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ORIGINAL PAPER

A spatially explicit methodology to quantify soil nutrient balances and their uncertainties at the national level

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Abstract A soil nutrient balance is a commonly used indicator to assess changes in soil fertility. In this paper, an earlier developed methodology by Stoorvogel and Smaling to assess the soil nutrient balance is given a major overhaul, based on growing insights and advances in data availability and modelling. The soil nutrient balance is treated as the net balance of five inflows (mineral fertilizer, organic inputs, atmospheric deposition, nitrogen fixation and sedimentation) and five outflows (crop products, crop residues, leaching, gaseous losses and erosion). This study aims to improve the existing methodology by making it spatially explicit, improving various transfer functions, and by modelling explicitly the uncertainties in the estimations. Spatially explicit modelling has become possible through a novel methodology to create a simulated land use map on the basis of the principles of traditional qualitative land evaluation. New literature data on the various inputs and outputs allowed improvement of the estimations of deposition, sedimentation, leaching, and erosion. Moreover, the uncertainty of the calculated soil nutrient balances was assessed. To illustrate the improved methodology, we applied it to Burkina Faso and revealed that nutrient depletion is occurring throughout the country at rates of $-20 \pm 15\,\mathrm{kg\,N\,ha^{-1}}$, $-3.7 \pm 2.9\,\mathrm{kg\,P\,ha^{-1}}$ and $-15 \pm 12\,\mathrm{kg\,K\,ha^{-1}}$. The resulting spatial soil nutrient balances at the national level can constitute the basis for targeting soil fertility policies at lower levels.

Keywords Land use · Soil fertility · Soil nutrient balance · Spatially explicit · Uncertainty analysis

Introduction

A soil nutrient balance is a commonly used indicator to assess changes in soil fertility (e.g., Bindraban et al. 2000; Roy et al. 2003). Stoorvogel and Smaling (1990) introduced a soil nutrient balance as a net balance of five inflows and five

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outflows, which indicates whether an agricultural system is a net winner or loser in terms of soil fertility. They constructed N, P and K balances for 37 sub-Saharan countries, which revealed that soil fertility is generally following a downward trend on the African continent (Stoorvogel and Smaling 1990; Stoorvogel et al. 1993). Although the methodology has been widely used, it was also criticized for lack of validation, the use of simple transfer functions, and not taking into account spatial and temporal variability and unknown uncertainties (Scoones and Toulmin 1998; Hartemink 2003; Faerge and Magid 2004). Practical alternatives were, however, not suggested, and the 'old' methodology continued to be applied until today. In the meantime many more data have become available to develop better validated regression models or to have them replaced altogether by more advanced simulation models. Furthermore, new geographic data sets and remote sensing images make it possible to calculate soil nutrient balances in a spatially explicit way. As a result regional differences due to soil and climate variability can be taken into account and national soil fertility policies can be better targeted towards the lower levels, e.g., district or cooperation region (FAO 2004).

The objective of this study was to revisit the methodology developed by Stoorvogel and Smaling (1990). No changes were made to the overall goal of the methodology to assess soil nutrient balances for agricultural land in any African country using publicly available data. Where the basic conceptual framework did not change, we focused the improvements on:

- Developing techniques to make the methodology spatially explicit. The original study used the so-called "land-water classes" (FAO 1978; Alexandratos 1988) as the basic calculation units. A better assessment of the soil nutrient balances is only possible if land use maps are available. A new methodology to develop these land use maps need to be developed. Only then, land use maps can be overlain by other spatially explicit data (e.g., soil and climate).
- Re-estimating the original regression models for the various nutrient flows or, if possible, replace them by simple simulation models. New data sets and models have become available that allow more accurate assessment of some of the processes.
- Assessing the uncertainties of soil nutrient balance estimates. Even at the farm level with detailed data, assessing the soil nutrient balance is found to be difficult. So, how accurate are the assessments for an entire country? It is clear that a proper evaluation of the accuracy of these nutrient balances is important.

The first part of our paper describes the changes that we propose for the assessment of the soil nutrient balances. Next, we present the results for an application of the methodology for Burkina Faso. Finally, the soil nutrient balance methodology and its uncertainty analysis are discussed.

The new methodology

The soil nutrient balance methodology includes a large number of different steps including the methodology to create a land use map and the estimation of each of the individual nutrient flows. This is followed by the actual calculation of the soil nutrient balance and an evaluation of the accuracy of the estimation. The various flows are summarized in Table 1 with the improvements applied in this study. Each flow is defined in this section.

Land use map

Nutrient balances reflect particular land use systems, including soil and climatic conditions. As a result the calculation can only take place on a site-specific basis in which soil, climate and crops are superimposed. Various authors developed approaches to calculate spatially explicit soil nutrient balances. Folmer et al. (1998), for example, made an assessment of soil fertility depletion in Mozambique using land units and land use types and calculated the soil nutrient balance following Stoorvogel and Smaling (1990). The approach was spatially explicit, but still based on classes instead of all soil and topographical characteristics and generalized land use systems

Table 1 New approaches, data sets and models in the nutrient balance calculation compared to Stoorvogel and Smaling (1990)

Land use system definition	Modelling land use systems through land suitability assessment
Nutrient stocks	WISE database (Batjes 2002)
IN1: mineral fertilizer	Fertilizer use data per crop (IFA/IFDC/FAO 2000) and total consumption from FAOSTAT
IN2: organic inputs	Livestock density maps (Wint et al. 2000) in combination with literature data on nutrient contents
IN3: atmospheric deposition	Map for Harmattan deposition New regression on nutrient concentrations and IIASA rainfall map (Leemans and Cramer 1991)
IN4: nitrogen fixation	Percentage of leguminous crop production and related to rainfall (Leemans and Cramer 1991)
IN5: sedimentation	Sedimentation calculated using the LAPSUS model (Schoorl et al. 2002)
OUT1: crop products	No changes
OUT2: crop residues	No changes
OUT3: leaching	New regression model based on review by De Willigen (2000)
OUT4: gaseous losses	New regression model based on data from IFA/FAO (2001)
OUT5: erosion	Erosion calculations using the LAPSUS model (Schoorl et al. 2002)
Uncertainty assessment	Analysis including cross and spatial correlations following Heuvelink (1999)

instead of individual crops. Furthermore, the compilation of the land use system map was not straightforward and remained country-specific. De Koning et al. (1997) and Priess et al. (2001) calculated spatially explicit soil nutrient balances for Ecuador, following the methodology of Stoorvogel and Smaling (1990) for grid cells of 5 arc minutes. A land use map was constructed indirectly by relating sample sites of the national agricultural statistics census to grid cells. Such an approach is suitable when a sound, geo-referenced system of agricultural statistics is available. However, for African countries such a database is normally not available.

The estimation of nutrient flows and balances starts with the definition of the various land use systems. Therefore we considered a land use map to be the appropriate basis for the methodology. However, land cover data, as derived from satellite images, do not describe crop distribution at the national level with sufficient detail, i.e., only agricultural areas or crop groups can be distinguished. On the other hand, national statistics, such as provided by the FAOSTAT database, are not spatially explicit and can therefore not be linked directly to climate and soil data. To solve this problem we developed a new methodology, which generates land use maps for sub-Saharan African countries on the basis of available datasets. The proposed methodology is based on the principles of qualitative land evaluation, where land qualities are matched with land use requirements to assess the suitability of land for a given use (FAO 1976). The methodology is based on three key steps:

1. Identify land units with similar topography, climate and soil conditions.
2. Match properties of the land units with crop requirements.
3. Disaggregate harvested areas from FAOSTAT over the land units.

Land use map step 1

In a first step, land units are identified, as defined by topography, soil and climate. Metadata of the used datasets are described in Table 2. Quantitative data for the FAO soil map of the world (FAO/UNESCO 1997) were derived from the World Inventory of Soil Emission potential (WISE) database (Batjes 2002). This database consists of a set of homogenized worldwide data of 4382 geo-referenced soil profiles, classified according to the FAO-UNESCO original legend (1974) and the revised legend of 1988. Finally, the agricultural areas were identified from the land cover map using a reclassified version of the 'seasonal land cover region' legend (USGS et al. 2000). All maps were overlain into a single 1-km grid. The databases were linked and a table with the following land characteristics was created for each grid cell: land cover, length of growing

Table 2 Overview of used spatial metadata

Input	Name	Resolution	Source
Soil	Soil map of the World	1:5,000,000	FAO/UNESCO (1997)
Altitude	Hydro1k Africa. Elevation data	1 km	USGS (1998)
Land cover	Africa land cover characteristics database	1 km	USGS et al. (2000)
Climate	The IIASA database for mean monthly values of temperature, precipitation and cloudiness on a global terrestrial grid	0.5°	Leemans and Cramer (1991)
Growing period	Global Agro-Ecological Zones	0.5°	FAO and IIASA (2000)
Livestock density	Livestock Atlas	5 arc min	Wint et al. (2000)
Poultry density	Rural population in sub-Saharan Africa	5 arc min	Dixon et al. (2001)
Irrigation	A digital global map of irrigated areas	5 arc min	Döll and Siebert (2000)

period, rainfall, temperature, soil depth, texture, drainage and altitude.

Land use map step 2

The second step encompasses the traditional matching process as described by the FAO qualitative land evaluation system (FAO 1976), in which land qualities are compared to crop requirements. The land qualities were represented by the available land characteristics listed above. Crop requirements, expressed in the same way as land characteristics, were described by the crop environment response database ECOCROP (FAO 1998). An algorithm was developed that matches the land units with the main crops, as derived from FAOSTAT, through the respective land characteristics and crop requirements. The matching process then resulted in a classification of the land units on the basis of the suitability for the six key land characteristics. The land characteristics were sorted from highly important (left) to less important (right), which allows sorting of the land units on the basis of their suitability.

Land use map step 3

The final step of the procedure is the allocation of crops according to the suitability classification. The actual harvested areas of each crop were extracted from the FAOSTAT database. A predefined crop order file was developed on the basis of the economic importance of the crops (Fox et al. 1995). It allows crop allocation ranking, i.e., an important cash crop as cotton will be allocated to the most suitable locations, while an economically less important food crop as millet will be allocated to less suitable places. Each crop was distributed to the areas with the highest suitability for that specific crop, unless the area was already filled up with other crops. This means that crops that are high in the crop order are allocated to the most suitable places. An exception was made for fallow areas, because fallow is not based on suitabilities but on the character of a particular land use system. The fallow area was therefore split and allocated by ratio to the crops that are related to fallow systems, mainly cereals and root crops. This adaptation delivered a more realistic pattern, where fallow areas are located in the same area as the crops of that particular land use system. The output table of the simulation was linked to the original grid map and the resulting land use map showed the most likely distribution of crops, based on suitabilities.

Nutrient stocks

Nutrient flows and balances are not very meaningful without knowledge of nutrient stocks. After all, the rate of soil fertility decline is not just a ‘per hectare per year’ unit, but also a ratio indicating the percentage change of the total available nutrient supplies (Bindraban et al. 2000). Moreover, nutrient stocks play an important role as input data for the calculation of a number of nutrient flows, such as leaching, gaseous losses and sedimentation/erosion. The quantified soil properties were derived from the WISE database (Batjes 2002). The soil profiles from Africa were extracted from this database, yielding 1799 different soil profiles. The following soil properties were calculated for each soil unit: clay, pH, organic carbon, total N, exchangeable K, CEC, available P and bulk density. Soil depth and erodibility, necessary for the erosion–sedimentation model, are not included in the WISE database and therefore each soil unit was classified to a soil depth and a soil erodibility class based on general descriptions of soil groups and units (FAO 2001). The nutrient stocks were calculated for the first 30 cm of the soil, which was straightforward for N, but more complicated for P and K, since the WISE database has 'available' rather than 'total' values of these nutrients. Therefore, available P was converted to total P according to the classes of Langdon (1991), and for K only exchangeable K was used, since a very large part of total K in the soil is not available as nutrient.

Soil nutrient balance

To calculate the soil nutrient balances the simulated land use map was combined with other spatial data needed for calculations, which lead to a single database with all spatial data for each 1-km grid cell. Calculation of the nutrient flows and balance, as explained in detail below, was done in a database program. The results were exported to a GIS to create spatially explicit maps and to aggregate the results. We chose a resolution of 20-km for the aggregation, which still provided sufficient detail to represent the variation within a country, but also justified the use of input data at less detailed resolution, i.e., soil and climate data. Besides, aggregation leads to a reduction of the uncertainty of the soil nutrient balance results, because of averaging effects.

IN1: mineral fertilizer

Mineral fertilizer input was calculated per crop as a fraction of the total national fertilizer consumption, obtained from FAOSTAT. The fractions were based on data of the 'fertilizer use per crop' studies of IFA/IFDC/FAO (2000). However, these data are not available for each country, in which case the fractions were estimated with data from surrounding countries with similar agro-ecological zones, e.g., for Burkina Faso data from Mali and Senegal was used.

IN2: organic inputs

Manure is the main organic input for most African countries and is related to the number of livestock. Livestock density maps for the major livestock classes, i.e., cattle and small ruminants (sheep and goats), provided the spatial distribution of livestock over the country. These maps were based on climate, geography, population density and statistical data (Wint et al. 2000). Since no poultry density map was available, we created one based on the rural population map of sub-Saharan Africa (Dixon et al. 2001), for which we assumed a linear relationship between rural population density and the abundance of poultry.

The total amount of nutrients from manure was calculated by multiplying the livestock densities by the excretion per animal per year and the nutrient content of the manure for each livestock class. The nutrient content and excretion factors (Table 3) were based on various literature sources for African conditions (Baijukya et al. 1998; Budelman and Defoer 2000; Lekasi et al. 2001; Smaling et al. 1999; Williams et al. 1995).

Based on the livestock maps the total amount of nutrients produced could be calculated. However, losses and distribution still had to be determined. According to Fernandez-Riviera et al. (1995) and Schlecht et al. (1995), 43% of the manure is excreted at night, when animals are in their stable/corral/boma. This amount, losses excluded, can be relocated to specific crops. The remaining 57% of the manure, losses excluded, remains on the field. Livestock from grid cells that were not classified as cropland, e.g., pasture land, had to be included, because part of the nutrients

Table 3 Nutrient content of manure (fresh weight) and excretion

	N (%)	P (%)	K (%)	Excretion[a]
Cattle manure	0.76	0.15	0.67	6.2
Sheep/goat manure	0.79	0.20	0.50	7.2
Poultry manure	1.08	0.39	0.35	7.8

[a] Excretion in kg fresh matter per kg body weight per year

from pastures is transferred to stables and afterwards to other crops. The livestock density maps were therefore aggregated to a 20-km grid representing the livestock density of that region. This value was multiplied by an aggregation factor and a crop factor. The estimated aggregation factor was country dependent and related to the human population density, i.e., more manure relocation occurs in countries with a higher population density (e.g., Ethiopia). An estimated crop factor determined if a specific crop received manure (1), double quantity of manure (2) or no manure (0).

During grazing, manure losses occur along roadsides and other places where no crops are growing. These losses were estimated at 15% for each country. Losses during storage were estimated to be larger, because farmers use manure for other purposes as well, e.g., fuel or construction material. Losses also occur because of storage itself, manifested through leaching, denitrification and volatilization. Since this loss factor depends on the type of management, it was estimated for each country, based on population density, livestock system and the relative importance of manure as a fertilizer, e.g., 'zero grazing' versus 'free range' systems. Losses due to leaching, denitrification and volatilization for the calculated manure application were accounted for in OUT3 and OUT4. The final calculation of organic inputs per grid cell for each livestock class (cattle, small ruminants and poultry) can be written as:

$$\begin{aligned}\mathrm{IN2} = {} & (\text{livestock density} \times \text{excretion} \\ & \times \text{nutrient content} \times \text{losses (grazing)}) \\ & + (\text{aggregated livestock density} \\ & \times \text{aggregation factor} \times \text{crop factor} \\ & \times \text{excretion} \times \text{nutrient content} \\ & \times \text{losses (storage)})\end{aligned} \tag{1}$$

IN3: atmospheric deposition

Atmospheric deposition occurs in two forms, wet deposition related to rainfall and dry deposition related to Harmattan dust. Wet deposition also includes nitrogen fixation through lightning, because formed NO_x dissolves in water and precipitates during rainfall. This is an important source of nitrogen, especially for the wet tropics, where many lightning storms occur (Bond et al. 2002). The amount of precipitation was derived from the IIASA rainfall map (Leemans and Cramer 1991). Nutrient concentrations are based on a regression of relevant measurements in Africa (Langenberg et al. 2002; Stoorvogel et al. 1997b; Bruijnzeel 1990; Baudet et al. 1989; Pieri 1985; Jones and Bromfield 1970; Richard 1963; Meyer and Pampfer 1959) with an average value of 4.9±2.5 g N ha^{-1} mm^{-1}, 0.6±0.5 g P ha^{-1} mm^{-1} and 2.6±1.1 g K ha^{-1} mm^{-1}. For Harmattan dust we created a map (Fig. 1), based on interpolation of the dust measurements and wind stream patterns with an average nutrient content of 3.8±0.6 g N kg^{-1} dust, 0.8±0.4 g P kg^{-1} dust and 19±12 g K kg^{-1} dust (Stoorvogel et al. 1997a; Drees et al. 1993; Moberg et al. 1991; Tiessen et al. 1991; Pye 1987; McTainsh and Walker 1982; McTainsh 1980; Kalu 1979).

IN4: nitrogen fixation

Biological nitrogen fixation is an important source of nitrogen for leguminous crops through symbiosis, but other crops can also profit indirectly through non-symbiotic N fixation and N fixing trees. Values for symbiotic N fixation were obtained from literature and expressed as percentages of total N uptake: groundnut 65%, soybean 67%, pulses 55% and sugarcane 17% (Giller 2001; Danso 1992; Giller and Wilson 1991; Hartemink 2003).

Non-symbiotic N fixation by cyanobacteria is an important process in soils under wetland rice. We estimated the contribution at 15 kg N ha^{-1} $year^{-1}$, which is lower than most experiments revealed, but according to Giller (2001) the effect of cyanobacteria is overestimated and does not occur in all fields. N fixation by cyanobacteria only occurs under wetland rice, however, the FAOSTAT data do not differentiate between wetland and upland rice. The value was therefore multiplied by the cropping index of wetland rice according to IPCC (1997). As last we accounted for small contributions from non-symbiotic N fixation and N fixing trees assuming a positive relationship between

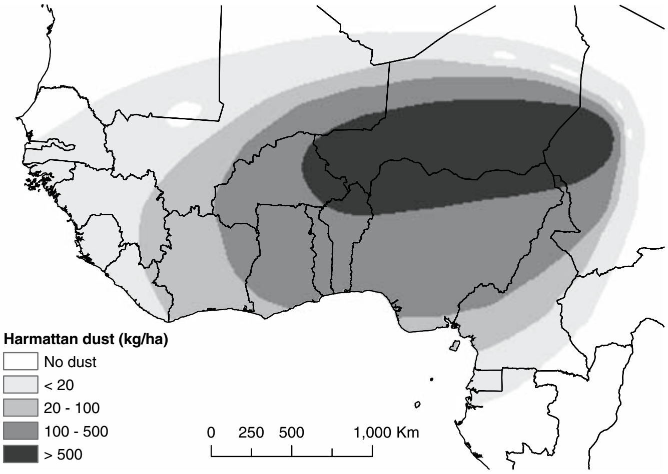

Fig. 1 Interpolated distribution of Harmattan dust in West Africa

rainfall and N fixation. Based on the land/water classes of Stoorvogel and Smaling (1990), we defined the following equation:

$$N_{\text{fixed}} = 0.5 + 0.1 \times \sqrt{\text{rainfall}} \qquad (2)$$

with rainfall in mm year^{-1} and N_{fixed} in kg N ha^{-1} year^{-1}.

IN5: sedimentation

The final inflow is built up of two components, input of nutrients by irrigation water and by sedimentation. Irrigated areas were derived from the global map of irrigation areas (Döll and Siebert 2000). The amount of irrigation water was estimated at 300 mm ha^{-1} year^{-1}, and nutrient content values of Stoorvogel and Smaling (1990) were used: 3.3 mg l^{-1} for N, 0.4 mg l^{-1} for P and 1.4 mg l^{-1} for K. Sedimentation was calculated by the LAPSUS model (Landscape Process Modelling at Multidimensions and Scales) (Schoorl et al. 2002), which simulates erosion and sedimentation, see details under OUT5. The model calculated the net height differences, which were multiplied by the bulk density, an enrichment factor and nutrient contents to obtain the nutrient input.

OUT1: crop products

Nutrient output by crop products is normally the most important outflow. To obtain OUT1 we multiplied the yield, derived from FAOSTAT, by the nutrient content of the crop, which were taken from Stoorvogel and Smaling (1990).

OUT2: crop residues

The output by nutrients in crop residues was calculated by multiplying yield, nutrient content of the crop residues and a removal factor. The latter is crop and country specific and we based it on scarce literature and expert knowledge. The removal factor reflected the type of management, population density and livestock importance. Burning of crop residues is a special form of residue removal. However, at the national level it is very difficult to determine the extent of burning. It was, therefore, only considered for cotton, because these residues are normally burned to prevent pests and diseases (Camara 1996). The assumption was made that all nitrogen is lost by volatilization and 50% of all potassium by leaching.

OUT3: leaching

Leaching can be an important outflow for nitrogen and potassium. For nitrogen leaching, the regression model of De Willigen (2000) was used. This model is based on an extensive literature search and is valid for a wide range of soils and climates. For potassium leaching we developed a new regression model, based on the same data set of De Willigen (2000).

$$\mathrm{OUT3_N}(\mathrm{kg\ N\ ha^{-1} year^{-1}}) = (0.0463 + 0.0037 \times (\mathrm{P}/(\mathrm{C} \times \mathrm{L}))) \times (\mathrm{F_N} + \mathrm{D} \times \mathrm{NOM} - \mathrm{U}) \quad (3)$$

$$\mathrm{OUT3_K}(\mathrm{kg\ N\ ha^{-1} year^{-1}}) = -6.87 + 0.0117 \times \mathrm{P} + 0.173 \times \mathrm{F_K} - 0.265 \times \mathrm{CEC} \quad (4)$$

where

P = precipitation (mm year^{-1})
C = clay (%)
L = layer thickness (m) = rooting depth, derived from Allen et al. (1998)
F_N = mineral and organic fertilizer nitrogen (kg N ha^{-1} year^{-1})
D = decomposition rate of organic matter (1.6% year^{-1})
NOM = amount of nitrogen in soil organic matter (kg N ha^{-1})
U = uptake by crop (kg N ha^{1} year^{-1})
F_K = mineral and organic fertilizer potassium (kg K ha^{-1} year^{-1})
CEC = cation exchange capacity (cmol kg^{-1})

The N leaching regression model was based on 43 experiments and accounted for 67% of the variance (De Willigen 2000). The equation was slightly adapted for perennial crops by multiplying the amount of available nitrogen from soil organic matter with 0.5. This prevented overestimation of N leaching, because perennials take up nitrogen throughout the year, contrary to annual crops. Moreover, most of the leaching experiments were conducted under annual crops. The K leaching regression model was based on 33 representative experiments and accounted for 45% of the variance.

OUT4: gaseous losses

Denitrification and volatilization are the main processes for gaseous nitrogen emissions. Denitrification takes place under anaerobic conditions, although a soil does not have to be entirely saturated for denitrification to take place. A moist soil already loses nitrate through microbial processes in wet films and pockets. We expected nitrogen losses through denitrification to be highest in wet climates, on highly fertilized and clayey soils. Ammonia volatilization is linked to the amount of mineral and organic fertilizer and plays a role in alkaline environments (Bouwman 1998). However, such soils are not very common in sub-Sahara Africa. Volatilization was therefore not treated separately, but together with denitrification. We developed a regression model to estimate gaseous losses for N_2O, NO_x and NH_3, based on literature data for tropical environments, derived from a larger data set (IFA/FAO 2001). The regressions were combined into the following equation, which had an R^2 of 0.70.

$$\mathrm{OUT4}\ (\mathrm{kg\ N\ ha^{-1} year^{-1}}) = 0.025 + 0.000855 \times \mathrm{P} + 0.130 \times \mathrm{F} + 0.117 \times \mathrm{O} \quad (5)$$

where

P = precipitation (mm year^{-1})
F = mineral and organic fertilizer nitrogen (kg N ha^{-1} year^{-1})
O = soil organic carbon content (%)

OUT5: erosion

To estimate erosion we used the LAPSUS model (Schoorl et al. 2002). The model simulates the amount of water erosion and sedimentation at the landscape scale and has been calibrated with ^{137}Cs for a study area in Southern Spain (Schoorl et al. 2004). The advantages of process-based modelling of soil redistribution are the generation of quantitative data, consideration of erosion at landscape scale and inclusion of sedimentation. We preferred modelling above literature estimates, which are mainly based on plot experiments that are generally not representative for the national level (Schulze 2000).

The modelling approach is based on the principle of the potential energy content of flowing water over a landscape surface as the driving force for sediment transport (Kirkby 1986) and the use of the continuity equation for sediment movement (Foster and Meyer 1975). The model evaluates the rates of sediment transport by calculating the transport capacity of water flowing downslope from one grid cell to another as a function of discharge and slope gradient. A surplus of capacity is compensated by detachment of sediment, depending on the erodibility of the surface, which provokes erosion. When the rate of sediment in transport exceeds the local capacity, the surplus is deposited, causing sedimentation. Routing of overland flow and resulting model calculations were done with a multiple flow algorithm to allow for a better representation of divergent properties of a convex topography.

Main input data of the LAPSUS model are the topographical potentials derived from a digital elevation model (USGS 1998) and rainfall surplus, derived from the rainfall map (Leemans and Cramer 1991). Other input data are soil depth and erodibility, which were based on the soil map (FAO/UNESCO 1997), and a land cover map (USGS et al. 2000). With these inputs the model simulated runoff and erosion–sedimentation for one year at a 1-km resolution. The loss or gain of nutrients was calculated by multiplying the erosion or sedimentation by the soil nutrient contents and an enrichment factor. This factor was introduced, because finer and more fertile soil particles are dislodged first during erosion. Enrichment factors were set at 2.3 for N, 2.8 for P and 3.2 for K, based on Stocking (1984, 1986), Cogle et al. (2002) and Khisa et al. (2002).

Fallow

The FAO statistics give no information about the area under fallow. However, it was possible to calculate the fallow area indirectly by subtracting the total sum of harvested areas from the total arable land area. However, this calculation only included temporarily uncropped arable land, but not bush fallow. The latter is not recognized as arable land on satellite images and not included in the FAO statistics. The procedure to calculate the soil nutrient balance for fallow was slightly different, because it is not like a crop for which production data are available. Mineral fertilizer (IN1) and crop product (OUT1) are not relevant for fallow. IN2 and OUT2 are related to each other by grazing and defecating livestock, however, it was unknown whether IN2 should be greater or smaller than OUT2. Not all manure is left on the field (only about 57%), but on the other hand a lot of animal feedstuff is obtained from sources other than crop residues, e.g., roadside grazing. Hence, for fallow land we assumed the amount of nutrient input by manure (IN2) to be equal to the amount lost by grazing (OUT2). All other nutrient flows were treated equally as for other crops.

Uncertainty assessment

The results of the soil nutrient balance are only meaningful when they have sufficient accuracy. It is risky to draw conclusions and base decisions on results that are untrustworthy and that may deviate strongly from reality. The soil nutrient balance calculations are based on several assumptions and simplifications, and hence the risk of highly uncertain results is present. To analyse the accuracy of these results, it was necessary to track down how uncertainties in the input variables propagate to the soil nutrient balance results. This was not an easy task, because there are many inputs and the uncertainties associated with these variables are largely unknown. The uncertainty analysis also had to take cross and spatial correlations between the various uncertainties and the scale-dependency of uncertainties into account (Heuvelink 1999). In spite of these difficulties, we estimated the uncertainties of the variables and calculated how these propagate to the final results.

The soil nutrient balance and flow calculation involved sums and products of variables. In case of summation, the calculation may be formulated as:

$$Y = \sum_{i=1}^{n} a_i X_i \tag{6}$$

where Y is the resulting soil nutrient balance and X_i is the nutrient in- and outputs. The multiplication factors a_i are introduced to allow both for addition ($a_i = 1$) and subtraction ($a_i = -1$).

The expected value (μ_Y) and variance (σ_Y^2) of Y are given by:

$$\mu_Y = \sum_{i=1}^{n} a_i \mu_i \tag{7}$$

$$\sigma_Y^2 = \sum_{i=1}^{n} a_i^2 \sigma_i^2 + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} a_i a_j \rho_{ij} \sigma_i \sigma_j \tag{8}$$

where μ_i and σ_i are the mean and standard deviation of X_i, respectively, and where ρ_{ij} is the correlation coefficient between the uncertainties in X_i and X_j. Next, we consider the case in which the nutrient flow is defined as the product of variables:

$$Y = X_1 \cdot X_2 \cdot \cdots \cdot X_n = \prod_{i=1}^{n} X_i \tag{9}$$

Calculation of the mean and variance of Y is more complicated in this case. However, by assuming that the X_i are uncorrelated and ignoring higher order terms in the Taylor series expansion of the product function, we obtain (Heuvelink 1998):

$$\mu_Y \cong \prod_{i=1}^{n} \mu_i \tag{10}$$

$$\sigma_Y^2 \cong \sum_{i=1}^{n} \left(\frac{\sigma_i^2}{\mu_i^2} \prod_{j=1}^{n} \mu_j^2 \right) = \sum_{i=1}^{n} \sigma_i^2 \cdot \mu_1^2 \cdot \mu_2^2 \cdot \cdots \cdot \mu_{i-1}^2 \cdot \mu_{i+1}^2 \cdot \mu_{i+2}^2 \cdot \cdots \cdot \mu_n^2 \tag{11}$$

The uncertainties in the variables (Table 4) were either estimated, e.g., for the fertilizer use per crop parameters, or calculated, e.g., for the nutrient content of manure. The relative uncertainties for each nutrient flow could then be calculated according to Eqs. (8) and (11), whereby all uncertainties of the variables were considered uncorrelated.

The uncertainty of the total soil nutrient balance can be calculated when the relative uncertainties of all nutrient flows are known. However, not all nutrient flows are independent, some flows are correlated to others, e.g., the gaseous nitrogen losses are correlated to the mineral fertilizer and organic inputs. The covariance of the correlated flows should therefore be included in the uncertainty analyses (Oenema and Heinen 1999). With Eq. (8) the variance of the soil nutrient balance was calculated, including the covariance for the correlated nutrient flows (Table 5). The correlation coefficients (ρ_{ij}) were calculated with SPSS (Pearsons correlation), based on the calculated nutrient flows for each grid cell. The correlation coefficient was set to 0 for correlations between nutrient flows other than those given in Table 5.

Spatial aggregation

For each grid cell, the variance could now be calculated at the 1-km resolution. However, these results were aggregated to a 20-km grid, which influenced the variance of the soil nutrient balance because part of the variation and hence uncertainty was cancelled. Spatial aggregation can be formulated as:

$$Y_{\mathrm{agg}} = \frac{1}{n} \sum_{i=1}^{n} Y_i \tag{12}$$

where Y_{agg} is the aggregated soil nutrient balance, Y_i is the soil nutrient balance for the ith grid cell and n the number of aggregated grid cells (in our case n = 400). Spatial correlation occurs because part of the input data is spatially dependent, e.g., soil and rainfall data. We estimated the spatial correlation coefficient for each nutrient flow (Table 6), which ranged between 0 and 1. It indicates how the value of each nutrient flow in influenced by nearby observations, e.g., mineral fertilizer input is hardly spatially correlated, because one farmer can apply much fertilizer, while his neighbour might apply nothing. Atmospheric deposition, on the other hand, is highly spatially correlated, because variation in rainfall and dust deposition is not much at short distances. The degree of spatial correlation affects the variance of the aggregated results. In general, assuming that the variance of Y_i (σ^2) is equal for

Table 4 Relative uncertainties as standard deviations for variables and nutrient flows

Flow	Variables[a]	Calculation	Relative uncertainty
IN1	Fertilizer consumption (±*10%*) Fertilizer use per crop (±*100%*)	Product	100%
IN2	Livestock density maps (±*20%*) Nutrient content factor (± 50%) Excretion factor (±*20%*) Management factor (±*70%*)	Product	91%
IN3	Rainfall map (±*20%*) and nutrient content rainfall (±50%) ⇒54% Harmattan dust map (±*75%*) and nutrient content dust (± 50%) ⇒90%	Product and summation	60%
IN4	Symbiotic N-fixation factors (±30%) and crop uptake (±*50%*) ⇒58% Rainfall map (±*20%*) and regression (±*50%*) ⇒54%	Product and summation	60%
IN5	Irrigation map (±*30%*) Nutrient content irrigation water (±*100%*) (Error for sedimentation is included in OUT5)	Product	104%
OUT1	Crop production (±*50%*) Nutrient content crop products (±30%)	Product	58%
OUT2	Crop production (±*50%*) Nutrient content crop residues (±50%) Crop residue removal factor (±*50%*)	Product	87%
OUT3	Rainfall map (±*20%*) and clay content (±*20%*) ⇒28% Fertilizer application (±100%), decomposition rate (±*50%*), soil nitrogen content (±*30%*) and nitrogen uptake (±70%)⇒80% Regression model R^2 = 0.67 (57%)	Product and summation	102%
OUT4	Rainfall map (±*20%*), fertilizer application (± 100%) and organic carbon content (±*20%*)⇒50% Regression model R^2 = 0.70 (55%)	Product and summation	74%
OUT5	Digital elevation model (±*5%*) Infiltration map (±*20%*) Rainfall map (±*20%*) Soil depth (±*30%*) Soil erodibility (±*100%*) Soil nutrient content (±*20%*) Enrichment factor (±*20%*) Model factor (*100%*)	Product	150%

[a] Uncertainties in italic are educated guesses; other uncertainties were calculated based on available data

Table 5 Correlation coefficients for correlated nutrient flows (based on calculated nitrogen flows for Burkina Faso)

Correlated nutrient flows	Explanation	Correlation coefficient
(IN4, OUT1)	Symbiotic N fixation is positively correlated with crop production	0.55
(IN4, OUT2)	Symbiotic N fixation is positively correlated with crop residues	0.32
(OUT3, IN1)	Leaching is positively correlated with mineral fertilizer input	0.13
(OUT3, IN2)	Leaching is positively correlated with organic inputs	0.16
(OUT3, OUT1)	Leaching is negatively correlated with nutrient uptake	–0.06
(OUT3, OUT2)	Leaching is negatively correlated with nutrient uptake	–0.12
(OUT4, IN1)	Gaseous losses are positively correlated with mineral fertilizer input	0.99
(OUT4, IN2)	Gaseous losses are positively correlated with organic inputs	0.45
(OUT3, OUT4)	Leaching and gaseous losses are indirectly linked through IN1 and IN2	0.15
(OUT1, OUT2)	Harvested products and crop residue removal are positively correlated	0.84
(IN4, OUT3)	N-fixation and leaching are indirectly linked through OUT1 and OUT2	0.07

Table 6 Spatial correlation factors

Flow	ρ	Explanation
IN1	0.1	Mineral fertilizer application is strongly management related
IN2	0.2	Organic inputs are mainly management related
IN3	0.9	Atmospheric deposition has a strong spatial component (rainfall and Harmattan map)
IN4	0.5	Partly related to rainfall map and partly to management (crop production)
IN5	0.8	Sedimentation and irrigation have both a strong spatial component
OUT1	0.2	Harvested products are strongly management related
OUT2	0.2	Crop residue removal is strongly management related
OUT3	0.4	Leaching is partly management related (fertilizer) and partly spatial (rainfall, soil)
OUT4	0.3	Gaseous losses are partly management related (fertilizer) and partly spatial (rainfall, soil)
OUT5	0.8	Erosion is mostly spatial related (DEM, soil, rainfall, infiltration)

each grid cell, the variance of the aggregated result, as derived from Eq. (8), is:

$$\sigma^2_{Y_{\text{agg}}} = \left(\frac{1}{n}\right)^2 \times \left\{n\sigma^2 + (n^2 - n)\rho\sigma^2\right\} \tag{13}$$

where n is the number of grid cells that are involved in the aggregation and ρ is the spatial correlation coefficient. For large n this may be approximated by $\sigma^2_{Y_{\text{agg}}} = \rho\sigma^2$. The calculated variance of the aggregated soil nutrient balance varies between the two extremes:

$$\sigma^2_{Y_{\text{agg}}} = \frac{\sigma^2}{n} \quad \text{if } \rho = 0 \tag{14}$$

$$\sigma^2_{Y_{\text{agg}}} = \sigma^2 \quad \text{if } \rho = 1 \tag{15}$$

We calculated an overall spatial correlation coefficient by the weighed average of all nutrient flows. The weight of each nutrient flow was determined by the absolute uncertainty. For determination of the final uncertainty of the aggregated soil nutrient balance we used Eq. (13).

Case study Burkina Faso

To illustrate the improved nutrient balance methodology we applied it to Burkina Faso, which was selected as being representative of the type of soil fertility problems in Sub-Saharan Africa, i.e., low agricultural production due to low nutrient inputs. Burkina Faso is one of the smaller Sahelian countries with a size of 274,000 km^2, a population of 12.4 million people, and a gross national per capita income of 360 US dollars year^{-1}. The country has few natural resources and fragile soils. About 90% of the population is engaged in (mainly subsistence) agriculture, which represents 31% of the total GDP (World Bank 2005). Recent droughts and desertification are severely affecting agricultural activities, population distribution, and the economy. Overgrazing, soil nutrient depletion and deforestation are important causes of land degradation, but soil rehabilitation has also been reported, particularly on the Central Plateau (Reij and Thiombiano 2003).

The arable land area is 3.8 million ha, occupying 14% of the total land area. Sorghum, millet and maize are the main food crops, while cotton is the main cash crop and export product. The most important crops that we considered are listed in Table 7, which comprised 99.2% of the total harvested area. The soil nutrient balance was calculated for the year 2000, based on a three-year average (1999–2001) of production and fertilizer data. The average total mineral fertilizer consumption was 12.1×10^6 kg nitrogen, 6.9×10^6 kg phosphorus and 7.2×10^6 kg potassium (FAO 2003). Cattle, sheep, goats and chickens are the main livestock categories in Burkina Faso. They are kept under extensive grazing on shrub lands and on the fields after harvest. The fertilizer consumption factors, crop residue removal and manure application factors are given in Table 7.

Table 7 Crop management data for Burkina Faso

Crop	Harvested area (1,000 ha)	Crop residue removal (%)	N-fertilizer fraction	P-fertilizer fraction	K-fertilizer fraction	Manure application[a]
Sorghum	1345	60	–	–	–	1
Millet	1248	60	–	–	–	1
Maize	288	80	0.23	0.18	0.18	2
Groundnuts	280	80	–	–	–	1
Cotton	256	60	0.53	0.43	0.50	2
Fallow	128	5	–	–	–	0
Pulses	90	80	–	0.15	0.08	0
Rice	46	35	0.10	0.10	0.10	0
Sesame seed	37	60	0.05	0.05	0.05	1
Karite nuts	28	15	0.02	0.02	0.02	0
Vegetables	28	80	0.05	0.05	0.05	1
Fonio	17	60	0.01	0.01	0.01	1
Fruits	13	50	0.01	0.01	0.01	1

[a] 0 = no manure, 1 = manure, 2 = twice as much manure

The simulated land use map for Burkina Faso (Fig. 2) shows that sorghum, millet, cotton and maize are the dominant crops in the north and east of Burkina Faso. Millet is more drought resistant than sorghum and therefore preferentially allocated towards the north and sorghum more towards the wetter south of Burkina Faso. Groundnuts, pulses, rice and vegetables were mainly allocated in the wetter southwest by the land use model. Figure 3 shows the simulated erosion–sedimentation map for Burkina Faso. The highest water erosion rates are found in the wetter and more mountainous southwest of the country, whereas the northern part has low erosion rates because of low rainfall. Based on the simulated land use map, the soil nutrient balance for Burkina Faso was -20 ± 15.1 kg ha^{1} year^{-1} for nitrogen, -3.7 ± 2.9 kg ha^{-1} year^{-1} for phosphorus and -15 ± 12.1 kg ha^{-1}year^{-1} for potassium (Table 8). However, the differences between the crops are large. All dry land cereals have on average the most negative soil nutrient balances, whereas rice, sesame and fallow have near neutral soil nutrient balances.

Agriculture in Burkina Faso is based on very low inputs; on average the sum of mineral fertilizer and organic inputs was only 5–6 kg N ha^{-1} year^{-1} (Table 9), whereas natural inputs by atmospheric deposition and N fixation were estimated to be higher. However, the differences between crops were large. Cotton received about 25 kg N ha^{-1} year^{-1} as mineral fertilizer, while no

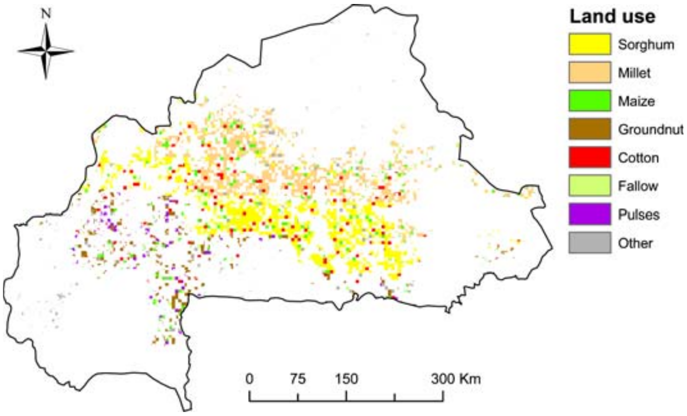

Fig. 2 Simulated land use map for Burkina Faso

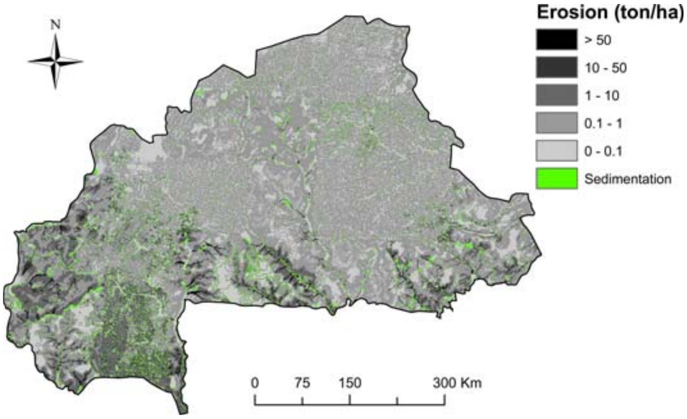

Fig. 3 Simulated water erosion and sedimentation map for Burkina Faso

Table 8 Soil nutrient balance and uncertainty expressed as standard deviation (kg ha^{-1} year^{-1}) per crop

Crops	Area (1,000 ha)	N	P	K
Sorghum	1345	–21.1 (±9.7)	–5.8 (±2.7)	–11.7 (±10.3)
Millet	1248	–21.0 (±7.4)	–4.8 (±2.2)	–20.9 (±12.6)
Maize	288	–32.9 (±9.1)	–3.9 (±3.4)	–27.4 (±14.8)
Groundnuts	280	–15.4 (± 25.2)	–4.2 (± 3.6)	–12.0 (±12.4)
Cotton	256	–13.9 (± 9.9)	–2.0 (± 3.2)	–13.1 (± 10.5)
Fallow	128	–5.5 (±10.0)	0.7 (±0.9)	6.7 (±4.8)
Pulses	90	–16.6 (±16.6)	8.5 (±2.7)	–10.8 (±10.2)
Rice	46	–4.1 (±10.3)	6.5 (±4.1)	–18.5 (±14.8)
Sesame Seed	37	–6.0 (±6.2)	6.2 (±2.5)	8.5 (±7.2)
Karite nuts	28	–5.1 (±6.8)	4.4 (±1.3)	–3.7 (±7.0)
Vegetables	28	–68.5 (±14.0)	–3.2 (±6.1)	–60.2 (±24.1)
Fonio	17	–18.5 (±7.9)	0.6 (±2.2)	–13.6 (±11.1)
Fruits	13	–3.2 (±11.2)	6.4 (±2.8)	–18.7 (± 12.2)
Total	3819	–20 (±15.1)	–3.7 (±2.9)	–15 (±12.1)

mineral fertilizer was applied to food crops. The most important nutrient outflows were crop products, crop residues and nitrogen leaching. For the outflows the differences between the crops were smaller. As stated before the results of the soil nutrient balance in kg per hectare units do not express the seriousness of nutrient depletion, because the relation to the nutrient stocks is unknown. Therefore we also calculated the nutrient depletion as percentage of the nutrient stocks

Table 9 Nutrient flows for three main crops (kg ha^{-1} year^{-1})

Crops	IN1	IN2	IN3	IN4	IN5	OUT1	OUT2	OUT3	OUT4	OUT5
N cotton	25.1	3.7	5.5	3.6	0.7	21.1	9.4	13.9	4.7	3.3
P cotton	11.6	0.8	0.8	–	0.0	10.9	0.0	–	–	0.3
K cotton	14.1	2.9	7.0	–	0.1	10.2	10.1	6.1	–	0.7
N groundnuts	0.0	2.2	5.9	34.7	13.1	33.4	11.4	10.1	1.3	15.2
P groundnuts	0.0	0.5	0.8	–	2.4	5.3	1.7	–	–	0.8
K groundnuts	0.0	1.7	6.0	–	3.6	7.3	10.7	3.7	–	1.5
N millet	0.0	2.0	5.2	3.4	0.6	13.7	8.8	7.8	1.1	0.7
P millet	0.0	0.4	0.8	–	0.0	4.3	1.7	–	–	0.1
K millet	0.0	1.5	7.7	–	0.1	3.9	25.7	0.6	–	0.1
N total	3.2	2.4	5.4	6.3	1.8	16.8	7.9	10.3	1.6	2.8
P total	1.8	0.5	0.8	–	0.3	5.1	1.9	–	–	0.2
K total	1.9	1.8	7.2	–	0.5	5.0	18.7	2.3	–	0.4

per year, which were on average 0.3% for nitrogen, 1.1% for phosphorus and 2.1% for potassium (exchangeable K).

The calculated soil nutrient balances were linked to the GIS data to make them spatially explicit. The 1-km resolution results were aggregated to a 20-km grid, using average values of all smaller grid cells, to obtain a picture of the total farming system (Fig. 4). Nitrogen depletion turned out to be more or less equally distributed over the country, with the highest depletion rates in the centre, which corresponds with the cereal area. For phosphorus the pattern of depletion is rather homogenous and not directly related to any specific crop, while potassium depletion is highest in the central north, associated with millet, and in the southwest, where maize, pulses and groundnuts are grown. However, when we look at nutrient depletion as a percentage of the nutrient stocks, the spatial pattern of nutrient depletion changed, especially for phosphorus. The areas with the highest relative depletion were found in the southeast of Burkina Faso, which correspond to areas with Plinthic Luvisols that are low in phosphorus.

Discussion

Case study Burkina Faso

The results show that nutrient depletion is occurring throughout Burkina Faso. Especially food crops such as maize, sorghum and millet have a strongly negative soil nutrient balance. In relation to the nutrient stocks the results are less alarming for nitrogen, because of the occurrence of soils that are relatively rich in nitrogen (Plinthic Fluvisols and Eutric Regosols). For phosphorus and potassium, the stocks are generally lower and large parts of Burkina Faso suffer nutrient depletion rates of more than 2% of the stocks (relative to the original stock) per year. One should take into account, however, that the definition of P and K stocks is problematic. Nutrient stocks are based on data that were collected mainly in the 1970s, which means that current nutrient stocks are probably much lower. The resulting soil nutrient balances confirmed soil fertility loss at the national level as determined in previous studies (Table 10). At farm or village level, however, the soil nutrient balance can be positive.

Water erosion did not influence the soil nutrient balance very much in Burkina Faso, since the erosion rates were rather low in the areas with arable lands, because of low rainfall and relatively flat topography. Wind erosion may be more important for dry Sahelian countries. However, results of wind erosion and deposition measurements are highly variable and difficult to compare due to a variety of research methods (Sterk 2003). Besides, at the national level fluxes due to wind erosion are negligible and only Harmattan dust should be accounted for (Schlecht and Hiernaux 2004). Therefore, we did not take regional wind erosion and deposition into account.

Methodological improvements

The calculation procedure underwent a number of important methodological improvements as compared to the original study by Stoorvogel and Smaling (1990). First of all, the methodology was made spatially explicit. This made it possible to take spatial variation of soils and climate into account and to show where soil nutrient depletion is occurring within the country. Furthermore, the procedures to calculate the nutrient flows were improved significantly. The most important improvements were the incorporation of livestock density maps for IN2, the Harmattan deposition map for IN3, the LAPSUS model for the feedback between erosion and sedimentation for IN5 and OUT5, and the availability of new data to improve the regression models. Finally, the soil nutrient stocks were quantified for each soil unit, instead of using three soil fertility classes, based on soil classification orders.

Data related problems

The compilation of many global and continental maps during the past years made a spatially

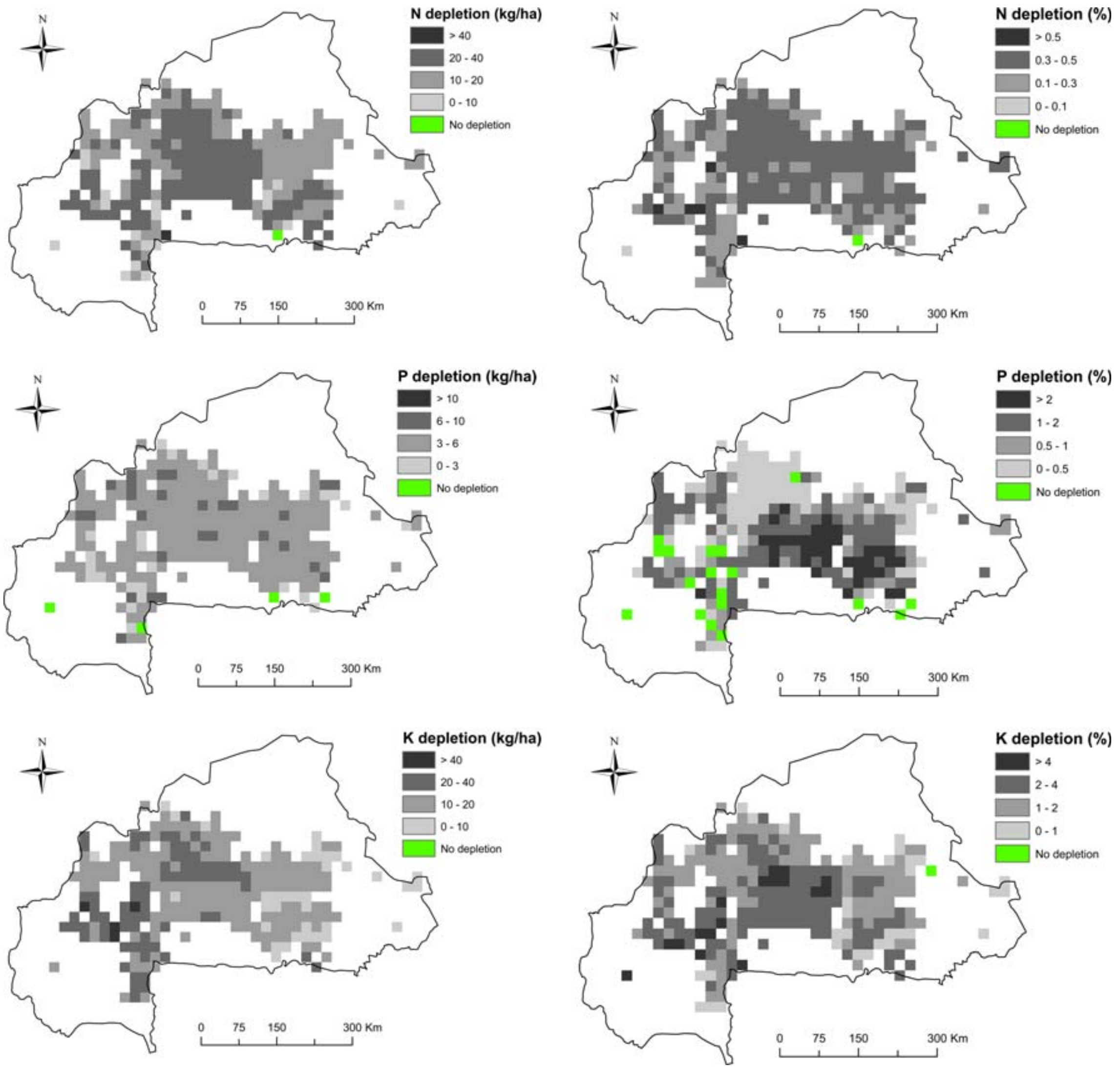

Fig. 4 Nutrient depletion in kg ha^{-1} year^{-1} and as percentage of the nutrient stocks for aggregated grid cells with at least 10% arable land

explicit approach possible. Only for mineral fertilizers (IN1) and to a lesser extent crop products (OUT1) and crop residues (OUT2), national values had to be spread evenly over the country for each crop, because no spatial data were available. The land cover map was

Table 10 Comparison of soil nutrient balances (kg ha^{-1} year^{-1}) for Burkina Faso

Reference	N	P	K
This study	–20	–3.7	–15
Stoorvogel and Smaling (1990), for 1983	–14	–1.7	–10
Stoorvogel and Smaling (1990), for 2000	–17	–2.2	–13
Van der Pol (1998)	–30	–1.8	
Varinuts (SC-DLO et al. 2000), four villages	–20	3.5	11
Lompo et al. (2000), one village	–15	–2.2	–30

based on satellite images of 1992–1993 that were classified without elaborate ground truthing. The map shows little cultivated land on the border between the semi-arid and sub-humid zones, which coincides with the south and southwest of Burkina Faso, while long-term field observations show that cultivation is common and covers large areas (Kruska et al. 2003). The classified map should therefore be confirmed by local field checks, but this has hardly been done for the African continent.

Next to spatial data, tabular data also differ in quality. For example, FAOSTAT crop data are based on sample surveys and not on total census data, while livestock data are normally better registered and available as total census data. Another point of attention is the use of regression models, which are supposed not to be used outside their own boundaries. However, due to limited datasets the boundaries do not cover the whole range of African conditions of soils, climate and management. The N leaching regression model had boundaries of 40–2,000 mm rainfall, 3–54% clay content and 0.25–2 m layer thickness (De Willigen 2000). For the K leaching regression model less data was available, which limited the borders to 1.3–8.1 cmol/kg for CEC, 211–2420 mm for rainfall and 0–273 kg ha^{-1} for the amount of fertilizer. Besides, most of these experiments were fertilizer trials, in which more than average fertilizer was applied.

Land use map

The land use map was based on crop suitabilities, which means that crops with high requirements were allocated to the best locations and that crops with low requirements were used to fill up remaining grid cells. This should be the expected situation, but will be beside reality, because of socio-economic, demographic and political drivers (Stéphenne and Lambin 2001). Multiple and inter cropping systems could not be simulated, because each land unit could only be allocated to one crop. However, the regional distribution of crops was more important than the accuracy of individual grid cells, because the results were aggregated afterwards to 20-km grid cells. Satellite images classified according to land use, i.e., crop distribution, would be an improvement. New initiatives, such as Africover (www.africover.org), offer an alternative for the simulated land use map. This multi-purpose land cover database is based on better and newer satellite images, has been thoroughly checked in the field and has a more specific legend. However, this map still does not distinguish individual crops or fallow periods but cropping systems and is only available for ten East-African countries up to now.

Erosion modelling

The quantitative results of erosion modelling with the LAPSUS model have to be treated with care. The model was developed at watershed level (25 m grid cell resolution) while we used it at the national level (1 km grid cell resolution). This means that topography is not correctly represented at the watershed scale, because small valleys and ridges are levelled out (Temme et al. 2006). Nevertheless, the erosion–sedimentation patterns appear to be simulated well, although verification at this scale level is hardly possible. A factor that is not included in the model but which affects erosion is agricultural land management (Schoorl and Veldkamp 2001). However, this could not be incorporated at this scale, because this is highly variable between farmers and no data at national level are available. Nevertheless, the LAPSUS model is so far the only model that can simulate erosion and sedimentation in a dynamic way and in quantitative terms at this scale.

Uncertainty assessment

The uncertainty assessment showed that the total uncertainty of the soil nutrient balances was relatively low, compared to the uncertainties of all input data. The uncertainties demonstrate that for most crops soil nutrient depletion is a fact. The uncertainty analysis also showed that cross and spatial correlations between the various nutrient flows and uncertainties affect the total uncertainty of the nutrient balance. However, a more rigorous uncertainty analysis is required to gain more confidence in the outcomes. Questions that need to be addresses in further studies are: (i) how realistic are the assumptions, (ii) which assumptions and uncertainties can be improved and (iii) what is the sensitivity of the uncertainty assessment and the spatial aggregation procedure. It should also be noted that in the uncertainty analysis we did not pay attention to the effect of model error, which potentially is an important source of error. However, assessment of model error was beyond the scope of this study.

Concluding remarks

For these results to become more meaningful at a policy and private sector level, it is useful to downscale them to specific regions (e.g., cotton-based, livestock-based, millet-based), as was done for Mali, Ghana and Kenya (FAO 2004). Policy interventions to replenish soil fertility should take place at this so-called meso-level, which is sufficiently large to provide benefits for all farmers and small enough to target local policies that deal with local conditions. It also allows recognition of areas that managed to bounce back after a period of degradation, such as parts of the Mossi Plateau in Burkina Faso (Reij and Thiombiano 2003). However, FAO (2004) showed that at this level the availability of data, and especially spatial data, is problematic and often national data and maps have to be used. Therefore, the results of the soil nutrient balances at the national level offer a good starting point to target soil fertility policies at the lower level. One can choose a crop/farming system or a specific region where soil fertility decline is most pronounced or threatening farmers' income or food security. Besides, the spatially explicit soil nutrient balances at the national level offer the possibility for extrapolation of soil fertility research that was successful at the district or village level.

The nutrient balance is only an indicator of sustainability as far as soil fertility (management) is concerned; it does not reveal 'best practices' that make prevailing or alternative agro-ecosystems more sustainable. A functional link with nutrient stocks, farming systems, and integrated nutrient management systems is needed (Smaling and Dixon 2006). Results presented in kg ha^{-1} do not offer direct entry points for intervention and are not very meaningful for policy makers. They prefer outcomes in terms of yield loss or monetary values. A next step is therefore the linkage of soil nutrient balances to other tools and data to widen its use, e.g., a simple crop production model to express soil nutrient depletion in terms of yield losses. Other attractive indicators to possibly attach to the soil nutrient balance are the nutritive value of diets and food and cash need. Up to now the soil nutrient balance was presented as a static tool, which calculated soil nutrient balances for a specific year. The next step is to create a dynamic soil nutrient balance model, linked to a land use change model, which includes changes in land use and land management. The temporal dimension of such a model will improve the results, especially for dynamic farming systems.

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