and the model output yield displayed is an average of all simulated years.

The average yields at country level are also well estimated (Table 5).

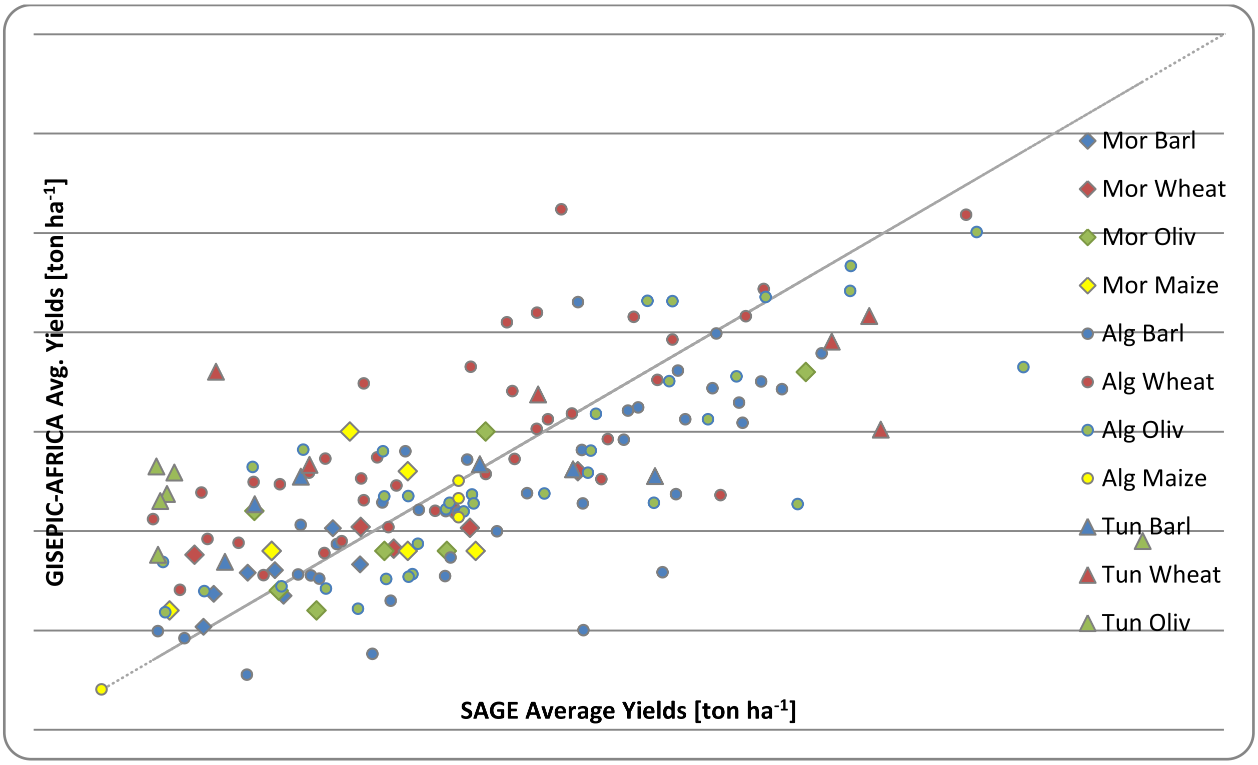


Figure 9. Comparison between simulated yields and sub-regional statistical yields in Algeria, Morocco and Tunisia for barley, wheat, olive and maize.

Table 5. Average country crops yields in Algeria, Morocco and Tunisia according to EPIC and SAGE.

Crop	***Algeria***		***Morocco***		***Tunisia***	
	Yield [ton ha^{-1}]		*Yield [ton ha^{-1}]*		*Yield [ton ha^{-1}]*	
	SAGE	***GISEPIC***	***SAGE***	***GISEPIC***	***SAGE***	***GISEPIC***
Wheat	1.3	1.5	1.0	1.0	1.7	1.7
Barley	1.5	1.2	0.7	0.8	1.1	1.2
Olive	1.4	1.3	1.1	1.1	0.9	1.1
Maize	1.8	1.4	0.9	1.0	-	-

3.1.2 Scenario analysis

Once validated, the model was then used to perform scenario analysis focusing mostly on nutrient and water management strategies. The sustainability of current agricultural practices was analyzed and different ways of increasing crop yield were investigated. Four different management scenarios of irrigation and fertilization strategies were assessed: the first scenario (S1) is the most conservative and is characterized by a rain fed agriculture with minimal fertilization set according to FAO data (20 kg ha^{-1} for Morocco and 60 kg ha^{-1} for Algeria in the case of maize and 20 kg ha^{-1} for Morocco and 90 kg ha^{-1} for Algeria and Tunisia in the case of wheat); the second scenario (S2) is characterized by the use of irrigation but with the actual fertilizer input; third scenario (S3) is the "high production potential" with no limitation (up to the maximum allowed application) for both fertilizers and irrigation; finally the scenario 4 (S4) is characterized by no irrigation at all with no fertilizer input limitation. As expected the scenario with no water-nutrients limitations is also the one with highest environmental impact on soil and water systems (Figure 10). It is interesting to note that the "Nord Ouest" region in Morocco has the highest maize production potential (compared to the actual one), but it is also characterized by one of the highest nitrogen leaching losses. Other regions, such as Oriental and Centre Nord in Morocco and Batna, Khenchela and Oum El Bouaghi in Algeria, show a good maize production potential by preserving at the same time the environment: in the most productive scenario the combined use of fertilization and irrigation allows crop to grow and to uptake a greater part of the nitrogen available in the soil thus preserving nitrogen leaching. In many regions an increase in the crop yield corresponds to a decrease of the nutrient losses in water leaching. This aspect is particularly evident in the scenario S4: this scenario is not so common but it is a good example to stress the importance of crop nutrient uptake by optimizing fertilizer application according to crop requirement and the available stock in the soil, in preserving water and soil quality. In this scenario the low amount of fertilizer used is mainly lost because crops cannot grow due to water limitation.

Analyzing the most productive scenario (S3) is quite clear that it corresponds to a more productive agriculture, but with additional economic and environmental costs. Indeed, the fertilizers required to reach the potential high yields is around 35000 tons of nitrogen fertilizers for maize only, which would account for 13 % of the current total consumption of nitrogen fertilizer in these countries (276000 ton/year according to FAO statistic for year 2002). The current use estimated for crop maize is instead only 5000 ton of nitrogen fertilizer that accounts for 1.8 % of total N fertilizer used in the studied area. Another issue to be considered is water: the optimal yield potential is reached with an intensive irrigation (the model applies the maximum allowed water for irrigation set to 400 mm y^{-1} in this study), because maize is a highly water demanding crop and this will significantly affect water withdrawal, causing extra economic and environmental impacts. Regionally, the nitrogen leached under these different maize cropping scenarios is generally not very high, ranging from 3.5 to 13.4 kg N-NO_3^- ha^{-1} (Table 7). There is an increase of the nitrogen leaching around 70% from the most conservative (S1) to the most productive (S3) scenario and around 380% from S2 to S3. The analysis of scenario S4 shows that the actual applications are almost optimal for rain fed maize (no significant change in total yield between S1 and S4), while for wheat there is an under application of nitrogen fertilizer and a doubling of the yield can be achieved in rain fed wheat with optimal application rates. The scenarios S2 and S3 highlight the importance of irrigation practices, which can lead not only to a more productive agriculture but in some case to a more sustainable production: the crop can grow without water stress and is thus able to efficiently uptake the nutrients available in the soil or added as fertilizer that are no longer available for leaching or losses with surface runoff.

In the case of wheat, differences between S1 and S2 scenarios are in general less evident probably because the crop is less sensitive to water stress and also since wheat is already quite productive (respect to its optimal potential) with actual management strategies. The importance of irrigation as a driver of agriculture efficiency is evident by the comparison of scenario S2 and S3 with the others. In the most productive scenarios wheat yields are comparable to those of Western Europe, however, with an increase by a factor of 3 of the nitrate leaching.

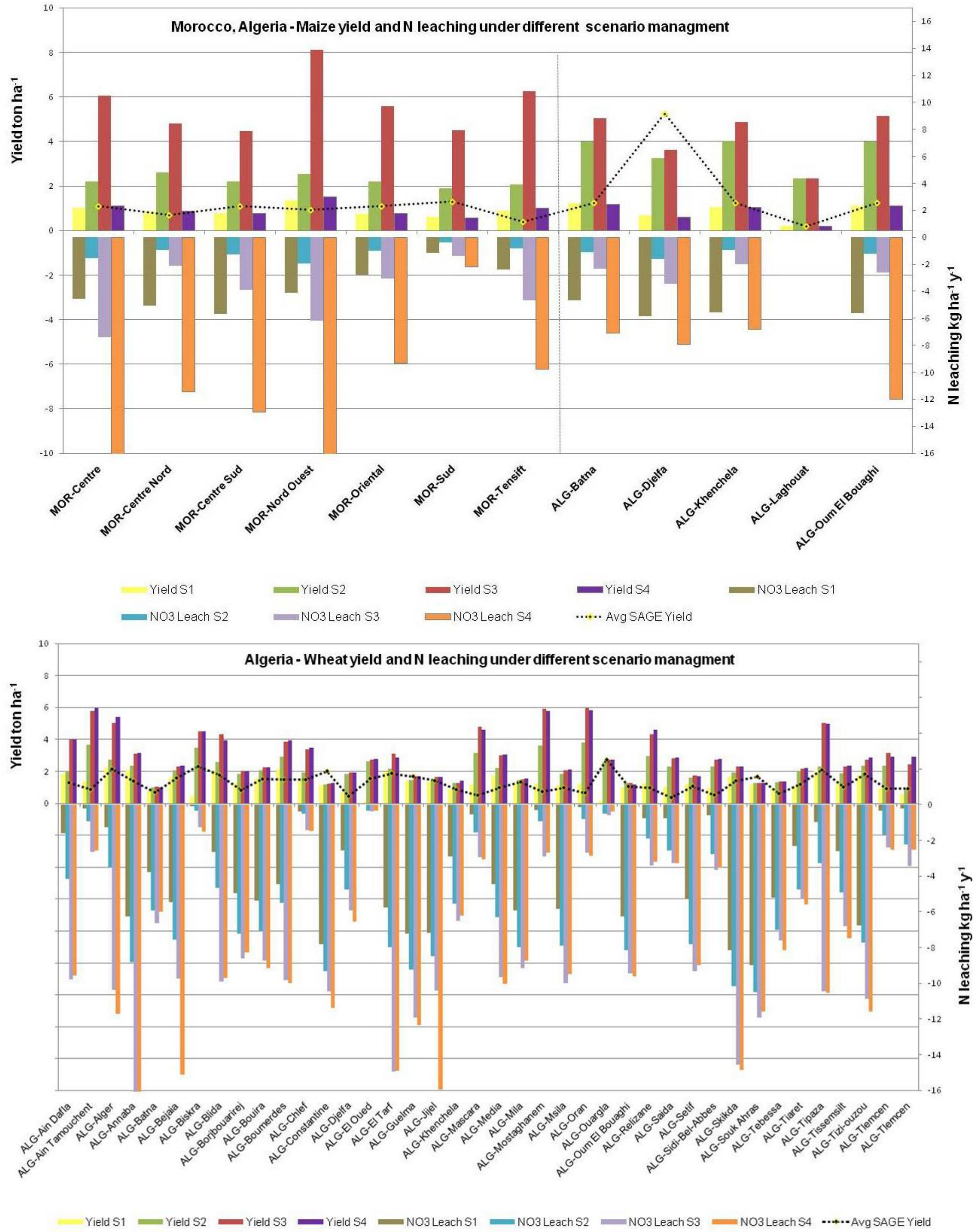


Figure 10. Comparison of corn yields and Nitrogen leaching under different management strategies in Morocco and Algeria main regions as simulated by EPIC.

Table 6. Comparison of maize yields and nitrogen leaching under different management strategies in Morocco and Algeria main regions.

Region	***Type***	***Unit***	***S1***	***S2***	***S3***	***S4***	***Relative change S1-S2***	***Relative change S1-S3***	***Relative change S1-S4***	***Relative change S3-S4***
Batna	Yield	ton ha^{-1}	1.2	4.0	5.0	1.2	232%	317%	-3%	-77%
	N Leach	kg ha^{-1}	4.7	1.1	2.3	7.1	-77%	-51%	51%	207%
Centre	Yield	ton ha^{-1}	1.0	2.2	6.1	1.1	115%	491%	9%	-82%
	Leach	ton ha^{-1}	4.6	1.6	7.4	17.6	-66%	62%	284%	137%
Centre Nord	Yield	ton ha^{-1}	0.9	2.6	4.8	0.9	204%	464%	2%	-82%
	Leach	ton ha^{-1}	5.1	0.9	2.1	11.4	-82%	-58%	126%	440%
Centre Sud	Yield	ton ha^{-1}	0.8	2.2	4.5	0.8	184%	474%	0%	-83%
	Leach	ton ha^{-1}	5.7	1.3	3.9	12.9	-77%	-32%	127%	232%
Djelfa	Yield	ton ha^{-1}	0.7	3.3	3.6	0.6	380%	434%	-11%	-83%
	Leach	ton ha^{-1}	5.9	1.6	3.4	7.9	-73%	-42%	36%	132%
Khenchela	Yield	ton ha^{-1}	1.1	4.0	4.9	1.0	281%	359%	-1%	-79%
	Leach	ton ha^{-1}	5.6	1.0	2.0	6.8	-83%	-64%	23%	240%
Laghouat	Yield	ton ha^{-1}	0.2	2.4	2.4	0.2	1075%	1075%	-5%	-92%
	Leach	ton ha^{-1}	0.0	0.0	0.0	0.0	-	-	-	-
Nord Ouest	Yield	ton ha^{-1}	1.3	2.5	8.1	1.5	89%	506%	13%	-81%
	Leach	ton ha^{-1}	4.1	1.9	6.2	16.1	-53%	49%	289%	161%
Oriental	Yield	ton ha^{-1}	0.8	2.2	5.6	0.8	193%	643%	4%	-86%
	Leach	ton ha^{-1}	2.8	1.0	3.1	9.3	-64%	11%	237%	204%
Oum El	Yield	ton ha^{-1}	1.1	4.0	5.2	1.1	250%	353%	-4%	-79%

Region	Type	Unit	S1	S2	S3	S4	Relative change S1-S2	Relative change S1-S3	Relative change S1-S4	Relative change S3-S4
Bouaghi	Leach	ton ha^{-1}	5.6	1.2	2.6	12.0	-79%	-54%	114%	362%
Sud	Yield	ton ha^{-1}	0.6	1.9	4.5	0.6	215%	641%	-5%	-87%
	Leach	ton ha^{-1}	1.1	0.4	1.4	2.2	-65%	23%	91%	56%
Tensift	Yield	ton ha^{-1}	0.9	2.1	6.3	1.0	134%	606%	12%	-84%
	Leach	ton ha^{-1}	2.4	0.8	4.7	9.8	-65%	96%	306%	108%

Table 7. Fertilization, yields and nitrogen leaching under the four simulated scenarios for maize and wheat cultivation.

REGIONAL RESULTS			Scenario			
			S1	S2	S3	S4
CROP	VAR.	UNIT				
Maize	N fert. input	ton y^{-1}	3.2	4.8	43.7	7.5
	N fert. avg	kg ha^{-1}	13.5	20.0	183.9	31.3
	Yield	10^3ton y^{-1}	229.0	514.0	1471.7	252.2
	Yield avg	ton ha^{-1}	1.0	2.2	6.2	1.1
	NO_3^- leaching	ton y^{-1}	0.8	0.3	1.4	3.2
	NO_3^- leaching	kg ha^{-1}	3.5	1.2	5.9	13.4
Wheat	N fert. input	ton y^{-1}	205.0	249.8	1058.5	508
	N fert. avg	kg ha^{-1}	43.2	52.6	223.1	107.1
	Yield	10^3 ton y^{-1}	5064.1	8806.4	23714.3	9942.1
	Yield avg	ton ha^{-1}	1.1	1.9	5.0	2.1
	NO_3^- leaching	ton y^{-1}	13.8	21.4	46.2	29.9
	NO_3^- leaching	kg ha^{-1}	2.9	4.5	9.7	6.3

3.2 Application of EPIC at continental scale

3.2.1 Introduction

In this application the system was used to perform an analysis at continental scale mainly focusing on nutrient and water management strategies. In order to analyze the whole African continent, no specific crop was considered, because each region is characterized by very specific agricultural use. The system was then applied by selecting for each SITE unit (15 km x 15 km) the 5 most dominant crops. Current crop production and agriculture sustainability was firstly assessed and in a second phase different ways (scenarios) of increasing crop yield production were investigated mainly focusing on their potential impact on water quality.

In order to show the results all over the African continent, the output parameters were averaged for the 5 most used crops in each SITE and for all the years simulated (1980-2006): the output values showed in tables and maps are the result of an average (respect to crop area) of different crops and different years.

It is important to stress that output data showed in this section should be considered preliminary, as the system was specifically validated for the Northern region of African continent, while other analysis are required at continental scale, which is characterized by different environmental conditions (climate, soils and crop management).

3.2.2 The actual scenario

The main factors limiting crop production under current agriculture practices and management in Africa are nutrient and water inputs. In order to study the importance of these two aspects and their distribution in Africa we applied two different and simple indexes. Considering nutrient aspect, we defined for each SITE a balance value calculated as the difference between the nitrogen input and the nitrogen uptake from the crop, defined as:

$$N\ index = FERT\ N_{model\ input} - N_{model\ crop\ uptake}$$

Under actual fertilization scenario according to model simulation only 11 countries have a positive or null nitrogen balance (Figure 11). Egypt, as expected, it is the country where the average balance value for the 5 dominant crops is higher (> 30 kg ha^{-1}); as said, the value is the average of 5 dominant crops, thus including also the non-fertilized ones (for example, clover, fodder, or some fruit trees). Other countries with a positive or balanced *N index* are Tunisia, Lybia, Liberia, Equatorial Guinea, Djibouti, Algeria, Botswana, Namibia and South Africa. A lot of countries show a negative balance and this aspect is critical as it means that crops are getting most of the nitrogen required for growing from the soils, potentially reducing soil nitrogen content and in general soil fertility.

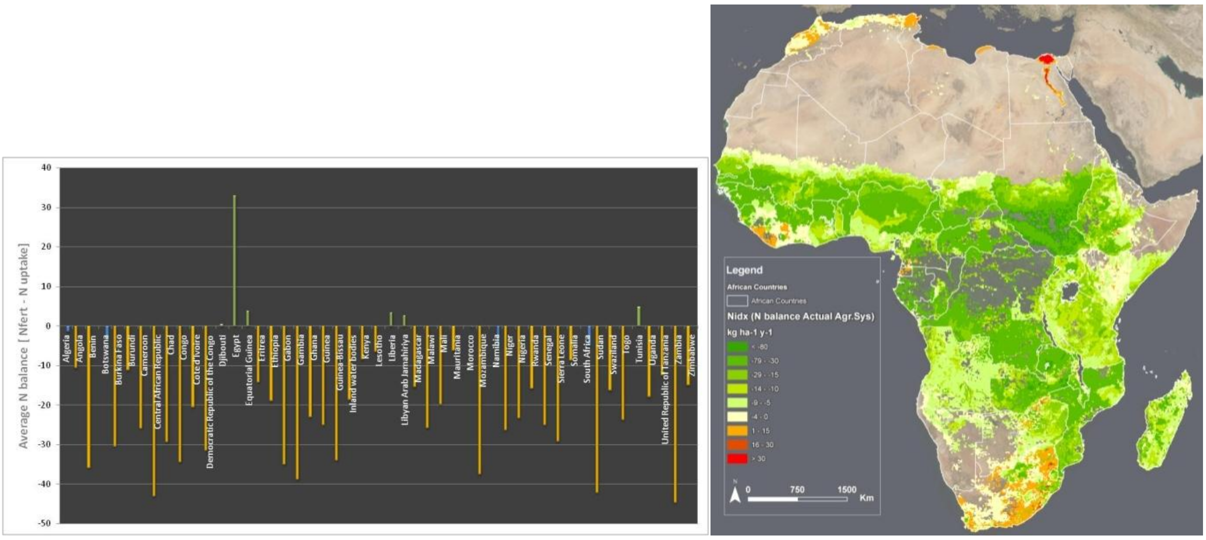


Figure 11. Nitrogen balance at country level under actual fertilization practices for 5 most diffused crops.

Beyond the nitrogen input another crucial aspect to be considered for crop production in Africa is irrigation. For example, 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. Furthermore, the Commission for Africa (2005) has called for doubling the investments on irrigation infrastructure and also NEPAD (2003) suggested a new irrigation strategy and water management in Africa as major instruments of economic and agriculture development. Furthermore, water availability is supposed to be also affected by climate change and it will be one of the first factor on which invest efforts to increase crop production in the next years.

In this context, GIS-EPIC AFRICA system allows to study new irrigation and water management strategies (increase efficiency, extend area under irrigation, higher volumes, etc.), their influence on crop yield, their potential impact on environment and also their real (economically) sustainability.

Increased irrigation use will probably lead to water consumption problems, at least in those countries where water scarcity is already an issue, and will possible cause higher impact on water quality (increase of nitrogen leaching, erosion, etc.).

In order to identify regions where water scarcity is a major issue, we used a simple index calculated from the difference between rainfall and actual evapotranspiration (AET). We used the average AET from the simulation of the 5 most diffused crops in each SITE.

As highlighted in Figure 12, the agricultural areas where water availability is more limited are mainly located in all of the Northern Africa, in the central Africa in the area closest to northern desert region, in the East Africa, and in Southern Africa, mainly in the North and South-East part.

More specifically, the countries with lower values for excess of rain are, in order of scarcity:

Somalia, Mauritania, Niger, Eritrea, Djiobouti, Botswana, Namibia, Lybia, Morocco, Egypt (negative value) and Algeria and Tunisia (positive value, but less than 10 mm of excess water).

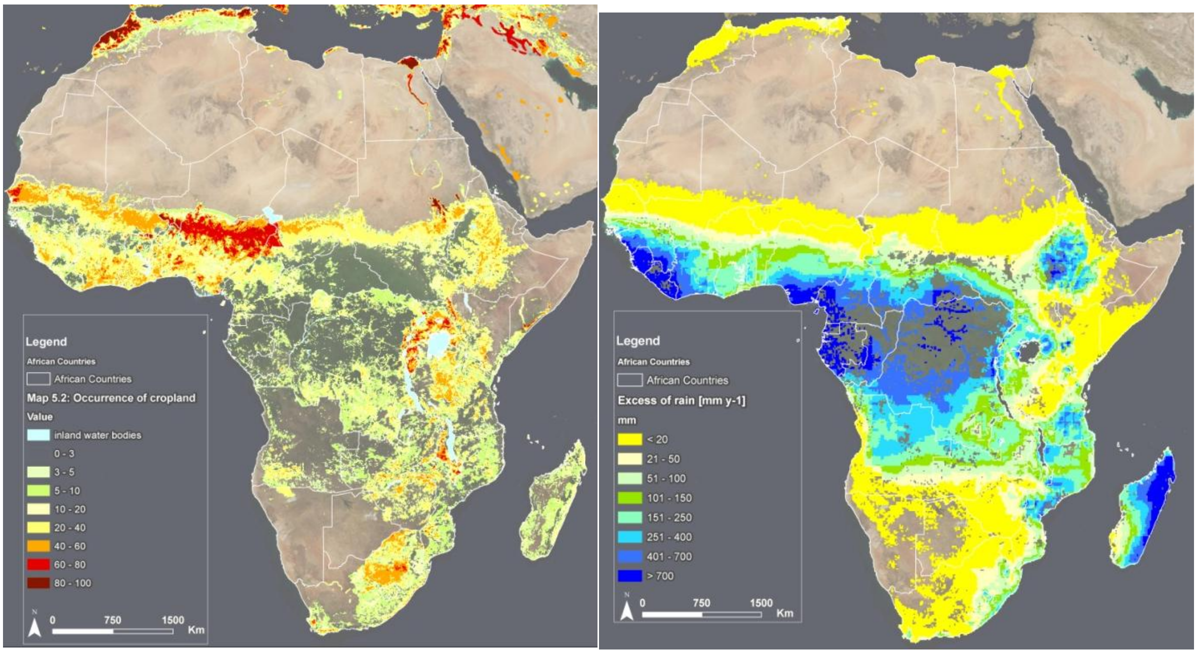


Figure 12. “Excess of rain” at SITE level considering average AET simulated and Rain.

The environmental impact associated with current and future agricultural production systems can be partially assessed considering nitrogen leaching, which is a potential source of contamination of groundwater or subsurface water, and with nitrogen loss in the surface runoff, a source of potential contamination of surface waters. As highlighted by the nitrogen and water indexes, current agriculture practices in many regions of Africa are characterized by very low use of fertilizer and water inputs, resulting in a low productive agriculture, but also in a minor environmental impact. The nitrogen leaching at country level is always less the 10 kg ha^{-1} in the year (Figure 13).

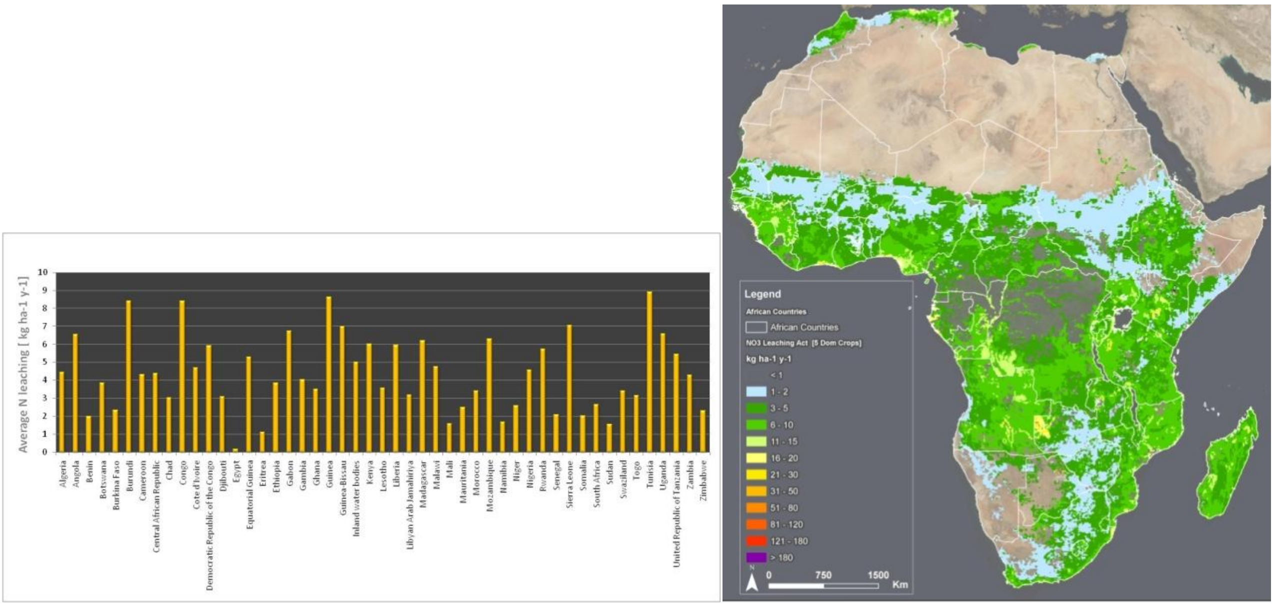


Figure 13. NO_3 leaching for current scenario in Africa.

This minor environmental impact is supposed to increase in the next years following an increase in the use of fertilizer and irrigation. As reported in the following section, GISEPIC AFRICA allows assessing this impact by simulating modified management scenarios.

3.2.1 Scenarios analysis

In this report we present an example application for two simple scenarios:

- SC1 - The optimal fertilization scenario: the GISEPIC AFRICA system was set to auto-fertilization, with no limit for nitrogen input. The irrigation management was not changed and it is set-up as the actual scenario. With this configuration the model will apply nitrogen in order to maximize the yield. This model set-up is a way to simulate the influence of a non-limited fertilization management under actual irrigation practices.

- SC2 - The potential scenario: this is intended to simulate the higher potential production of agriculture in Africa in order to assess the potential impact on water resources under maximum use of both fertilizers and irrigation.

The countries that showed the highest potential to increase the yield (Cote d'Ivoire, Swaziland, Togo, Ghana, Burkina Faso, Cameroon, Mozambique, Madagascar, Nigeria, United Republic of Tanzania, Mali, etc; see Table 8) are generally characterized by low fertilizer input and, as highlighted by the comparison between actual scenario and the “free fertilization” scenario (SC1), the main limiting factor for agriculture production can be identified in the nutrient fertilization. An important aspect to be considered is that also the increase of leaching in these more productive scenarios is quite important (100% and + 120% respectively for SC1 and SC2, see Table 8). Furthermore, it is possible to observe that in many countries the increase of leaching is much more evident in the scenario SC1, where no irrigation increment is introduced. In this scenario the addition of nitrogen fertilization to waters stressed crops may be less efficient and the new available nitrogen can be lost, because crop uptake is very limited. Another important aspect is that countries located in the tropical and sub-tropical climate show under the most productive scenarios the highest increase in the impact on water quality as both nitrogen leaching and nitrogen runoff losses are increasing. This is probably caused by the higher precipitation of these areas that, together with the increased irrigation practices, will increase the amounts of water leaching and runoff water.

Other countries, among which stand out Egypt, Djibouti, Sudan, Morocco, Tunisia, South Africa and Eritrea, are characterized by an agriculture production that seem mainly limited by water input: in these countries the yield increase under free fertilization scenario (S1) is generally limited (< 40%) while there is a much more important increment when irrigation is set-up as readily available.

All these aggregated data highlights the crop production potential of each region and allow to take into account water and nitrogen requirements (see Figure 16) and show an example of how to use the

GISEPIC system for scenario analysis and finally to find environmental sustainable solutions for more productive agriculture in the African region.

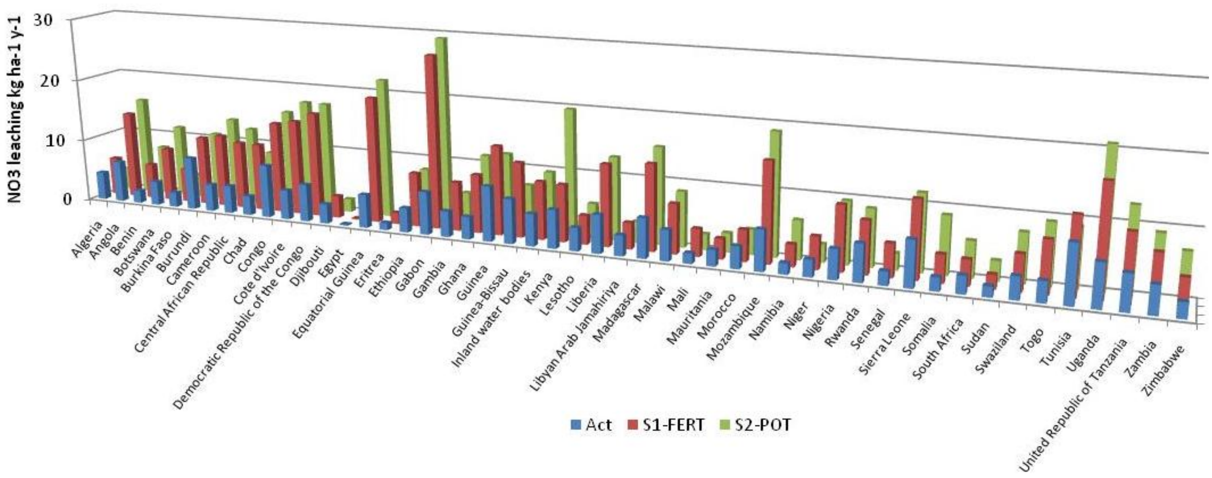


Figure 14. Comparison of Nitrogen leaching under different scenarios in the African Countries.

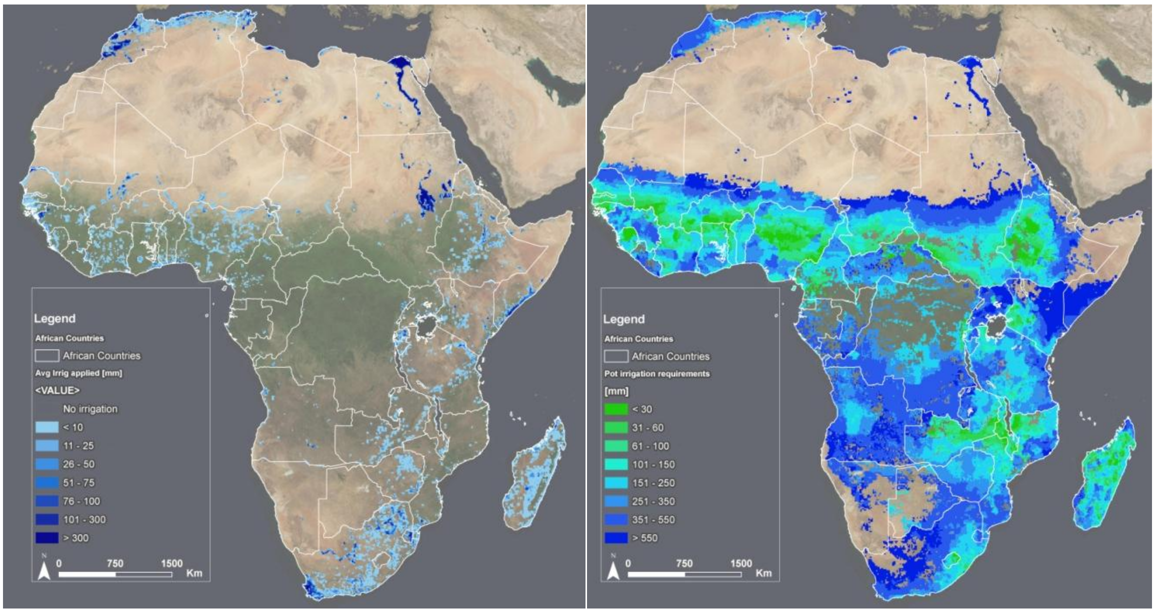
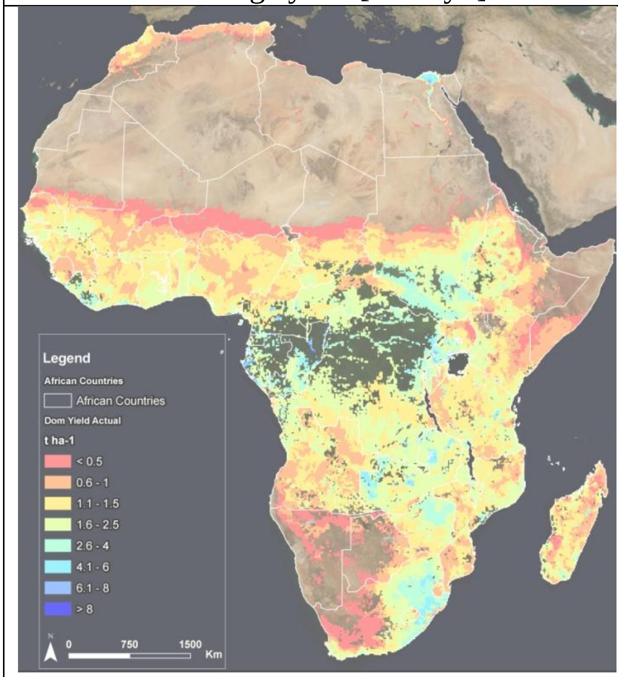


Figure 15.Actual and potential irrigation areas and average volumes applied under different scenarios (Actual and SC2) in Africa.

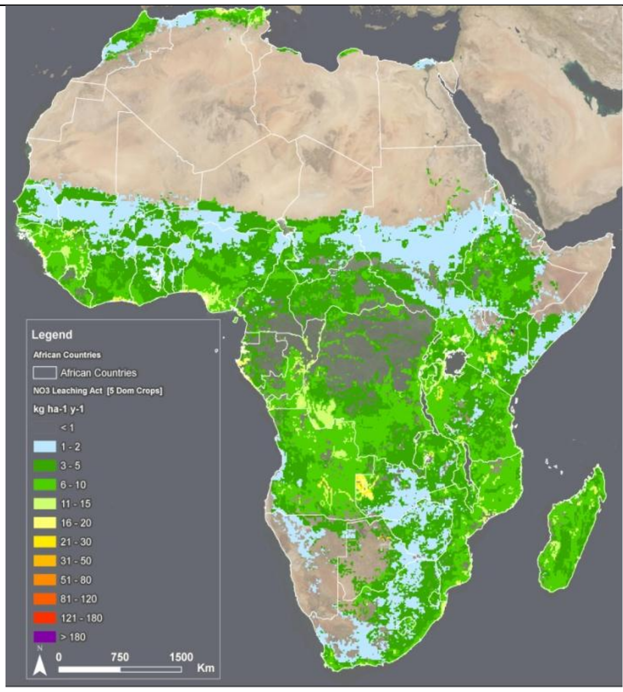
COUNTRY	Average yield relative change		Average leaching relative change		Main crop limitation	
	SC1-Actual	Diff SC2-SC1	Diff SC1-Actual	Diff SC2-SC1	N limited	Wat. Limited
Algeria	75	177	36	-42		x
Angola	195	60	112	12	x	
Benin	219	14	177	39	x	
Botswana	97	304	121	34		x
Burkina Faso	284	20	132	-32	x	
Burundi	79	131	31	-1		x
Cameroon	272	26	168	17	x	
Central African Republic	179	34	143	14	x	
Chad	195	34	250	-20	x	
Congo	49	39	72	8	x	x
Cote d'Ivoire	400	26	222	16	x	
Democratic Republic of the Congo	193	26	180	5	x	
Djibouti	1	1752	13	-41		x
Egypt	< 1%	97	0	4		x
Equatorial Guinea	206	11	275	11	x	
Eritrea	47	229	56	-34		x
Ethiopia	149	34	120	-3	x	
Gabon	169	22	303	7	x	
Gambia	71	7	90	-34	x	
Ghana	308	27	161	24	x	
Guinea	169	30	62	-15	x	
Guinea-Bissau	72	5	67	-38	x	
Inland water bodies	124	44	80	7	x	
Kenya	74	178	49	121		x
Lesotho	88	37	25	20	x	
Liberia	126	18	113	2	x	
Libyan Arab Jamahiriya	58	280	27	-21		x
Madagascar	264	25	117	13	x	
Malawi	141	9	62	12	x	
Mali	223	44	165	-43	x	
Mauritania	68	231	25	-6		x
Morocco	34	310	41	-20		x
Mozambique	268	37	145	22	x	
Namibia	153	343	102	76	x	x
Niger	170	121	91	-44	x	x
Nigeria	256	20	119	-4	x	
Rwanda	87	53	41	9		x
Senegal	134	36	142	-49	x	
Sierra Leone	166	15	68	0	x	
Somalia	190	287	107	109	x	x
South Africa	45	126	46	42		x
Sudan	19	47	34	43		x
Swaziland	364	45	60	37	x	
Togo	334	7	148	19	x	
Tunisia	40	102	31	-23		x
Uganda	147	117	153	25	x	x
United Republic of Tanzania	251	40	84	27	x	
Zambia	175	19	77	21	x	
Zimbabwe	76	89	96	55	x	x

Table 8. Relative changes at country level of average yields for dominant crops and nitrogen leaching.

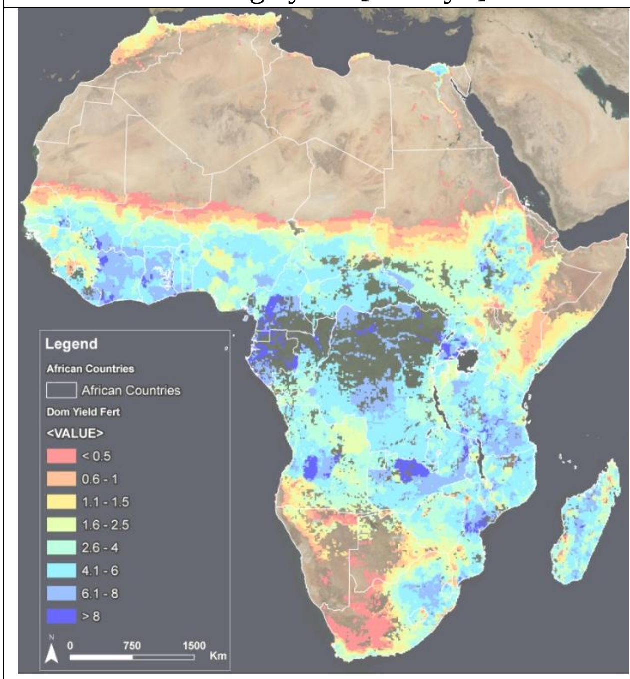
ACTUAL SCENARIO
Average yield [t ha^{-1} y^{-1}]



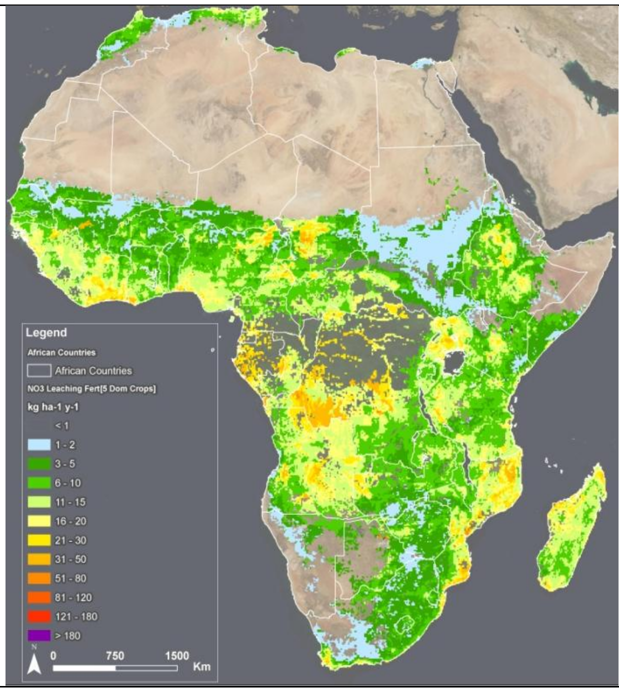
Average leaching [kg ha^{-1} y^{-1}]



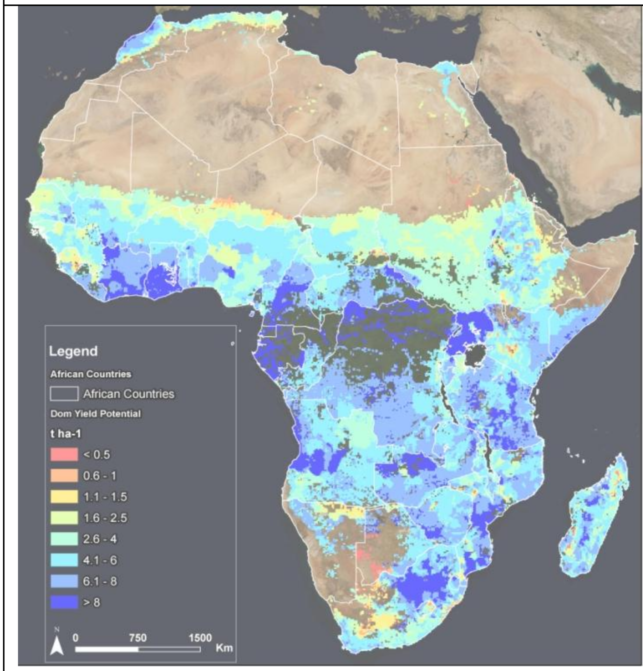
SCENARIO SC1
Average yield [t ha^{-1} y^{-1}]



Average leaching [kg ha^{-1} y^{-1}]



SCENARIO SC2 Average yield [t ha^{-1} y^{-1}]	Average leaching [kg ha^{-1} y^{-1}]



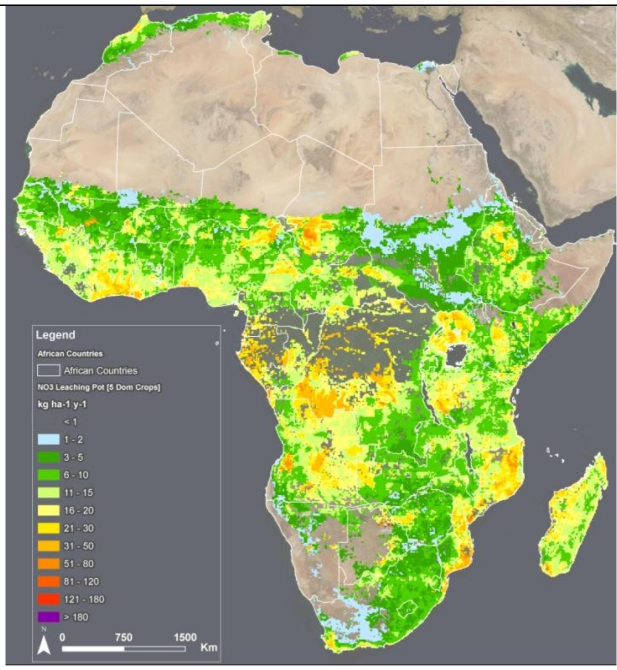


Figure 16. Comparison of average yields and nitrogen leaching for dominant crops under different management strategies in Africa.

5 Conclusion

This report shows how GISEPIC AFRICA can be used to spatially assess environmental impacts of different agriculture scenarios on water and soils. The development of a harmonized geodatabase for continental Africa including all data required to apply the EPIC model is described. Furthermore, a GIS system was developed and optimized in order to integrate the model and the geodatabase. The integration of the model in the GIS system and the development of a robust geodatabase allowed to quickly performing different simulations on 135000 different sites in Africa. Validation of the system focused mostly on crop yield as it is the only measured data readily available for the entire African continent. The model performed rather well at regional and sub-regional scale in North Africa for the major crops grown in the area (R^2 statistics ranging from 0.4 to 0.8), even though some problems were encountered partly explained by the reliability of the input data and the quality of observed data.

The comparison of four management scenarios for maize and wheat in North Africa pointed out a potential increase of the environmental impact on water and soil under future more productive agriculture in Africa. Both nitrogen leaching and runoff losses, which are potential sources of contamination of groundwater, surface water and soils, increased significantly under more productive scenarios. Even if the increase of nitrogen leaching is an inevitable consequence of higher fertilizer application rate, required to achieve higher productions, this is an important trade-off that should be considered. The analysis illustrated the importance of irrigation practices influencing environmental impact of different scenarios: specifically it was shown how irrigation practices can bring to a more sustainable production: the crop can grow without water stresses and is thus able to efficiently uptake the nutrients available in the soil or added with fertilizer, which are no longer available for leaching or transport with surface runoff.

The study at continental scale by comparing the current management scenario with two more productive ones, showed how the expected potential increase of crop production in Africa is strictly linked with fertilization, but above all with irrigation issue and pointed out a potential high increase of environmental impact. As evidenced by nitrogen and water indexes current agriculture practices in many regions of Africa are characterized by very low use of fertilizer and water inputs, resulting in a low productive agriculture, but also in a minor environmental impact. The current nitrogen leaching at country level is always less the 10 kg ha^{-1}, and its increase in the more productive scenarios can be quite important (100% - 120%). More specifically countries located in the tropical and sub-tropical climate show under the more productive scenarios the highest increase in the impact on water quality because both nitrogen leaching and nitrogen runoff losses are increasing. This is probably caused by the higher precipitation of these areas that together with the increased irrigation practices will increase the amounts of water percolation and nutrient leaching and runoff losses.

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Abstract
Nearly all of the population growth is expected to occur in the developing countries and all the projections suggest that market demand for food will continue to grow (population growth, higher standard of living, biofuels, etc.), requiring a general increase of food production by 70 % between 2005 and 2050. Food crop production in developing countries will have to almost double to adapt to the new needs. Furthermore, agriculture will have to adopt more efficient sustainable cropping methods to adapt to climate change. Supplying right water and nutrients amount can bring crop yield to higher level in Africa, however possibly affecting the environment including drinking water, soil degradation, deforestation and biodiversity.

In this context, it is of utmost importance to have tools allowing to quickly assess the impact of these potential future agricultural development scenarios on the environment, and more specifically on water availability, water quality degradation and soil.

In this report a GIS system integrating the biophysical continuous simulation model EPIC (Williams et al., 1995) with a geodatabase, GISEPIC AFRICA, is described and tested in the African continent. The GIS system works with a grid of a spatial resolution of 15 km on the whole African continent, integrating daily meteorological, crop land distribution, digital elevation, soil and management data. It allows simulating up to 46 different crops for a period ranging from 1965 to 2006.

The GISEPIC AFRICA system was used to spatially assess environmental impacts of different agriculture scenarios on water and soils by assessing nitrogen leaching and runoff losses. The comparison of different management scenarios pointed out a potential increase of the environmental impact on water and soil and highlighted the importance of irrigation practices influencing environmental impact of different scenarios: it was shown how irrigation practices can bring to a more sustainable production reducing water stresses and allowing the crops to uptake efficiently the nutrients available in the soil or added with fertilizer, which are no longer available for leaching or transport with surface runoff.

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