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Calculating soil nutrient balances in Africa at different scales

II. District scale

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Abstract

In a recent study on the NPK balance of land use systems in sub-Saharan Africa, it was found that scale-inherent simplifications were inevitable (Stoorvogel et al., 1993). This article reports on a similar exercise in a well-inventorized smaller area (Kisii District, Southwestern Kenya). Land use types and land/water classes (combinations of rainfall zones and soil units) were combined into geographically well-defined land use systems with NPK inputs by mineral fertilizers, manure, wet and dry deposition, and biological N fixation, and outputs by aboveground crop parts, leaching, denitrification, and erosion. Primary data were available on applied mineral fertilizers and manure, crop yields, nutrient contents, residue removal and erosion. Deposition, leaching and denitrification were estimated using rainfall, clay, N and K content, and fertilizer input. Erosion was estimated along the lines of the Universal Soil Loss Equation.

The aggregated nutrient balance for the Kisii District was $-112\,kg\,N$, $-3\,kg\,P$, and $-70\,kg\,K\,ha^{-1}\,yr^{-1}$. For all nutrients, removal of harvested product was the strongest negative contributor, followed by erosion. In terms of land use, nutrient depletion was highest under pyrethrum and lowest under tea. Sensitivity analysis revealed that changing mineralization rate and soil N content had an important impact on the N balance. Varying slope gradient and length, soil erodibility, land cover and the enrichment factor for eroded material affected all nutrients.

Examples are given of possible ways to improve the NPK balance in the Kisii District by manipulating inputs and outputs. The methodology can prove valuable in any area where the farming community is receptive to integrated nutrient management systems.

Introduction

In natural ecosystems, loss of nutrients (outputs) is generally compensated by nutrient gains (inputs). Even in traditional bush-fallow systems with some nutrient input by manure and household waste, the soil fertility level can be stable (Jones, 1971). However, as soon as land is transferred to agricultural use on a more permanent basis, soil fertility tends to decline at a rate that is largely governed by the type of land use systems introduced and their management. Nutrient depletion in African soils has been described and analyzed in various studies (Pichot et al., 1977; Pieri, 1985, 1989; Van der Pol, 1992; Velly & Longueval, 1977; Wetselaar & Ganry, 1982).

Recently a comprehensive study was published of the nutrient balance in the arable land of 38 sub-Saharan African countries (Stoorvogel & Smaling, 1990; Stoorvogel et al., 1993). The NPK balance in the rootable soil layer was calculated as the sum of inputs (mineral fertilizers, manure, wet and dry deposition, biological

N fixation and sedimentation) minus the sum of outputs (aboveground crop parts, leaching, denitrification and erosion). Because of the small scale, calculations were constrained by a number of factors:

(i) data on land use systems and their geographical position were unevenly distributed among and within countries;

(ii) instead of explicit input/output determinants such as texture, soil N and soil P content, and water holding capacity, a discrete soil fertility classification was used (low = 1, moderate = 2, high = 3), based on the Soil Map of Africa, at a scale of 1:5 000 000 (FAO/UNESCO, 1974);

(iii) the range in reported crop yields and nutrient contents was very wide;

(iv) quantitative information on deposition, leaching and denitrification was very scarce and unevenly distributed over the region;

(v) quantitative information on erosion was rather scarce; at the same time, the impact of erosion on the nutrient balance and hence on model output was considerable.

Because of these scale-inherent limitations, the study was repeated for the Kisii District, South-western Kenya. As a result of past inventories, part of the assumptions and estimates used in the regional study could be replaced by primary data. Hence, input and output of nutrients for the Kisii District for 1990 could be calculated with greater reliability for well-defined agro-ecological entities.

Basic data on the Kisii District

The Kisii District is located around latitude 0° 45′S and longitude 34° 50′E, with a total land surface of 220 000 ha at altitudes between 1500 and 2200 m, and approximately 1 500 000 inhabitants in 1990 (Jaetzold & Schmidt, 1982, data extrapolated). The district has a high agricultural potential, but at the present population density may well be on the verge of overexploitation.

Primary data were available on climate, landforms, soils and land use, use of mineral fertilizers and farmyard manure, crop yields and residues and their nutrient content (Andriesse & Van der Pouw, 1985; Jaetzold & Schmidt, 1982; Wielemaker & Boxem, 1982). Research data on erosion in Kenya were also at hand (Avnimelech & McHenry, 1984; Gachene, 1987; Kilewe et al., 1989; Tong'i & Mochoge, 1991; Ulsaker & Onstad, 1984; Wenner, 1981). Ten percent of the area was assumed to be under urban centres, villages, farm houses and roads.

For the purpose of this study, the agricultural land in the district was partitioned in two temperature zones, at annual mean temperatures of 16.2–18.0°C (TZ 1) and 18.0–20.5°C (TZ 2), respectively (Table 1). In these zones, seven land use types (LUT) have been distinguished, as indicated in Figure 1. They include extensive grazing in bushland, intensive grazing on improved pastures, tea, pyrethrum, coffee, banana, sugarcane, maize and beans, either as sole crops or intercropped, tuber crops, i.e. mainly sweet potatoes, and fallow. The composition of the various land use types in each temperature zone is listed in Table 1, whereas relevant characteristics for the calculation of the nutrient balance are given in Table 2. A high yield and capital input

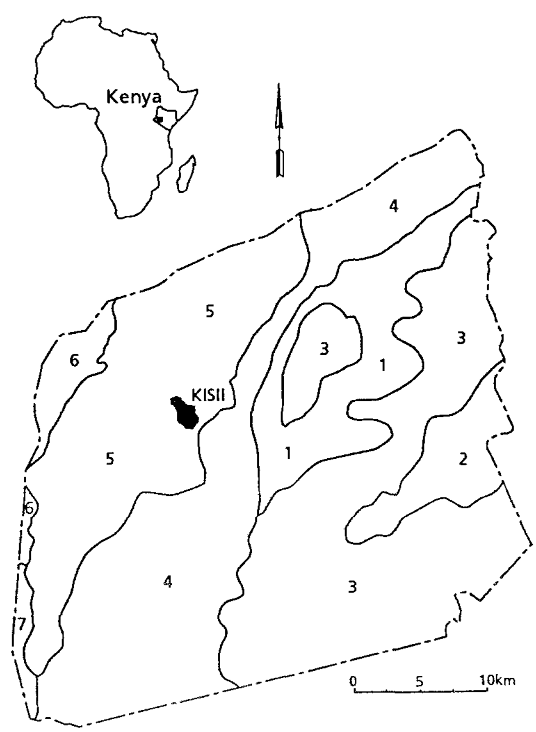

Fig. 1. Land use types in the Kisii District (after Wielemaker and Boxem, 1982). Descriptions are given in Tables 1 and 2.

Table 1. Distribution of land use types in the Kisii District

TZ	LUT	Area (ha)	Distribution (%)													
			Fallow	Grazing		Semi/perennial crops					Season	Annual cropping systems				
			Fa-1	Ge	Pa	Te	Py	Co	Ba	Su		Ma	Be	Ma + Be	Tu	Fa-2
1	1	23100	5		17	33	8				1	11		16		
											2		10			17
	2	10700	5		17	21	20				1	11		16		
											2		10			17
	3	67200	5		17	10	24				1	12		22		
											2		10			24
2	4	56500	5		17	14	3	14		3	1	4	2	28		
											2	1	6	10		17
	5	48000	5		17			24	7		1	4	2	28	3	
											2	1	6	10		20
	6	13100	5	25	9			6			1	6	3	32	4	
											2	1	7	10		27
	7	2200	5	25	9					10	1	4	2	29	6	
											2	1	6	9		25

TZ = temperature zone; 1 = 16.2–18 C, 2 = 18.0–20.5 C;
LUT = land use type (see Fig. 1);
Season 1 = February–July, season 2 = August–December;
Fa-1 = fallow (year-round), Fa-2 = fallow (seasonal); Ge = extensive grazing; Pa = continuous pasture; Te = tea; Py = pyrethrum; Co = coffee; Ba = banana; Su = sugarcane; Ma = maize; Be = beans; Tu = sweet potatoes.

level was assumed for tea and pyrethrum when grown in TZ 1, but a low level of both was assumed for TZ 2 (Wielemaker & Boxem, 1982). A medium yield and capital input level was assumed for all other crops, apart from beans grown in intercropping systems, for which low levels were assumed (Wielemaker & Boxem, 1982).

Five rainfall zones have been distinguished, at mean annual precipitation values of 2050, 1900, 1700, 1500 and 1350 mm, and 20 soil units, mainly developed on volcanic rocks of acid (Y), intermediate (I) and basic (B) origin, often enriched with fresh pyroclastics (Fig. 2). Excluded were isolated hills and scarps with a rootable topsoil too shallow for agricultural use, and swamps and bottomlands, prone to periodic flooding, salinity or sodicity. The input factor 'sedimentation' is thus not considered in this study. Table 3 shows the relevant properties of the six soil units that comprise three-quarters of the agricultural land of the district. Fifty different combinations of soil unit and annual rainfall, designated 'land/water class' (LWC), have been identified. Combining prevailing land use types (LUT) with the LWC results in a total of 107 relevant land use systems (LUS).

Calculating inputs

Mineral fertilizers (IN 1)
Kenya is one of the major users of mineral fertilizers on the African continent. During the past decade, fertilizer use increased such that available data for 1980 for the Kisii District had to be multiplied by 2.5 for N, by 2.0 for P and by 3.0 for K to obtain approximations for 1990 (FAO, 1988; Jaetzold & Schmidt, 1982). The NPK input for each LUT is given in Table 2. Tea received most of the N fertilizers, whereas P was mainly applied to maize (and beans).

Manure (IN 2)
Most animal manure was applied to coffee and banana, and was mainly supplied from paddocks and stables. In LUTs that include extensive grazing or improved pasture, however, it was returned directly to the soil by grazing livestock. For that situation, 45 (Ge) and 72% (Pa) of the removed nutrients will be returned in manure if assuming that the animals spend 50 (Ge) and 80% (Pa) of the day in the field, and 10% of the nutrients is retained in the animal body. Part of the nutrients is excreted in urine, and when in contact with warm soil, nitrogen may be lost

Table 2. Properties of land use types necessary to calculate inputs (*IN*) and outputs (*OUT*); explanation of abbreviations in Table 1

LUT Component	TZ	*IN 1* Nutrients in mineral fertilizer ($kg\,ha^{-1}\,yr^{-1}$)			*IN 2* Manure dry wgt. ($kg\,ha^{-1}\,yr^{-1}$)	*OUT 1* Harvested product ($kg\,ha^{-1}\,yr^{-1}$)		*OUT 1* Nutrients in harvested product ($kg\,t^{-1}$ harv. prod.)			*OUT 2* Nutrients in crop residues ($kg\,t^{-1}$ harv. prod.)			*OUT 2* Residue removal (%)	*OUT 5* Land cover factor C(−)
		N	P	K				N	P	K	N	P	K		
Fa-1	1	0	0	0	0	0		not relevant			not relevant			0	0.05
	2	0	0	0	0	0									
Ge	1	0	0	0	*	2000	leaves	10.0	1.5	10.0	0.0	0.0	0.0	0	0.05
	2	0	0	0	*	2000									
Pa	1	0	0	0	*	10000	grasses	15.0	2.3	15.0	0.0	0.0	0.0	0	0.01
	2	0	0	0	*	10000									
Te	1	43	8	5	0	5000	green	13.9	1.0	7.0	0.1	0.0	0.0	0	0.05
	2	26	1	4	0	2500	leaves								
Py	1	0	0	0	0	600	dried	40.0	5.0	40.0	13.3	2.2	13.3	10	0.4
	2	0	1	0	0	300	flowers								
Co	1	not cultivated						5.9	0.4	5.6	0.8	0.6	3.1	20	0.2
	2	8	0	0	820	3000	cherries								
Ba	1	not cultivated						1.2	0.2	1.8	1.5	0.2	4.8	25	0.3
	2	0	0	0	310	5000									
Su	1	not cultivated						6.1	0.9	14.7	3.1	1.2	4.2	100**	0.2
	2	0	0	0	0	3500	sugar								
Ma-1	1	3	16	0	10	3000	seed	9.3	3.4	3.6	4.3	1.4	12.3	75	0.5
	2	0	7	0	80	3000									
Be-1	1	6	0	1	0	1200	beans	16.5	2.7	8.1	8.5	0.8	9.5	75	0.4
	2	0	3	0	60	1200									
Ma-1***	1	0	11	0	10	2500		9.3	3.4	3.6	4.3	1.4	12.3	75	0.3
	2	4	4	0	190	2500									
Be-1***	1	0	14	0	10	500		16.5	2.7	8.1	8.5	0.8	9.5	75	0.3
	2	0	3	0	80	500									
Tu-1	1	0	1	0	0	5000		4.6	0.3	2.9	1.9	0.5	3.1	50	0.3
	2	0	1	0	0	5000									
Ma-2	1	not cultivated						9.3	3.4	3.6	4.3	1.4	12.3	75	0.5
	2	0	10	0	0	2500									
Be-2	1	3	1	1	0	1500		16.5	2.7	8.1	8.5	0.8	9.5	75	0.4
	2	0	0	0	0	1500									
Ma-2***	1	not cultivated						9.3	3.4	3.6	4.3	1.4	12.3	75	0.3
	2	5	7	0	40	2000									
Be-2***	1	not cultivated						16.5	2.7	8.1	8.5	0.8	9.5	75	0.3
	2	0	3	0	0	750									
Fa-2	1	0	0	0	0	0		not relevant			not relevant			0	0.3
	2	0	0	0	0	0									

* 45% of nutrients in Ge and 72% of nutrients in Pa (*OUT 1 + 2*) will be returned to the field as manure (*IN 2*)
** 100% N removal (burning), but no P and K removal
*** Maize (Ma) and beans (Be) as part of the maize/beans intercropping system

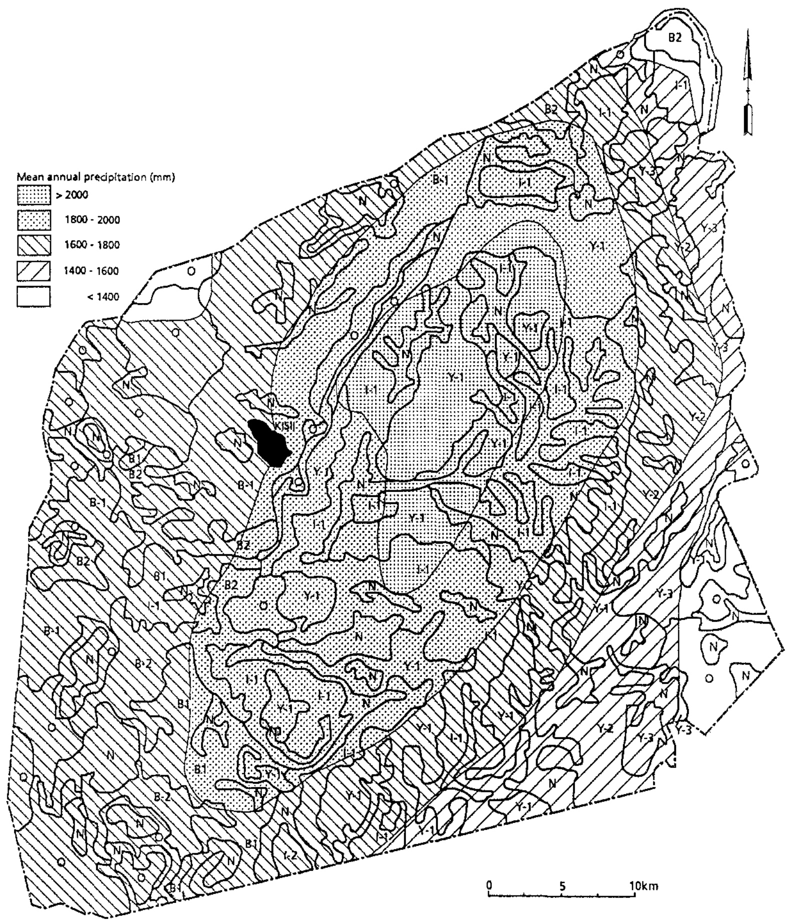

Fig. 2. Land/water classes in the Kisii District (after Wielemaker and Boxem, 1982). Soils: Y-1: Humic to Dystro-Mollic Nitisols and Chromo-Luvic Phaeozems; Y-2: Ando-Luvic Phaeozems; Y-3: Nito-Rhodic Ferralsols; I-1: Humic to Dystro-Mollic Nitisols; B-1: Mollic Nitisols; B-2: Chromo-Luvic Phaeozems and Mollic Nitisols; O: Other Soils; N: Non arable land.

Table 3. Soil properties of the major soil units necessary to calculate inputs and outputs

Soil unit	N_{tot} [1] ($g\ kg^{-1}$)	P_{tot} [2] ($g\ kg^{-1}$)	K_{exch} [3] ($mmol\ kg^{-1}$)	Clay content (%)	Slope gradient s (%)	Soil erodibility K (–)
Y-1	4.0	1.50	18	43	12	0.07
Y-2	2.4	1.35	16	31	12	0.08
Y-3	1.6	0.50	9	47	10	0.08
I-1	3.5	0.95	19	62	10	0.06
B-1	3.0	0.95	18	66	10	0.07
B-2	3.7	0.85	13	40	10	0.07

Y (acid), I (intermediate), and B (basic) parent material;
[1] semi micro-Kjeldahl;
[2] digestion with Fleischmann's acid;
[3] double acid (HCl-H_2SO_4).

rapidly by volatilization. This has not been taken into consideration for reasons of model simplicity. Table 2 shows the use of manure in the different LUT components (Jaetzold & Schmidt, 1982). The nutrient contents in the manure were set at 1.3 (nitrogen), 0.5 (phosphorus) and 1.6 (potassium) as percentages of dry weight (Cooke, 1982; Jones, 1971; Van der Noll & Janssen, 1983). Owing to increased arable cropping in a district with intensive agriculture, the scope for expansion of grazing grounds was very limited. Therefore, it was assumed that 1980 data on the production and application of manure were also valid for 1990.

Wet and dry deposition (IN 3)
Local data on wet and dry deposition were not available; hence, regression equations derived from the study on sub-Saharan Africa (Stoorvogel & Smaling, 1990) were used linking nutrient input (kg ha^{-1} yr^{-1}) to the square root of average rainfall (P, in mm yr^{-1}) (Stoorvogel & Smaling, 1990). The regression coefficients were 0.14, 0.023 and 0.092 for N, P and K, respectively.

Biological N fixation (IN 4)
French beans (*Phaseolus vulgaris*), the only leguminous species in the LUTs contribute to the N balance by symbiotic fixation. Because of low P availability in most soils of the Kisii District, it was assumed that 50% of the N requirement is derived from biological fixation, although values up to 75% are found in literature (Munyinda et al., 1988; Tisdale et al., 1985, Wetselaar & Ganry, 1982). In addition, a small rainfall-dependent contribution A (kg ha^{-1} yr^{-1}) from non-symbiotic N-fixers was accounted for in each LUT, as derived from the continental study (Stoorvogel & Smaling, 1990):

$$A = 2 + (P - 1350) * 0.005 \quad (1)$$

Calculating outputs

Export in harvested product (OUT 1) and crop residues (OUT 2)
Removing harvested product from the land entails loss of NPK, the quantity being determined by the yield and nutrient content of the product (Table 2). Differences in nutrient use efficiency (kg grain per kg nutrient taken up) related to soil type, crop cultivar and husbandry level occur, but insufficient information was available to take that into account in the present study. For LUTs that include grazing (Ge, Pa), part of the 'harvested' product is returned to the system directly in animal manure.

Export in crop residues was calculated in a similar way, taking into account the fraction of residues removed from the arable field (Table 2). For sugarcane (Su), all the N in crop residues was assumed to be lost because of burning.

Leaching (OUT 3)
There are no studies on leaching in or around the Kisii District. Therefore, we attempted to estimate leaching by means of transfer functions, using generally accepted determinants such as rainfall, texture, soil N and K content, and fertilizer input (Wagenet et al., 1991). Although comprehensive simulation models exist on solute leaching in soils, their data demands are too high for this study. Moreover, most have not been sufficiently validated for reliable prediction of leaching under field conditions (Addiscott & Wagenet, 1985; De Willigen, 1991; Grimme & Juo, 1985). A simple, non-mechanistic model as developed by Burns (1975) would have been promising for the present exercise. He calculated leaching of surface-applied nitrogen (LN_{fert}) as a function of the quantity of water draining through the soil and the volumetric water content at field capacity. Data are required on rainfall and evaporation, soil porosity, initial water content, and water content at field capacity. Even these data have not been consistently collected in the Kisii District. Moreover, LN_{fert} and leaching of soil-derived nitrogen (LN_{soil}) tend to have different values in soils with continuous macropores. Lack of equilibrium between soil solution and drainage water does not allow calculation of leaching of newly mineralized soil-N inside aggregates from the fraction of water percolating (Wild, 1972). Literature data on LN_{fert} refer to a Hapludoll (18% clay) with 18 and 30% N leaching at application rates of 90 and 180 kg N ha^{-1} yr^{-1} respectively (Walters & Malzer, 1990), a Paleudult (16% clay)

with 28% (split application) to 53% N leaching (single application) (Arora & Juo, 1982), and a Nigerian acid sand with 1900 mm rainfall per year, where LN_{fert} was 34% at an application rate of $40\,kg\,N\,ha^{-1}\,yr^{-1}$ (Omoti et al., 1983). These data formed the basis for Table 4, which gives estimates of leaching as a function of rainfall and soil texture.

In this study, total mineral soil N (N_{min}; $kg\,ha^{-1}$) was calculated from total soil N, assuming a fixed annual nitrogen mineralization rate M, set at 2.5% for TZ 1 and 3.0% for TZ 2. Total N content in the 0–20 cm soil layer is thus:

$$N_{min} = 20 \times N_{tot} \times M \quad (2)$$

LN_{soil} was then calculated from Table 4 and ranged between 15% and 40% of N_{min}, depending on clay content (%) and average rainfall ($mm\,yr^{-1}$). In soil unit B-1, for example, N_{min} is $20 \times 3.0 \times 3 = 180\,kg\,ha^{-1}\,yr^{-1}$. At a clay content of 66% and under 1500 mm of rainfall, LN_{soil} is $16.5\% \times 180 = 30\,kg\,ha^{-1}\,yr^{-1}$. For lack of alternatives and to be in line with literature data, LN_{fert} was also derived from Table 4, and ranged between 15 and 40% of total fertilizer input (*IN 1* + *IN 2*).

Leaching of K on an acid sandy soil in southern Nigeria amounted to $16\,kg\,ha^{-1}\,yr^{-1}$ of soil-derived potassium (LK_{soil}) and $10\,kg\,ha^{-1}yr^{-1}$ surface-applied potassium (LK_{fert}) at an application rate of $60\,kg\,K\,ha^{-1}\,yr^{-1}$ (Omoti, 1983). In fine-textured soils, however, K leaching generally does not exceed $2\,kg\,ha^{-1}\,yr^{-1}$ (Tisdale et al., 1985). In soils with a high cation exchange capacity, as those in Kisii, a high percentage of soil and fertilizer K is adsorbed. High organic carbon contents, however, tend to enhance K leaching as the adsorptive force of organic matter for monovalent cations is low (Uribe & Cox, 1988). In our study, K leaching was expressed as a function of rainfall, clay content and exchangeable K (Tables 3 and 4). In soil unit B-1, K_{exch} is $1404\,kg\,ha^{-1}\,yr^{-1}$, and LK_{soil} is 0.55% of 1404 = 8 kg ha. LK_{fert} was also derived from Table 4, i.e. 0.5–1.0% of *IN 1* + *IN 2*.

Leaching of phosphorus was assumed to be negligible as most soils contain fresh volcanic constituents and, as a consequence, tend to strongly retain phosphorus.

Denitrification (OUT 4)

Extensive literature is available on denitrification in temperature regions of the world (Grant, 1991; Von Rheinbaben, 1990), but there have been few systematic studies on tropical soils (Grimme & Juo, 1985). Denitrification is known to occur under upland conditions when oxygen diffusion is impaired by water layers around structural elements and plant roots. However, N losses observed under waterlogged conditions are generally much higher than at field capacity or lower moisture levels (Dubey & Fox, 1974; Ekpete & Cornfield, 1964; Pilot & Patrick, 1972). Studies on Puerto Rican soils showed that denitrification losses were correlated with moisture level, organic carbon content and texture (Dubey & Fox, 1974). After two weeks of incubation, following an N application of $400\,mg\,kg^{-1}$ soil, an Oxisol with $6\,g\,kg^{-1}$ organic carbon and 22% clay and an Ultisol with $18\,g\,kg^{-1}$ organic carbon and 30% clay showed no denitrification at field capacity, and 8% and 22% respectively at waterlogging. An Oxisol with $23\,g\,kg^{-1}$ organic carbon and 70% clay, however, showed 7% denitrification at field capacity and 31% at waterlogging.

In this study, these results have been used to

Table 4. Nitrogen and potassium leaching as percentage of soil and fertilizer N and K for different average annual rainfall (1350, 1500, 1700, 1900 and 2050 $mm\,yr^{-1}$) and clay content

Clay content (%)	Leaching (%)									
	1350		1500		1700		1900		2050	
	N	K	N	K	N	K	N	K	N	K
<35	25	0.80	29	0.85	32.5	0.90	36	0.95	40	1
35–55	20	0.65	22.5	0.70	25	0.75	27.5	0.80	30	0.85
>55	15	0.50	16.5	0.55	17.5	0.60	18.5	0.65	20	0.70

quantify denitrification as a function of clay content (%), average rainfall (P, mm yr^{-1}), and mineral soil N and fertilizer N. Denitrified soil N (DN_{soil}; percentage of N_{min}) and fertilizer N (DN_{fert}; percentage of $IN\,1 + IN\,2$) are then calculated as follows:

$$DN = -9.4 + 0.13 \times \text{clay content} + 0.01 \times P \quad (3)$$

For soil unit B1, at 66% clay and 1500 mm precipitation, the percentage denitrification is thus 14.2%.

Erosion (OUT 5)

Erosion was calculated along the lines of the Universal Soil Loss Equation (USLE), which estimates annual soil loss per ha as a function rainfall erosivity (R), soil erodibility (K), slope gradient (S) and slope length (L), land cover (C) and land management (P) (Wischmeier & Smith, 1965).

The R factor is not easily derived from commonly collected meterological data. On the basis of literature data, however, this factor was set at 0.25 for the entire district (Ulsaker & Onstad, 1984; Wenner, 1981).

The K factor is listed in Table 3 for the major soils of the district, as derived from soil texture, organic matter content and permeability (Mitchell & Brubenzer, 1980; Wischmeier et al., 1971), bearing in mind that many of the deep volcanic soils in the district show very stable micro-aggregation (Ahn, 1977). In previous studies in Kenya, it has been shown that on a deep volcanic Nitisol, runoff and erosion was 5–8 times less than on a Luvisol with an unstable surface structure, leading to K-values of 0.06 and 0.2 respectively (Barber et al., 1979).

The factors S and L were derived from Mitchell and Brubenzer (1980) as follows:

$$S = (0.43 + 0.30 \times s + 0.043 \times s^2)/6.613 \qquad (4a)$$

$$L = (d/22.13)^{0.5} \qquad (4b)$$

in which s is the slope gradient (%) and d the slope length (m). The slope gradient is given in Table 3 for the major soil units. Slopes may be as long as 500 m, but since fences, hedges and homesteads act as barriers, the slope length was set at 100 m for the entire district. Equation (4b) then yields the value 2.1.

The degree of cover strongly varies temporally and spatially and was difficult to quantify in general terms for the district. Where on deep, red soils with a 10% slope in Southwestern Kenya very high erosion losses (140 tons ha^{-1}) were observed under young tea, mature tea on the same soils offered almost complete protection (Othieno, 1975). For the present study, an average C factor was estimated for each LUT component (Table 2).

Finally, the land management factor P was derived from (Wenner, 1981) as follows:

$$P = 0.2 + 0.03 \times s \qquad (5)$$

The slope gradient s is ranging from 10 to 12% for the major soil units (Table 3).

The resulting model was validated against soil loss measurements from experiments in and around the district (Gachene, 1987; Kilewe et al., 1989; Tong'i & Mochoge, 1991). For each soil unit, N_{tot} and P_{tot} (Table 3) and K_{tot} (Table 5 were used to convert soil loss into nutrient loss. K_{tot} was calculated from K_{exch} and clay content, the range of 0.2–0.6 g K kg^{-1} soil being in accordance with the scarce literature (Pagel et al., 1982). The nutrient losses arrived at were finally multiplied by an 'enrichment' factor of 1.5 (Avnimelech & McHenry, 1984; Stocking, 1984). Erosion implies loss of surface soil. Meanwhile, at the root base, soil formation is taking place. To take that into account, it was assumed in calculating *OUT 5* that the net loss of P and K was only 0.75 times the calculated loss at the surface.

Table 5. Total K (K_{tot}) in the 0–20 cm layer as a function of clay content (<35, 35–55, >55%) and exchangeable potassium (K_{exch})

K_{exch} (mmol kg^{-1})	K_{tot} (g kg^{-1} soil)		
	<35	35–55	>55
<10	2	3	4
10–20	3	4	5
>20	4	5	6

Fallow and multiple cropping

In addition to monocropping (cash crops, pasture), the bimodal rainfall pattern also entailed periods of zero use (fallow) and double use (multiple cropping).

For year-round fallow (Fa-1), estimated to occupy 5% of the total arable land (Table 1), equilibrium conditions were assumed ($IN-OUT=0$). The balance for the shorter seasonal fallow (Fa-2) was calculated similar to the other LUT components, as only a sparse vegetation cover is developed. Multiple cropping plays a role in LUTs with annual crops with different percentages of total land use for the first and the second season (Table 1). In TZ 2, two crops of maize can be grown annually, but in TZ 1 only the more rapidly maturing beans can be cultivated during the second season.

The nutrient balance quantified

For the district as a whole, the sum of the four input factors minus the sum of the five output factors rendered the values -112 kg N, -3 kg P, and -70 kg K ha^{-1} yr^{-1}, implying net depletion of the soil nutrient pool.

Average values for the various inputs and outputs are shown in Figure 3. For N, removal of harvested product (*OUT 1*) was the strongest negative contributor, followed by leaching (*OUT 3*) and erosion (*OUT 5*). For P and K, removal of harvested product and erosion were again the dominant factors in the nutrient balance. For P, nutrient losses were more or less offset by mineral fertilizers and manure. For K, however, the use of mineral fertilizers was negligible and the K export in removed crop residues was relatively high.

Table 6 shows the nutrient balance for each LUT component. Losses were particularly high under pyrethrum and, to a lesser extent, sugarcane and maize. The lowest depletion rates were found under tea. In Table 2, we indeed see that pyrethrum hardly receives any mineral or organic fertilizer, has a high nutrient content per unit harvested product and poorly protects the surface soil against erosion (C-factor 0.4). Tea,

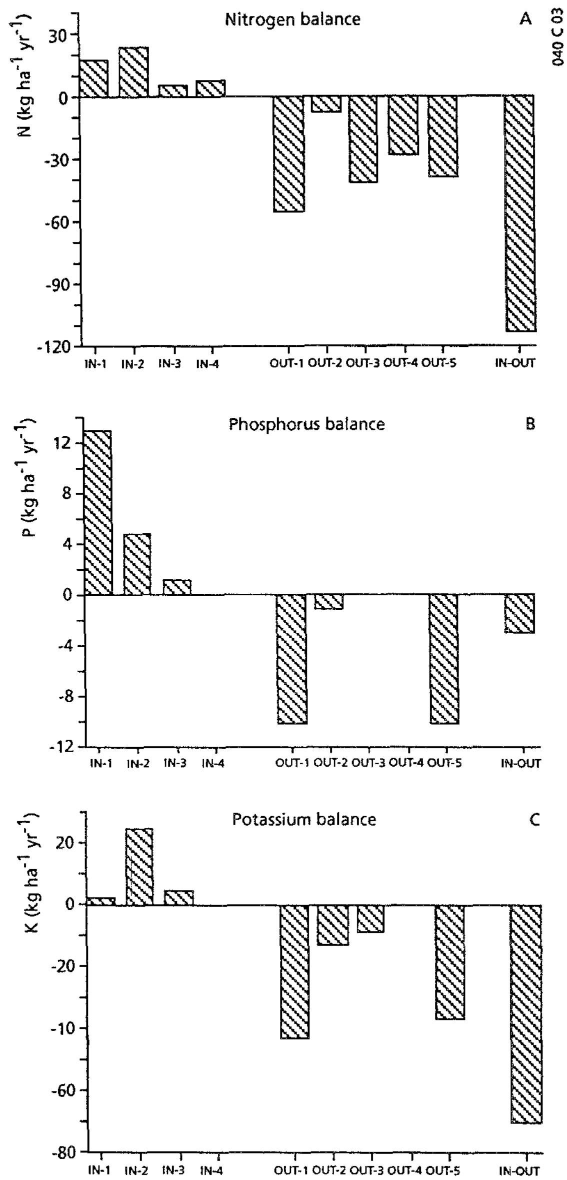

Fig. 3. Average inputs and outputs of N, P and K in the land use systems of the Kisii District.

however, receives substantial amounts of mineral fertilizer and adequately protects the topsoil (C-factor 0.05). Under the described conditions, soil P status was even improved under tea and maize. However, the presence of fresh volcanic constituents in most soils rendered P largely unavailable to crops and responses to point-placed P fertilizers were high.

Table 6. Nutrient balance of the different land use type components; explanation of abbreviations in Table 1

LUT component	Area (ha)	*IN-OUT* ($kg\,ha^{-1}\,yr^{-1}$)		
		N	P	K
Fa-1	8800	0	0	0
Ge	1800	−43	−1	−9
Pa	29200	−98	−6	−49
Te	19600	−67	6	−30
Py	17800	−147	−24	−96
Co	16500	−82	0	−34
Ba	2900	−87	−5	−48
Su	1500	−129	−10	−91
Ma-1	13400	−105	2	−83
Be-1	1900	−73	−6	−55
Ma + Be-1	42800	−83	11	−63
Tu-1	1600	−75	−6	−51
Ma-2	900	−102	−1	−80
Be-2	13800	−75	−13	−58
Ma + Be-2	9300	−78	4	−65
Fa-2	35600	−53	−7	−29
Mean	157700	−112	−3	−70

Table 7. Nutrient balance of land/water classes (LWC) exceeding 5000 ha

LWC		Area (ha)	*IN-OUT* ($kg\,ha^{-1}\,yr^{-1}$)		
soil unit	rainfall ($mm\,yr^{-1}$)		N	P	K
Y-1	2050	7500	−185	−11	−100
	1900	11300	−175	−13	−90
	1700	5200	−170	−10	−98
Y-2	1700	6800	−121	−11	−88
	1500	8200	−111	−8	−84
Y-3	1500	5500	−58	8	−53
I-1	2050	8100	−103	6	−62
	1900	16900	−103	3	−61
	1700	8200	−97	4	−61
B-1	1900	9800	−109	−5	−75
	1700	21200	−101	−4	−71
B-2	1700	8600	−130	−3	−61

Y (acid), I (intermediate), and B (basic) parent material.

Table 7 shows the nutrient balance for the twelve land/water classes (LWCs) that exceed 5000 ha (Fig. 2). Losses were highest in units Y-1 and lowest in Y-3. In Table 3, we indeed see that Y-1 has the highest N and P contents and a slope gradient of 12%, whereas Y-3 represents the poorer soils with slopes of 10%. The higher rainfall zones were, on average, more prone to nutrient losses than the drier zones.

The complete picture is only obtained by integrating the values from Tables 6 and 7, providing the nutrient balance for entire land use systems. Some indications for two LUS are given in Table 8, showing a higher proportion of land under pyrethrum in Y-2, and under tea in I-1. This explains higher nutrient depletion in Y-2 (Table 7). As Y-2-1700 has more or less the same land use as Y-2-1500, rainfall is the major factor explaining the different depletion rates between these two LWCs. This difference does not show up between I-1-2050 and I-1-1900, as the latter LWC has less tea and more maize plus beans, which are stronger nutrient miners (Table 6).

In the continental study (Stoorvogel & Smaling, 1990), the nutrient balance for the 'good rainfall' LWC in Kenya for 1990 was approximately $-75\,kg\,N\,ha^{-1}$, $-5\,kg\,P\,ha^{-1}$ and $-56\,kg\,K\,ha^{-1}$. All the soils would have been in fertility class 2 (moderate) with $1\,g\,N\,kg^{-1}$ soil and $0.2\,g\,P\,kg^{-1}$ soil, whereas they are in fact richer (Table 3). Pyrethrum, the big nutrient miner in this study, was not included at the continental level as it is of minor importance at that scale.

Table 8. Relative occupation of land/water classes (LWC) by different land uses

LWC		Area (ha)	Relative occupation (%)						
soil unit	rainfall ($mm\,yr^{-1}$)		Pa	Te	Py	Co	Su	Ma	Ma + Be
Y-2	1700	6800	19	16	25	0	0	13	22
	1500	8200	19	14	26	0	0	13	23
I-1	2050	8100	19	28	11	3	1	11	24
	1900	16900	19	18	13	7	1	10	31

Sensitivity analysis

The procedure followed in this study has been to develop transfer functions to calculate the factors leaching, denitrification and erosion, including determinants generally recognized in literature. Parameter values and class limits were chosen such that agreement between calculated results and available data was as close as possible.

The nutrient balance described here, although further detailed than in the continental study, still relies on a number of assumptions and estimates. A sensitivity analysis is therefore indispensable to evaluate the impact of changes in values of the determinants of the nutrient balance factors. The results appeared not very sensitive to amount of mineral fertilizer and manure, yield level, nutrient content, and percentage residue removal. When increasing their values by 10%, changes in the nutrient balance did not exceed 4 kg N ha^{-1}, 1 kg P ha^{-1} and 4 kg K ha^{-1}. Results were neither very sensitive to exchangeable K, clay content, and the contribution of weathering to P and K supply.

The determinants having greater impact are listed in Table 9. Changing mineralization rate and total soil N content had a great impact on the N balance. An increase in soil N content of 0.5 g kg^{-1} for example caused a decrease in nitrogen balance (*IN-OUT*) of 15.5 kg ha^{-1}. Varying slope gradient s and slope length d, K-factor, C-factor and enrichment factor, however, affected the balance of all nutrients. These factors are all used in calculating erosion. Apparently, there is not only a need to intensify erosion control, but also to increase quantitative research on erosion.

Table 9. Sensitivity analysis of some input-output determinants

Determinant	Variation	*IN-OUT* (kg ha^{-1} yr^{-1})		
		N	P	K
Mineralization rate	+ 0.5%	−10.5	0	0
N_{tot}	+0.5 g kg^{-1}	−15.5	0	0
P_{tot}	+0.1 g kg^{-1}	0	−1	0
K-factor	+0.01	−5.5	−1.5	−5.5
Slope gradient s	+2%	−15.5	−4	−15
Slope length d	+50 m	−7.5	−2	−8
C-factor	+0.05	−6.5	−1.5	−5.5
Enrichment factor	+0.25	−6.5	−1.5	−6

Recommendations for soil fertility conservation

In the continental study (Stoorvogel et al., 1993), ways to conserve soil fertility were discussed, which may now be considered in relation to the actual situation in the Kisii District.

Increasing *IN 1* can be combined with a decrease in *OUT 3, 4* and *5* by timely and possibly split application of modest amounts of the proper type of fertilizer, complying with recommendations that are specific for both LUT and LWC (Smaling & Van de Weg, 1990). In Kisii, mineral fertilizer is supplied by the Grain Growers Cooperative Union and the Tea Development Authority. The popular di-ammonium-phosphate is suitable for most P-deficient soils, but in the long run causes soil acidification.

Increasing *IN 2*, through better use of manure and household waste, provides nutrients and additional benefits such as increased water storage and nutrient retention. The long-term beneficial effect of organic manure on soil fertility has been demonstrated on a Nigerian sandy loam (Jones, 1971) where, after 18 years of continuous cultivation, the highest manure treatment (5 t ha^{-1}) gave a stable organic carbon level in the soil of 3.4 g kg^{-1}. In plots receiving no manure, however, it had decreased to 1.5 g kg^{-1}. In Kisii, there is limited scope for increasing input from animal manure as livestock mainly roams along roads and tracks, in bushland (Ge) and on pastures (Pa). Increasing herds is limited due to land shortage. Organic inputs such as urban or industrial refuse may be valuable, but the possibilities were little explored to date.

Introducing more nitrogen-fixing species in cropping systems may increase *IN 4*. Research on a Mollisol in the US showed that continuous maize yielded less grain (5.5 t ha^{-1}) than in rotation with a legume (7.6 t ha^{-1}). Also, maize following a legume in rotation produced maximum grain yield at 90 kg N ha^{-1}, while continuous maize required at least 180 kg N ha^{-1} for maximum yield (Peterson & Varvel, 1989). Research in Kenya has shown that maize-beans rotations outyield intercropping systems (Kilewe et al., 1989; Nadar & Faught, 1984). Although green manures, grain legumes and woody species may transfer up to 100 kg N ha^{-1} to a subsequent crop (Dommergues & Ganry, 1986), Phaseolus beans is the only N-fixing crop in the Kisii District. Owing to the low available P status of most soils, biological fixation is not very effective unless phosphatic fertilizers are applied. In TZ 1, planting beans during the short rainy season (Be-2) has the additional advantage that maize can be early-planted during the subsequent long rainy season (Ma-1 and Ma + Be-1).

OUT 2 can be reduced by grazing crop residues in the arable field, leaving residues as a mulch or ploughed into the soil. A Nigerian sandy loam, receiving a mulch of previous season groundnut shells each year had, after nine cropping seasons, an organic carbon content of 6.7 g kg^{-1} (Jones, 1971). Applying 52 kg N and 30 kg P ha^{-1} yr^{-1} as mineral fertilizers during the same period resulted in an organic carbon content of 5.3 g kg^{-1}, whereas that in the control plots was 4.5 g kg^{-1} (Jones, 1971). Treatments in which maize residues (4 t ha^{-1}) and weeds were burned during four seasons on a Plinthudult in Cameroon outyielded those in which crop residues were used as a mulch (2.7 vs. 2.3 t ha^{-1}) (Nguu, 1987). Such differences are generally ascribed to a short-lived pH increase and enhanced availability of mineral nutrients. In the longer run, however, burning practices lead to increased nutrient depletion in systems of continuous cultivation. Incorporating residues with a high C/N ratio, such as maize stover, causes temporary depressions in net N mineralization. The increased micropopulation uses soil and fertilizer N for its own sustenance until most of the residues have been decomposed (Smith & Sharpley, 1990). When leaving residues as a mulch in a monoculture, they may serve as host material for pests and diseases.

A considerable decrease in *OUT 5* can be realized when the conditions that determine erosion are adequately manipulated. This includes practices such as zero-tillage, mulching, strip cropping, alley or multi-storey cropping and terracing. In Kisii, zero-grazing systems are expanding, in combination with feeding of contour-planted tall grasses to stabled livestock. Most grass species, once established, grow vigorously, offer adequate soil protection and reduce slope length.

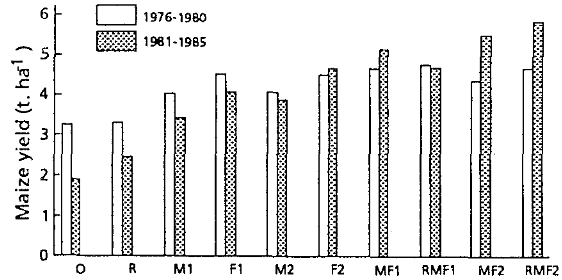

Fig. 4. Development of maize yields at different treatments on a Nitisol (after Qureshi, 1987). O = control, R = crop residues of previous season, M = organic manure (1 = 5 t ha^{-1}; 2 = 10 t ha^{-1}), F = mineral fertilizer (1 = 60 kg N and 25 kg P ha^{-1}; 2 = 120 kg N and 50 kg P ha^{-1}).

Long-term fertilizer trials on a deep Nitisol on relatively flat land near Nairobi showed trends which support the above aspects of integrated nutrient management (Qureshi, 1987). Figure 4 shows that during ten consecutive cropping years, maize received mineral fertilizers, manure and crop residues. Only when receiving a combination of these inputs, the mean yield in years 5–8 was 12% higher than the mean yield over the years 1–4.

In view of the relatively high costs of imported fertilizers in Kenya, and the need to increase food production for a growing population, the importance of conserving the productive capacity of the soils cannot be overemphasized. The results of both the supranational and the district study should be translated into packages to advice decision-makers at both levels in land use planning and extension. The methodology presented in this study can be applied and prove valuable in any area where researchers, policy makers and farmers are receptive to systems of integrated nutrient management.

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