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A decision-support model for monitoring nutrient balances under agricultural land use (NUTMON)

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ABSTRACT

A quantitative model of the balance between inputs and outputs of nitrogen, phosphorus and potassium in African land use systems (NUTBAL) was recently developed at two scales: supra-national (38 sub-Saharan African countries) and regional (Kisii District, Kenya). Calculating inputs (mineral fertilizer, organic manure, wet and dry deposition, biological nitrogen fixation, sedimentation) and outputs (removal of above-ground crop parts, leaching, denitrification, water erosion) led to the conclusion that there are considerable net fertility losses in each growing period.

In this paper, NUTBAL is elaborated into a decision-support model (NUTMON) to monitor the effects of changing land use, and suggest interventions that improve the nutrient balance. As input and output determinants cannot all be quantified equally well, the model recognizes primary data, estimates, and assumptions. The NUTMON determinants are mostly scale-neutral and can therefore be used to monitor nutrient balances at farm, regional, national and supra-national level. This is essential since the hierarchical levels interact. A number of recent interventions at the regional level (Kisii District, Kenya) are elaborated, including national fertilizer and produce price policies, fertilizer supply in small packages, zero-grazing, agroforestry, soil conservation measures, and increasing fertilizer use efficiency. It is shown that a major nutrient conservation effort in Kisii reduces nutrient depletion by approximately 50%, but does not entirely redress the N and K balance. To achieve the latter without reducing crop production, 75% of the district would have to be converted to a rotation system of maize and green manure cover crops, whereas 25% can remain under tea.

NUTMON has the potential to become a dynamic tool for land use policies, geared towards a balanced nutrient status in African land use systems. It can assist decision makers in determining the effects of current and alternative land use scenarios, taking account of both the productivity as well as the long-term sustainability of agro-ecosystems.

INTRODUCTION

Between 1975 and 1988, Africa's population grew from 415 to 610 million (FAO, 1989). This occurred in the absence of land use policies that address increased productivity simultaneously with sustainability of agro-ecosystems. Productivity is defined here as the output of valued product per unit of

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resource input, and sustainability as the capacity of a system to maintain output at a level approximately equal to or greater than its historical average (Conway, 1987; Lynam and Herdt, 1989).

As classical long-fallows have largely been replaced by systems of (semi-) permanent agriculture, maintenance of the soil nutrient balance has become a prominent requirement of agro-ecological sustainability. To follow on this theme, the United Nations Food and Agriculture Organization undertook to quantify the nitrogen (N), phosphorus (P) and potassium (K) balance in the root zone of 38 sub-Saharan African countries (Stoorvogel and Smaling, 1990; Stoorvogel et al., 1993). Production figures of 35 crops were used to define land use systems (LUS), characterized by nutrient inputs by mineral fertilizers (IN 1), animal manure (IN 2), wet and dry deposition (IN 3), biological N fixation (IN 4) and sedimentation (IN 5), and nutrient outputs by harvested crop parts (OUT 1) and crop residues (OUT 2), leaching (OUT 3), denitrification (OUT 4), and water erosion (OUT 5). Mean values of the nutrient balance ($\sum$ IN $-$ $\sum$ OUT) were -22 kg N, -2.6 kg P and -15 kg K per ha per year for the period 1982–1984. Not included were fluxes of nutrients within the soil, i.e. mineralization and immobilization of N and P in organic matter, surface retention of P by kaolinitic clay minerals and oxides, precipitation of P in salts, and adsorption/desorption of K in mica-derived clay minerals.

As scale-inherent simplifications were inevitable in this continental study, a similar nutrient balance study (NUTBAL) was done for the well-inventoried Kisii District in Kenya (Smaling et al., 1993). Table 1 shows that annual N and K depletion was severe, but the P balance was near equilibrium. Removal of nutrients in harvested product (OUT 1) was the strongest negative contributor to the balance, followed by water erosion (OUT 5) and, for N, leaching (OUT 3). In terms of land use, depletion was highest under pyrethrum (*Chry-*

TABLE 1

Nitrogen, phosphorus and potassium inputs (IN) and outputs (OUT) in the Kisii District (in kg ha^{-1} yr^{-1}; after Smaling et al., 1992)

	IN 1	IN 2	IN 3	IN 4	IN 5	OUT 1	OUT 2	OUT 3	OUT 4	OUT 5	Total
N	17	24	6	8	0	55	6	41	28	37	−112
P	12	5	1	nr	0	10	1	0	nr	10	−3
K	2	25	4	nr	0	43	13	9	nr	36	−70

IN 1: mineral fertilizers
IN 2: organic manure
IN 3: wet and dry deposition
IN 4: biological nitrogen fixation
IN 5: sedimentation
nr = not relevant.

OUT 1: removal of harvested crop parts
OUT 2: removal of crop residues
OUT 3: leaching
OUT 4: denitrification
OUT 5: water erosion

santhemum cinerariaefolium), with −147 kg N, −24 kg P, −96 kg K per ha per year, and maize with −105 kg N, +2 kg P, −83 kg K per ha per cropping season. Both crops received little fertilizer and provide poor soil cover in the early growth stages. Depletion of N and K was lowest under tea (−67 kg N, +6 kg P, −30 kg K per ha per year) and coffee (−82 kg N, 0 kg P, −34 kg K per ha per year).

Both studies showed that the soil nutrient pool is exploited every cropping season in order to allow nutrient export through agricultural products. As the land use systems involved are currently not sustainable, it is relevant to monitor soil nutrient balances in order to suggest corrective agronomic and policy interventions. This requires data collection and the formulation of land use scenarios based on regularly updated databases, to be used by decision makers at different levels in the agro-ecosystem hierarchy.

The present article describes a multi-level decision-support model for monitoring the soil nutrient balance (NUTMON). The model is developed on the regional level, using data from the Kisii District, Kenya. The regional level is the most appropriate for establishment and operationalization of the model. Possible corrective actions can be judged in relation to both national as well as farming system levels. National agricultural policies (e.g., produce prices, fertilizer subsidies) act as boundary conditions at the regional and farm level, whereas regional policies have to take account of constraints at the farm level such as capital and labour availability and land ownership.

MATERIALS AND METHODS

The structure of NUTMON

NUTMON is fed by a number of basic data, and by nutrient input and output data (Table 2). Basic data include the hectarage of the arable land, and the spatial patterns of land use systems, i.e. the combination of prevailing soils and climate on the one hand, and cropping and livestock systems on the other hand. Nutrient input and output data are reflections of the processes IN 1-5 and OUT 1-5. Each process has a certain value, and the nutrient balance is given by $\sum$ IN − $\sum$ OUT. This figure is the output of NUTMON for a given LUS at a given point in time. A second monitoring exercise at a later stage may yield different results, which may be due to changes in the LUS, or changes in the individual nutrient input and output values. As the changes have either aggravated or ameliorated the nutrient balance, NUTMON can support decision-making in the interest of sustainable forms of agriculture.

To determine nutrient input and output values, a step-wise approach is proposed, in which the different determinants of IN 1-5 and OUT 1-5 are calculated, estimated or assumed (Table 2). Some steps relate to data that are eas-

TABLE 2

The structure of NUTMON

Step	Description	Unit	Input
1-1	Fertilizer sales in the district	ton fertilizers	
1-2	Fertilizer types and NPK content	ton NPK	IN 1
1-3	Fertilizer application in each LUS	kg NPK per ha	
2-1	Livestock types and numbers in the district	x_i cows, y_j goats, z_k sheep, etc. stubble grazing,	
2-2	Livestock systems in the district	tethering, browsing, pastoralism, etc.	
2-3	Number and systems in each LUS	x_1 cows, 20% zero-grazing (graded), 80% browsing (zebu), etc.	
2-4	Manure collection for agricultural use in each LUS related to livestock systems	ton dry manure per ha	IN 2
2-5	Manure NPK content and loss percentage (L) before application	$(100-L)\% \times$ kg NPK per ha	
2-6	Household waste and NPK content for each LUS	kg NPK per ha	
2-7	Town and industrial refuse and NPK content for each LUS	kg NPK per ha	
3-1	Available point data on wet and dry deposition of NPK in the district	kg NPK per ha	
3-2	Development of suitable transfer functions on data points outside district	TF1	IN 3
4-1	Type and hectarage of N-fixing species in each LUS	a_1 ha groundnuts, b_1 ha wetland rice	
4-2	Percentage of N uptake (OUT 1+2) attributed to symbiotic fixation	e.g. groundnuts: 50%, wetland rice: 75%	IN 4
4-3	Contribution from non-symbiotic N-fixation via direct measurement or transfer functions	kg N per ha TF2	
5-1	Quantities of flood and irrigation water reaching LUS	m^3 water	
5-2	NPK content of waters for each LUS	kg NPK per ha	IN 5
6-1	Yield and hectarage of crops and pastures in the district	a_i tons coffee on p_i ha, b_i tons maize on q_i ha	
6-2	Yields and hectarage of crops and pastures in each LUS	a_1 tons coffee on p_1 ha, b_1 tons maize on q_1 ha	

Step	Description	Unit	Output
6-3	Nutrient content of crops and grasses	kg NPK per ton coffee, maize etc.	OUT 1
6-4	Nutrients in harvested parts per LUS	kg NPK per ha	
7-1	Amount of crop residues per LUS	6-2 in combination with harvest index	
7-2	Destination of residues in each LUS (residue management)	*r*% complete removal, (100-*r*)% left on the field	
7-3	Nutrient content in removed residues	kg NPK per ton coffee, maize etc.	OUT 2
7-4	Nutrients in removed residues per LUS	*r*% × kg NPK per ha	
8-1	Available point data on N and K leaching in the district	kg NK per ha	
8-2	Development of suitable transfer functions from data points outside the district	TF3	OUT 3
9-1	Available point data on denitrification in the district	kg N per ha	
9-2	Development of suitable transfer functions from data points outside the district	TF 4	OUT 4
10-1	Available point data on soil loss by erosion in the district	kg soil per ha	
10-2	NPK content of eroded soil	kg NPK per ha	OUT 5
10-3	Development of suitable transfer functions	TF 5	

Basic data requirements:
1. Size of the district and its arable land (ha).
2. Land use types: crops, livestock, forestry, game parks (LUT; ha).
3. Land units: rainfall and temperature zones, landforms and soils (LU; ha).
4. Land use systems: matching 2 and 3 (LUS; ha).
5. Population density (persons per km^2) and growth rate (% per yr).

ily measured or obtained from agricultural offices (e.g. step 1-1, 6-1), but others relate to more complex processes (step 8-1, 9-1). Some data need continuous recording, while others are required irregularly, e.g. once in 5–10 years. It is therefore convenient to group the data according to type, source and frequency of collection, as indicated in Table 3.

For IN 2, for example, the type of data required is livestock numbers and systems, the amount of manure reaching the arable field, and its nutrient content at the time of application. Similar information is needed on household waste and urban and industrial refuse, if applicable. With the necessary effort, steps 2-1 to 2-7 in Table 2 can thus all be measured (t-1 in Table 3). For OUT

TABLE 3

Data types, sources and required frequency of recording in NUTMON

Type		
t-1	Primary data	Direct measurement or retrieval from existing data bases
t-2	Estimates	Combinations of primary data and empirical quantitative relations (transfer functions)
t-3	Assumptions	Use of literature data and common sense, due to lack of primary data and transfer functions
Source		
s-1	Agricultural statistics	Agricultural extension, research institutes, produce and marketing boards, fertilizer market
s-2	Field observations	Soil, climate and crop-related measurements and farming system analysis
s-3	Laboratory analysis	Soil, plant, water and fertilizer/manure analysis
s-4	Specific research	Amongst others: calibration and validation of transfer functions
Frequency		
f-1	Seasonal (dynamic)	Properties that are dynamic over one growing period
f-2	Seasonal (static)	Properties that are static over one growing period, but dynamic over several growing periods
f-3	(Multi)-annual	Properties that are static over several growing periods

3, however, primary data for all LUS are seldomly available. Yet, Burns (1975) has shown that N leaching can be predicted when data are available on rainfall, initial and field capacity moisture content, inorganic soil N content and fertilizer rates. The required data are all measurable, but the relation between leaching and these determinants is an empirical "pedotransfer function" (Addiscott and Wagenet, 1985; Bouma and Van Lanen, 1987), resulting from regression analysis on scattered point observations. Hence, the value for OUT 3, obtained when entering the collected primary data in the transfer function, is no more than an estimate (t-2 in Table 3). Specific research is needed to validate the pedotransfer functions. Those used in NUTBAL (Smaling et al., 1993) are given in Table 4. Point data on, for example, atmospheric deposition (IN 3) may be non-existent in a country. NUTMON then uses assumptions based on supra-national point data (t-3 in Table 3).

Collection of data throughout the growing period (Table 3, frequency: f-1) is required on fertilizer sales in the region (Table 3, source: s-1), rainfall totals and intensities, temperature, development of leaf area index, and erosion rates (s-2). Data that are only to be monitored once per growing period (f-2) encompass hectarage of agricultural land, cropping and livestock systems with geographical distribution (s-1), fertilizer and manure application rates, hectarage and yields of crops with harvest indices, pastures and forests, residue removal from the field and destination, hectarage of N-fixing species, fallow

TABLE 4

Use of measurable determinants in transfer functions (after Smaling et al., 1993)

Measurable determinants	Transfer functions (TF)				
	1	2	3	4	5
Mean annual rainfall	×	×	×	×	×
NPK in mineral fertilizers			×	×	
NPK in manure at application			×	×	
Soil N mineralization			×	×	
Clay content			×	×	×
Total soil N			×	×	×
Total soil P					×
Total or exch. soil K			×		×
Rainfall intensity					×
Erodibility factor K					×
Slope gradient S					×
Slope length L					×
Land cover factor C					×
Land management factor P					×
Enrichment factor					×
Soil formation					×

TF 1: Nutrient input by wet deposition (IN 3; kg ha^{-1} yr^{-1}) is linked with the square root of average rainfall (rn, in mm/yr):

$N=0.14\times\sqrt{rn}$

$P=0.023\times\sqrt{rn}$

$K=0.092\times\sqrt{rn}$

TF 2: A small rainfall-dependent contribution A (kg ha^{-1} yr^{-1}) from non-symbiotic N-fixers was accounted for in each LUS:

$A=2+(rn-1350)\times0.005$

TF 3: Total mineral soil N in the 0–20 cm layer (N_{min}; kg per ha) was calculated from total soil N, assuming a fixed annual nitrogen mineralization rate M:

$N_{min}=20\times N_{tot}\times M$

Leaching of nitrogen, subdivided in LN_{soil} and LN_{fert}, ranges between 15 and 40% of N_{min} and (IN 1 + IN 2) respectively, depending on rainfall and clay content.

TF 4: Denitrified soil N (DN_{soil}, percentage of N_{min}) and fertilizer N (DN_{fert}, percentage of IN 1 + IN 2) are calculated from

$DN=-9.4+0.13\times clay\%+0.01\times rn$

TF 5: Erosion in the Kisii District was calculated along the lines of the Universal Soil Loss Equation (Wischmeyer and Smith, 1978), which estimates annual soil loss per ha as a function of rainfall erosivity (R), soil erodibility (K), slope gradient (S) and slope length (L), land cover (C) and land management (P).

$R=0.25$

$K=f$(clay content, organic matter content, permeability); range 0.06–0.08

$S=(0.43+0.3\times slope\,\%+0.043\times(slope\,\%)^2)/6.613$

$L=(slope\ length/22.13)^{0.5}$

$C=f$(crop type and development); range 0.01–0.5

$P=0.2+0.03\times slope\,\%$

percentage, soil conservation measures (s-2), nutrient content of soils, eroded sediment, fertilizers, manure, flood and irrigation water, and plant tissue (s-3). Multi-annual monitoring (f-3) relates to farm size distribution, organization of the agricultural extension service and produce and marketing boards, government produce and fertilizer price policies, and world market price development (s-1), and on some relatively stable soil properties, such as soil texture, bulk density and pH (s-3). Finally, literature search and specific regional research (s-4) is required on the different components of the nutrient balance. Examples are the deposition of nutrients in dust and rain (e.g. Poels, 1987), correlation between decomposition of organic matter and moisture and temperature (e.g. Jenkinson and Ayanaba, 1977), biological N-fixation in different agro-ecosystems (e.g. Giller and Wilson, 1991), solute leaching (e.g. Addiscott and Wagenet, 1985), denitrification rates under different soil and hydrological conditions (e.g. Von Rheinbaben, 1990), erosion under different slopes, cropping systems and land management, determination of the enrichment factor for eroded soil, and rates of soil formation by weathering (Ollier, 1979; Stocking, 1984; Lal, 1988).

Entering regional data into NUTMON

Basic data

The analyses in this study used data prior to 1989. At this time, the Kisii District in southwestern Kenya covered 220,000 ha of which 80% was considered suitable for agriculture (Government of Kenya, 1985–1990)*. Population was estimated at 1.5 million (680 inhabitants per km^2), the growth rate was 3.8% per year, and there were approximately 110,000 farm holdings. Data on land and land use were taken from Wielemaker and Boxem (1982) and Jaetzold and Schmidt (1982).

Soil units and rainfall zones are indicated in Fig. 1. Soils are predominantly well drained, very deep and rich in nutrients, with the exception of P (mainly Phaeozems and Nitisols; FAO, 1988). Mean annual rainfall ranges between 1350 and 2050 mm. Rainfall is bimodally distributed with peaks in April and November.

Farmers use approximately 0.5 ha of their holding for food crops, i.e. mainly intercropped maize and beans (*Phaseolus vulgaris*), and smaller portions of sweet potato, finger millet, and cabbages. Cash crops are grown on 0.2–0.5 ha and include tea and pyrethrum in the eastern parts, and coffee, banana and sugarcane, mainly in the western parts of the district. The remainder of the holding is occupied by homesteads, small improved pastures and, in the drier

*In 1989, the Kisii District was subdivided into Kisii and Nyamira District. The "new" Kisii District (southern, western and central parts of the "old" district) has an area of 131,500 ha, of which 102,600 ha is suited for agriculture.

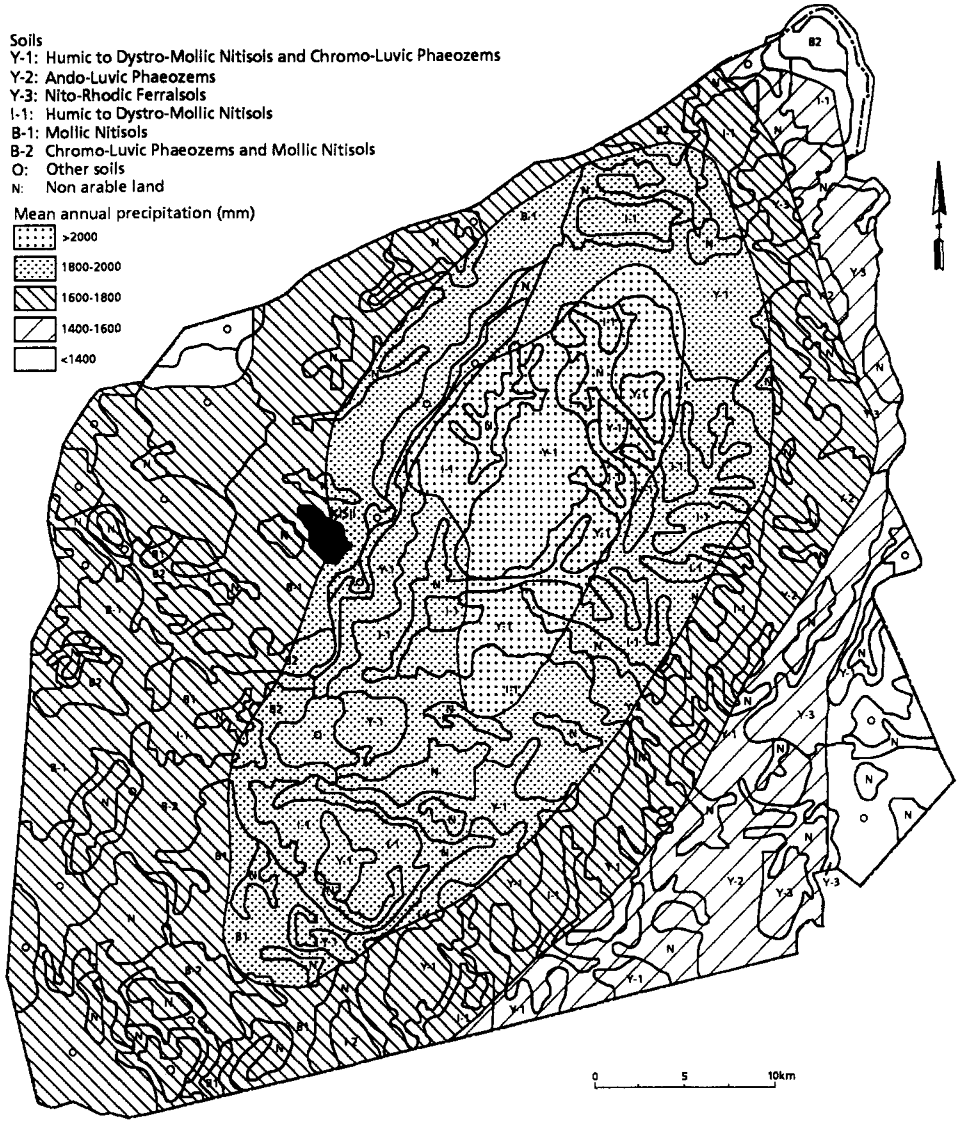

Fig. 1. Soil units and rainfall zones in the Kisii District.

parts of the district, bushland for livestock. Due to population pressure, only about 5% of the cultivated land in the district is left fallow each year.

Nutrient input data

IN 1 Table 5 shows that fertilizer consumption rose sharply during the 1980's.

TABLE 5

Fertilizer sales in Kisii between 1981 and 1991 (in tons)

Fertilizer	1981	1984	1987	1991*
25:5:5+5S	465	830	1500	2756
20:20:0+CAN	65	95	522	884
DAP+TSP	106	185	283	2232
Other	18	63	60	24
Total	654	1173	2364	5896

*For the "new" Kisii District, after subdivision (102,600 ha).

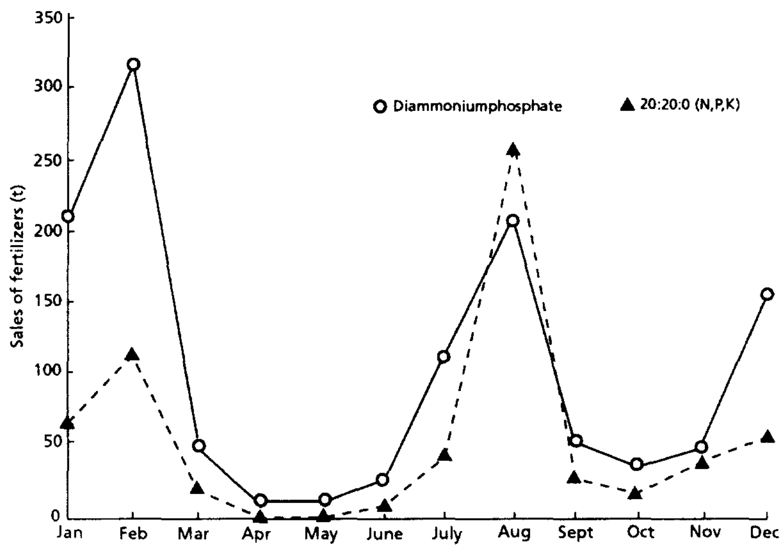

Fig. 2. Sales of DAP and 20:20:0 in the Kisii District through the year 1990.

Moreover, there was a shift away from straight fertilizers such as triple superphosphate and calcium ammonium nitrate towards the compound fertilizers diammoniumphosphate, 20:20:0, and 25:5:5+5S. In 1991, the latter was entirely applied to tea, and the other fertilizers to maize (70%) and pyrethrum and horticultural crops (30%). Coffee was not fertilized due to very low produce prices. The total tonnage of fertilizer, applied in 1991 in the "new" Kisii District coincides with an average fertilizer input (IN 1) of almost 20 kg nutrients per ha. Real fertilizer use is still higher, as not all stockists are included in the district records. Figure 2 shows that farmers apparently apply fertilizers during two periods of the year, in December–February for the long rains, and in July–August for the short rains.

IN 2 The district accommodates approximately 600,000 cows (1/3 grade, 2/3 local zebu) and 250,000 goats and sheep, mainly in a form of "semi-zero-grazing" (Government of Kenya, 1985–1990). The animals stay overnight in kraals, where they feed on residues of maize and banana. The manure is collected and stored for later application on arable fields. During daytime, cows are generally tethered on small improved pastures, whereas goats and sheep roam along the roadside and in bushland. For pastures, it was assumed that an estimated percentage of what is exported through grazing is returned in manure. Nutrients in manure are partly lost during storage by leaching, denitrification and ammonia volatilization, whereas nutrients in urine are lost almost entirely. Household waste and other refuse with varying nutrient contents are applied to cabbages and vegetables in the homegarden.

IN 3 Due to lack of point data on wet and dry deposition in the district, transfer functions were used, as previously established during the supra-national study (Stoorvogel et al., 1993), plotting nutrient input against the square root of average annual rainfall (Table 4).

IN 4 The hectarage of beans in the different LUS was 34,200 ha in 1987–88 (Table 6). It was assumed that beans, the only N-fixing arable crop in the district, draw 50% of their total N requirement from the atmosphere, and 50% from the soil (Giller and Wilson, 1991). For asymbiotic fixation, a small rainfall-dependent contribution was assumed (Table 4).

IN 5 Sedimentation did not play a role, as all bottomlands and floodplains

TABLE 6

Hectarage and yields (kg ha^{-1}) of major crops in Kisii; normative good yields (kg ha^{-1}) (after Wielemaker and Boxem, 1982)

Crop	1985–1986		1987–1988		Normative good yield
	ha	yield	ha	yield	
Coffee	7000	5080	7100	4110	7500 berries
Tea	13,400	4190	14,400	4290	5000 green leaves
Pyrethrum	2500	330	2800	470	750 dried flowers
Maize	51,800	3600	53,200	3550	6000
Beans	27,800	990	34,200	950	4000 pulses
Finger millet	3600	820	3200	840	1500
Banana	20,800	17,000	21,900	18,400	30,000
Sweet potato	2500	7000	1700	17,500	17,500
Cabbages	1100	15,000	1300	13,170	40,000
Sugarcane	no data	no data	3100	13,500	12,000 sugar

have periodic flooding and salinity and sodicity problems, and are thus not used for agriculture.

Nutrient output data

OUT 1 Table 6 shows crop hectarages and yields. By 1985, 62,000 farmers planted coffee on 7000 ha, and 43,600 farmers planted tea on 13,000 ha. Pyrethrum occupied up to 20,000 ha in the mid-seventies, then declined sharply to 1000 ha, but recent price incentives caused a rapid resurgence to 2800 ha in 1988. All farmers grow maize, very often intercropped with beans. In the warmer parts of the district, two crops of maize and beans can be grown in a year. In the colder zones, however, maize takes at least six months to mature, and beans are grown solely during the second season. Bananas are popular as a result of low labour input requirements and instant payment by traders from outside the district. Nutrient contents of the different crops were taken from Wielemaker and Boxem (1982).

OUT 2 The bulk of the residues of maize and banana is fed to livestock outside the arable field. The remaining maize stover is applied as a surface mulch. Most of the beans and sugarcane residues also remain in the field. The latter is often burned, implying almost complete N loss. Husks of coffee beans are widely used as a mulch. Pyrethrum residues are partly turned into nutritious cattle feed (Government of Kenya, 1985–1990).

OUT 3,4 Point data on leaching and denitrification are scarce in the tropics; hence, transfer functions were established, using recognized determinants such as rainfall, texture, soil N and K content, and fertilizer input (Table 4). A detailed description of the procedure is given by Smaling et al. (1993).

OUT 5 Erosion rates have been recorded in various parts of Kenya. They are mostly expressed in soil loss per ha, and still need to be converted into nutrient loss. In NUTBAL, the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978) was calibrated for the Kisii District. As Table 4 shows, a large number of determinants had to be measured to cover all the USLE factors. Values for N, P and K loss per ha still have to be multiplied with an estimated enrichment factor for eroded sediment, which is richer than soil in situ. Finally, a weathering factor is assumed for P and K (25% of OUT 5), representing new formation at the root base.

Assessing the effect of current agronomic practices and policy interventions using NUTMON

The above approach was followed to calculate the nutrient balance for the Kisii District. Attention was then turned to possible interventions, necessary to rectify or at least alleviate the unbalanced situation. A number of recent national and regional interventions are mentioned, which have had an impact on the nutrient balance, although not explicitly intended.

National price policies

Fertilizer subsidies and the artificially low consumer prices for the major food crops were recently abolished. This affects entire LUS, and in the nutrient balance, mainly IN 1 and OUT 1. The net effect of this national intervention on the nutrient balance follows from annual NUTMON updates.

Fertilizer supply

A recent incentive to farmers has been the supply of fertilizers in small packages, increasing IN 1. Figure 3 shows that 10 kg bags of fertilizer accounted for 41% of the total amount of diammoniumphosphate sold in 1990, with peak sales in January and July, prior to the rainy seasons. The subsequent decreases were the result of reduced availability, forcing farmers to buy 25 and 50 kg bags.

Zero-grazing

Owing to the virtual absence of idle land in the district, the scope for increasing stocking rates is limited. However, improvements in the quality and husbandry of livestock are supported by the government, in the form of establishment of zero-grazing units. The implications for NUTMON are an increase

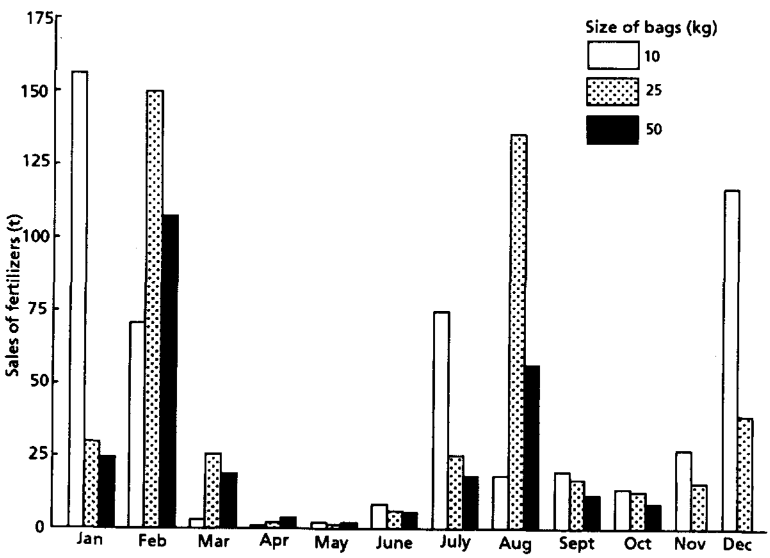

Fig. 3. Sales of DAP fertilizer in bags of different sizes through the year 1990.

in IN 2, because of better storage opportunities, and a reduction in OUT 5 when fodder grasses are planted on contour bunds.

Nitrogen fixation in beans

No use is made of *Rhizobium* inoculant to increase IN 4, as farmers do not yet consider beans important enough. Nadar and Faught (1984) found that sequential maize and beans systems often outyielded intercropping systems, which are common in the Kisii District. If in rotation systems beans would withdraw 75% instead of 50% of their N requirement from the atmosphere (Giller and Wilson, 1991), an increase of 30 kg N per ha of maize/beans rotation can be obtained in IN 4. Such improvements are triggered by the application of P fertilizer, enhancing nodulation.

Agroforestry

Planting of leguminous tree species has gained momentum in the past decade, although farmers often appreciate trees for other reasons (Kerkhof, 1990). *Calliandra calothyrsus, Sesbania sesban* and *Leucena leucocephala* are highly valued. *Grevillea robusta* is popular too, but is not a leguminous species. Approximately 50% of the farming community has adopted agroforestry practices, which can increase IN 4, reduce OUT 3 and OUT 5, and add nutrients to the topsoil from layers not accessible for the roots of annual crops.

Soil conservation

Soil conservation is gaining momentum as a result of active promotion by the government. A catchment approach was adopted, where the inhabitants of an entire village collaboratively undertake the protection of their land. The output includes cut-off drains, terraces, stonewalls and waterways, but also low-input farm operations such as ploughed strips, grass strips, cover crops, intercropping and mulching. In addition to reducing OUT 5, the latter practices may also increase IN 4 and reduce OUT 2.

Fertilizer use efficiency

Most nutrients leave the LUS in the harvested crop parts (OUT 1). In a situation of land scarcity as in the Kisii District, lowering this output is tantamount to lowering crop production. Next, farmers only increase fertilizer use (IN 1) when they expect crop harvests (OUT 1) to increase as well. Economic and environmental gains can both be obtained by increasing the ratio OUT 1/IN 1, i.e. the fertilizer use efficiency. This can be achieved by synchronizing type and amount of fertilizer and timing of application to the prevailing chemical soil fertility and the requirements of the crops to be grown in well-defined agro-ecological units (Smaling and Van de Weg, 1990). Fertilizer use on the basis of prevailing agro-ecological conditions implies increases in IN 1 and IN 2. This is offset by higher crop yields and nutrient withdrawal

(OUT 1), but the net benefit for the nutrient balance is that more residues are produced which can be left in the field, thus reducing OUT 2, fewer inputs are lost through leaching (OUT 3) and denitrification (OUT 4), and better crop development with higher leaf area indices reduces erosion (OUT 5). A certain fraction of the fertilizer (mainly P) may remain in the soil and contribute to soil fertility restoration.

Different land use scenarios

Knowing the current developments in the district, realistic changes in land use can be proposed, and their effect on the nutrient balance assessed. Three NUTMON scenarios were described, including agro-forestry practices (Scenario 1), zero-grazing and soil conservation (Scenario 2), and changing LUS (Scenario 3). As the phosphorus balance is positive in all scenarios, the attention is focussed largely on the nitrogen and potassium balances.

NUTMON Scenario 1 has NUTBAL (Table 1) as a starting point. In addition, it encompasses agroforestry practices in 50% of the district, occupied by annual crops and pastures. The changes in the nutrient balance for this area are assessed at:

- IN 4: +100% (inclusion of leguminous tree species),
- OUT 2: −50% (tree mulch partly replacing residues as fuel/fodder),
- OUT 3: −75% (interception of leaching nutrients and pumping up of nutrients not accessible to roots of annual crops),
- OUT 5: −50% (lowering of erodibility, slope length and crop cover factors in the USLE).

NUTMON Scenario 2 has Scenario 1 as a starting point. In addition, it includes zero-grazing and soil conservation practices. The changes brought about in the nutrient balance are assessed at:

- IN 2: +50%, in 50% of the district (better storage and efficient use of animal manure),
- OUT 5: −75%, for the entire district (successful catchment approach).

NUTMON Scenario 3 has Scenario 2 as a starting point. In addition, land use changes are proposed as follows: 25% of the district is to remain under tea, as it is a major foreign exchange earner. The changes brought about in the nutrient balance are assessed at:

- IN 1, OUT 1, OUT 2: data from Smaling et al. (1993) for tea,
- OUT 3, OUT 5: −75% of the mean value for the district (deep rooting and soil protecting crop),
- OUT 4: −50% of the mean value for the district (rain water reaches the surface gently, low risk of ponding and local saturation of soil aggregates).

The remaining 75% percent of the cultivated area is converted into a rotation of maize and green manure cover crops. The changes brought about in the nutrient balance are assessed at:
- IN 1: 0 kg N and K per ha,
- IN 4: +100%+35 kg N per ha (N fixing capacity of the green manure crop),
- OUT 1: 41 kg N and 12 kg K per ha (Smaling et al., 1992).
- OUT 2: 39 kg N and 49 kg K per ha (Smaling et al., 1992),
- OUT 3: −75% (no fertilizer leaching).

RESULTS AND DISCUSSION

Impact of interventions on the nutrient balance

NUTBAL was calculated by Smaling et al. (1993), and shows that $\sum$ IN − $\sum$ OUT is −112 kg N, −3 kg P and −70 kg K per ha per year, in the absence of corrective agronomic practices (Table 1). The results of the three alternative NUTMON scenarios are shown in Table 7. In Scenarios 1 and 2, improvements

TABLE 7

Agronomic interventions in the Kisii District, ameliorating the soil nutrient balance, using NUTMON (Scenarios 1, 2 and 3)

	IN 1	IN 2	IN 3	IN 4	IN 5	OUT 1	OUT 2	OUT 3	OUT 4	OUT 5	Total
Scenario 1: Agro-forestry programme in 50% of the district											
N	17	24	6	12	0	55	5	26	28	28	−83
K	2	25	4	nr	0	43	10	5	nr	27	−54
Scenario 2: Soil conservation programme in 100% of the district; zero-grazing units in 50% of the district											
N	17	30	6	12	0	55	5	26	28	9	−58
K	2	31	4	nr	0	43	10	5	nr	9	−30
Scenario 3a: Tea in 25% of the district											
N	43	0	6	8	0	70	0	10	14	9	−46
K	5	0	4	nr	0	35	0	2	nr	9	−37
Scenario 3b: Maize/green manure rotation in 75% of the district											
I. Maize											
N	0	36	6	16	0	41	19	10	28	9	−49
K	0	37	4	nr	0	12	24	2	nr	9	−6
II. Green manure											
N	0	36	6	85	0	0	0	10	28	9	+80
K	0	37	4	nr	0	0	0	2	nr	9	+30

are considerable, but N and K outputs still exceed the inputs. In Scenario 2, the annual N and K losses amount to approximately 50% of those in NUTBAL.

In Scenario 3, a balanced situation is reached in the district with respect to N and K. Under tea and maize, nutrient outputs still exceed nutrient inputs, but the green manure crop is included to offset the negative balance. To equilibrate the N balance, the green manure crop, for example *Mucuna* or *Pueraria*, should fix 69 kg N per ha, on top of the N fixed by the leguminous tree species of Scenarios 1 and 2 (16 kg N per ha). According to Juo and Kang (1989) and Giller and Wilson (1991), a well-established green manure can even fix 100 kg N per ha and above. The average balance for the rotation system is now +15.5 kg N and +12 kg K per ha per year. As this system comprises 75% of the total cultivated area, it offsets the −46 kg N and −37 kg K that is realized in the tea-based system, as can be derived from the following equation:

$$0.25 \times \mathrm{BAL}_{tea} + 0.75(0.5 \times \mathrm{BAL}_{maize} + 0.5 \times \mathrm{BAL}_{green\ manure}) \quad (1)$$

Maintaining maize production in NUTMON *scenario 3*

The common soil type I-1 (Fig. 1) has approximately 5000 kg N per ha, and is able to supply 150 kg N per ha at an annual mineralization rate of 3% (Smaling et al., 1993). This is sufficient to replenish the negative nitrogen balance figures arrived at in Scenarios 1 and 2. Nitrogen is apparently not limiting crop production on this soil for a period of at least $(5000 - \mathrm{BAL}_N/0.03)/\mathrm{BAL}_N$ years, in which BAL_N is the absolute value of the nitrogen balance. For Scenarios 1 and 2, BAL_N is equivalent to 83 and 58 kg per ha, implying that soil I-1 can adequately replenish the nitrogen balance for periods of 27 and 53 years respectively.

Meanwhile, fertilizer trials on the same soil revealed that maize yields were 2.7 t per ha (unfertilized), 4.4 t per ha (on applying 22 kg P per ha), and 5.8 t per ha (with an additional application of 5 t farmyard manure per ha) (Smaling et al., 1992). In other words, yields can be doubled by applying modest amounts of P fertilizer and manure. Maize yields in Scenario 3 can thus be maintained in spite of the reduction in cultivated area by 50%. The other 50% will recuperate under green manures, which, once established satisfactorily and fixing at least 69 kg N per ha, may partly be harvested to serve as a protein-rich cattle fodder. In such a way, the sustainable Scenario 3 may still appeal to farmers as crop production is not adversely affected, by virtue of the high P fertilizer use efficiency. Phosphorus is limiting production, and by applying it in fertilizer, more efficient use is made of the nitrogen and potassium reserves in the soil. As a consequence, no N and K fertilizers have to be applied to maize in Scenario 3, reducing total leaching losses. The rotation system does not have to be temporal. A farmer can accommodate 50% of both components at the same time, swapping them after every year. The tea system should also be included in the spatial rotation as soon as a tea stand has reached the end of its productive life cycle.

Applying NUTMON *at different scales*

Agro-ecosystems comprise various system levels that combine the biological hierarchy, ranging from the crop or pasture to the highest scale of the continent (or even the biosphere), with socio-economic units ranging from household to supra-national political system (Fresco et al., 1990). The concept of nutrient balance applies at each level, from the crop (field) to the region or the country and, finally, the continent. The determinants in NUTMON are mostly scale-neutral and can therefore be used to monitor nutrient balances at each hierarchical level. This is essential since the hierarchical levels interact and cannot be studied in isolation. The interaction takes shape in two directions: (a) each level constitutes an aggregation of nutrient balances at lower levels, so that, for example national nutrient balances can be calculated from combined regional level data sets, and (b) higher level policies may shape actions at lower levels, as is the case in the Kisii District, where booming pyrethrum prices have led farmers to apply fertilizer, manure and erosion control measures. Interventions at the national level can have a direct impact on IN 1 and OUT 1 at regional level. In addition, regional policies can markedly improve IN 2 and IN 4, and reduce OUT 2 and OUT 5. This applies particularly to Kenya, where a district focus for rural development was launched in the recent past. Positive effects on OUT 3 and OUT 4 also occur, but are indirect and less visible. The farmer is, in principle, able to influence all these input and output processes, depending on the relative profitability of land use alternatives.NUTMON can be used at national, regional, and farm level, and the data sets obtained can be interlinked. Monitoring of nutrient balances and the effects of interventions should be carried out in a comprehensive way, combining details from each of the levels.

REGNUTMON, the regional level model elaborated in detail in this article, consists of a fixed data base and continuous updates. It indicates both the gaps in knowledge as well as the effects of possible interventions. Regional agricultural staff should be aware of the potential and receptiveness of local farming systems as regards integrated nutrient management. Translating nutrient loss in economic terms, as was done by Van der Pol (1992) in the southern region of Mali, may appeal to decision makers at this level.

FARMNUTMON, the farm level application of NUTMON, allows the inclusion of land use specifications that are insufficiently reflected in the regional model, such as individual farmers' deviations from average cropping patterns. It also permits the setting of different boundary conditions of holding size, labour and capital, that limit cropping patterns, and the introduction of alternative practices to redress the nutrient balance. FARMNUTMON can not only be used as a decision support tool for individual farms, but also as a technique to generate data on "representative farm types" in a district, in order to produce more detailed specifications on relative losses per farm type and the flexibility of different farmers to absorb nutrient saving techniques. At farm level, considerable transfers of nutrients may take place through the application of manure or household waste. A seemingly stable balance may be achieved for plots surrounding the farm house, while at the same time nutrient depletion is rampant in the more distant parts of the farm. REGNUTMON can therefore not consist of a simple aggregation of farm level nutrient balances.

NATNUTMON, the application of NUTMON at national level, combines the standardized regional data bases on nutrient balances. As a policy tool, it sets objectives with respect to target production for each community, land tenure, subsidies and prices etc., and assesses their effects. It also reflects (multi)-annual dynamics in the national fertilizer industry, trade, consumption and handling in a country. The work done in this respect by the International Fertilizer Development Center in Togo and Burkina Faso deserves attention (André, 1990; André et al., 1991). Furthermore, the impact of large scale, subnational interventions such as reforestation or hydroelectric dams on the national nutrient balance can be estimated. NATNUTMON is most effective when updated regularly, say every 4–5 years. It can then be fed into a supranational (subcontinental) model, not only to improve assessments of nutrient depletion at that scale, but also to determine priorities for international research, and to formulate policies that transcend national boundaries. In the longer term, it may be employed to monitor effects of global change on agro-ecological zones and the corresponding effects on land use, as well as the effects of changes in land use on global models (Scharpenseel et al., 1991).

CONCLUSIONS

(1) Agricultural production systems are in a permanent state of change. As far as nutrient management is concerned, the direction and magnitude of this change is dictated by changes in any one or more of the NUTMON determinants discussed in this article. NUTMON indicates what types of data need to be monitored and priorities for data collection to refine it. Then, the effects of interventions aimed at amelioration of the soil nutrient balance can be assessed. NUTMON can become a dynamic tool for land use policies, geared towards a balanced nutrient status in agricultural LUS. The model is scale-neutral and links data at farm, regional, national and supra-national levels.

(2) At the regional level (Kisii District, Kenya), some current interventions were shown to alleviate a strained nutrient balance, but they do not entirely redress it in a situation of continuous cultivation. An attempt to balance all nutrients in the arable land implies that 25% of the district can remain under tea, whereas another 75% should be put to a spatial or temporal rota-

tion of 50% annual cropping and 50% green manuring. The latter land use scenario does not necessarily have to be "socially unacceptable", as it was found that modest applications of P fertilizer and manure can raise maize yields from 2.7 to around 5 t per ha. Continuous cultivation without interventions is definitely "environmentally unacceptable", as crop yields will decline with time. The playground in between such social and environmental boundaries is what we call "integrated nutrient management systems", which can be quantified with the help of NUTMON.

(3) Many of the ways of influencing the nutrient balance discussed here are feasible in the Kisii District by virtue of favourable soil and climatic conditions. The potential for agroforestry and zero-grazing systems, for example, is much higher in the Kenyan highlands, than in a situation of low biomass production such as in Mali (Van der Pol, 1992). In such areas, however, topography is much flatter and soils are less fertile, thus having less to lose than soils enriched by volcanic materials in areas with rolling topography.

(4) Data requirements for NUTMON are considerable and demand a serious investment. Nonetheless, in many parts of the world numerous sources of LUS data exist that have hardly been integrated into a decision tool. At the same time, however, in spite of the wealth of information on a district like Kisii, many data are only available in the form of assumptions or estimates. Whatever the situation, the integration of existing information and a continuous updating of NUTMON will assist decision makers in determining the effects of current and improved land use scenarios.

(5) NUTMON takes account of both productivity as well as sustainability, operationalized here as the maintenance or improvement of the soil nutrient status (Conway, 1987; Fresco and Kroonenberg, 1992). Decisions on sustainable land use require a calculation of the effects of alternative scenarios at different hierarchical levels, including specific sets of boundary conditions acceptable to different groups of users (farmers, extensionists, conservationists, politicians) in their spatial and temporal perspective. Once tested and operational, NUTMON may be turned into a decision-support system, comparing and advocating "nutrient-friendly" land use alternatives through optimization procedures.

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