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Estimates of sub-national nutrient balances as sustainability indicators for agro-ecosystems in Ecuador

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Abstract

Using a model, inputs and outputs of nitrogen, phosphorus and potassium were calculated for Ecuadorian agro-ecosystems, in order to assess sustainability of different land use types in terms of a soil fertility balance. For 5 × 5 minute land cells of a homogeneous geographical grid covering the Ecuadorian territory, the nutrient balance was calculated on the basis of the separate contributions of the inputs and outputs: Mineral fertilizer, organic fertilizer, atmospheric deposition, biological N-fixation, sedimentation, harvested product, removed crop residues, leaching, gaseous losses and erosion. The estimates were aggregated to sub-national and national level. In general, the estimates show a depletion of the soil nutrient stock in Ecuadorian agro-ecosystems. At a national scale for the land use type temporary crops there is mainly a deficit of nitrogen (42 kg ha^{-1} yr^{-1}), while for permanent crops both nitrogen and potassium balances are clearly negative (40 and 25 kg ha^{-1} yr^{-1}, respectively). For grassland overall, losses are smaller. Erosion is a major cause of nitrogen loss, leaching and denitrification also contribute significantly. In permanent crops relatively large amounts of potassium leave the agro-ecosystem through harvested products, due to high potassium concentrations in these products and high yields. At sub-national scale, nutrient depletion under current land use is more severe in the Andean region than the coastal region, mainly as a result of higher erosion losses. In the Andean region, this situation is likely to worsen due to the exploitation of marginal lands under the high pressure on the land. The Amazon region is still largely unexploited but this study suggests that the current conversion of forest to agricultural land, may cause serious nutrient balance problems at a local level. The presented approach allows the sub-national assessment of soil nutrient balances as sustainability indicator. It appears a useful tool to indicate areas of interest for more detailed follow-up studies. Furthermore, it may assist in the exploration of the effects of land use changes. © 1997 Elsevier Science B.V.

Keywords: Nutrient balances; Agro-ecosystems; Sustainability; Land use; Ecuador

1. Introduction

In recent years, and especially since the 1992 United Nations Conference of Environment and Development, there has been a growing awareness on the need for sustainable development in order to prevent the exhaustion of earth's natural resources in an alarmingly high rate. In agricultural research, this has lead to the need for indicators to assess sustainability of agro-ecosystems systems.

An indicator proposed by Smaling (1993) is the soil nutrient balance, that takes into account inputs and outputs of the main nutrients in the production

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Table 1
Components of a nutrient balance (after Smaling, 1993)

Inputs	Outputs
IN1 mineral fertilizer	OUT1 harvest product
IN2 organic fertilizer	OUT2 removed crop residues
IN3 atmospheric deposition	OUT3 leaching
IN4 biological N fixation	OUT4 gaseous losss
IN5 sedimentation	OUT5 erosion

process. A highly positive balance can result in pollution of ground and surface water, while a negative balance may lead to mining of the soil nutrient stock with subsequent loss of soil fertility, diminishing crop yields and finally the abandoning of previously suitable agricultural land. The main nutrient inputs and outputs that should be quantified when monitoring nutrient balances under agricultural land use are shown in Table 1. These were combined into the so-called NUTMON model by Smaling and Fresco (1993).

This concept was used to assess nutrient flows and budgets for Sub-Saharan Africa at a supra-national scale (Stoorvogel et al., 1993), using the FAO 1:5 million soil map and FAO land/water classes. They concluded that nutrient loss is high in most Sub-Saharan countries and according to current trends are likely to exacerbate in the future.

Next to this broad continental approach, the model has been applied to district level. Studies for a well described Kenyan district, using data at a much larger scale and replacing estimates being made at the supra-national scale with primary data from inventories, indicated that nutrient depletion was also severe at the district scale (Smaling et al., 1993). Similarly, in a study covering a section of the Atlantic Zone of Costa Rica, Stoorvogel (1993) calibrated the nutrient balance model as used for the Kenyan district scale, in order to optimise the distribution of land utilisation towards a minimum of nutrient depletion, using linear programming techniques. The NUTMON approach is now elaborated to include farm level management variables.

However, thus far there has been no effort to use nutrient balances at national level with explicit attention to spatial distribution. The study of Stoorvogel et al. (1993) used very broad land water-classes and aggregated national statistics for selected crops.

This paper takes the NUTMON approach one step further and calculates regional nutrient balances on the basis of a standard geographical grid with uniformly sized cells in which all data are geo-referenced and linked. For separate land use systems and total land use, nutrient balances are assessed per grid cell, and aggregated to different spatial units. Such an approach provides better geo-referencing and thus more scope to explore the effects of changes in land use on nutrient balances. Furthermore, to estimate outcomes at aggregated (sub-national) level calculations are performed at a much lower aggregation level in order to account for spatial variability.

As a test case, Ecuador was selected, a country with a high agro-ecological diversity, that is characterised by an increasing pressure on land use, over-exploitation of natural resources, low productivity and threats to biodiversity (Quiroz et al., 1995).

2. Data

2.1. Spatial resolution

The basis for the analysis was a homogeneous geographical grid with a grid cell size of 5 × 5 minutes (approximately 9 by 9 km), covering the Ecuadorian territory according to the protocol of Rio de Janeiro 1942. A cell was considered an Ecuadorian land cell when at least 50% of its surface existed of Ecuadorian territory excluding sea. The total number of Ecuadorian land cells that was created this way was 2981. The grid approach and the chosen resolution are related to the resolution of biophysical as well as socio-economic input data that are being used within a broader research programme in which the causes and effects of land use changes in Ecuador are investigated, using the CLUE methodology (Veldkamp and Fresco, 1996) that describes land use dynamics as a result of interacting biophysical and human drivers at different spatial scales.

2.2. Soil data

The 1:1 million soil map of Ecuador (González et al., 1986) was used. This map has been constructed on basis of detailed soil maps (varying from 1:50.000

Table 2
Attributes of soil units, their specification and information source as used in the model

Soil attribute	Specification	Source
Texture	Clay % classes: (1) < 35%; (2) 35–55%; (3) > 55%	Soil map
Slope	Slope % classes: (1) < 2%; (2) 2–8%; (3) 8–16%; (4) 16–30%; (5) > 30%	Soil map
Total N	g/100 g	Reference profiles
Exchangeable K	mmol/100 g	Reference profiles
Bulk density	$g\ cm^{-3}$	Reference profiles
pH		Reference profiles
Erodibility	Erodibility classes: (1) low; (2) medium; (3) high; (4) very high	Literature

to 1:200.000) of the PRONAREG/ORSTOM program of the Ecuadorian Ministry of Agriculture, applying the USDA Soil Taxonomy classification system. On this map, 36 great groups are distinguished, which are further subdivided into 62 soil units, on the basis of parent material, climate, phys-

Table 3
Climatic zonation of Ecuador (after Cañadas, 1983). Temperature is the average day temperature

Climatic zone	Estimated area (1000 ha)	Altitude (masl)	Temperature (°C)	Rainfall ($mm\ yr^{-1}$)
Desertical tropical	187	0–300	23–26	< 200
Sub-desertical tropical	980	0–300	23–26	200–500
Very dry tropical	1368	0–300	23–26	500–1000
Dry tropical	1104	0–300	23–26	1000–1500
Sub-humid tropical	912	0–300	23–26	1500–2000
Humid tropical	6738	0–300	23–26	2000–3000
Very humid tropical	1848	0–300	23–26	> 3000
Very dry sub-tropical	491	300–1800	18–23	200–500
Dry sub-tropical	1014	300–1800	18–23	500–1000
Sub-humid sub-tropical	943	300–1800	18–23	1000–1500
Humid sub-tropical	1004	300–1800	18–23	1500–2000
Very humid sub-tropical	2001	300–1800	18–23	2000–3000
Rainy sub-tropical	1580	300–1800	18–23	> 3000
Dry temperate	117	1800–3000	12–18	200–500
Sub-humid temperate	814	1800–3000	12–18	500–1000
Humid temperate	881	1800–3000	12–18	1000–1500
Very humid temperate	488	1800–3000	12–18	1500–2000
Rainy temperate	490	1800–3000	12–18	2000–3000
Very rainy temperate	66	1800–3000	12–18	> 3000
Sub-humid sub-temperate	110	3000–4000	6–12	200–500
Humid sub-temperate	975	3000–4000	6–12	500–1000
Very humid sub-temperate	835	3000–4000	6–12	1000–1500
Rainy sub-temperate	263	3000–4000	6–12	1500–2000
Very rainy sub-temperate	100	3000–4000	6–12	2000–3000
Pluvial sub-temperate	5	3000–4000	6–12	> 3000
Humid páramo[a]	26	4000–5000	3–6	200–500
Very humid páramo[a]	208	4000–5000	3–6	500–1000
Rainy páramo[a]	161	4000–5000	3–6	1000–1500
Very rainy páramo[a]	52	4000–5000	3–6	> 1500

[a] Páramo: alpine natural grasslands

iography, relief, soil texture, and chemical and mineralogical soil properties. The soil units on the soil map were matched with the base grid by assigning to each grid cell the two biggest occurring soil units with their respective surface fractions. These two soil units were maintained as separate units without averaging their physical and chemical properties.

Soil attribute data required for calculation of the nutrient balance (Table 2) were derived from different sources. Texture and slope classes of the 62 soil units were derived directly from the soil map. Texture classes on the soil map correspond with the texture classes from the USDA soil texture triangle. These texture classes were converted to three clay percentage classes. Slope classes vary from (almost) plane (less than 2%), undulating (2% to 8%), substantially undulating (8% to 16%), hilly (16% to 30%), to steeply dissected mountainous (more than 30%) (González et al., 1986).

In order to assign chemical soil attributes (total N, exchangeable K, bulk density and pH), the soil units were re-classified into 16 groups, on basis of parent material, climate and clay mineralogy using soil descriptions of Beinroth et al. (1985). For these 16 groups, soil attribute data were determined on basis of descriptions of 139 reference soil profiles for Ecuador. Furthermore, erodability classes were established for each soil unit, as will be explained later.

2.3. Climate data

Climate data were derived from the 1:1 million bio-climatic map of Cañadas (1983). He distinguished 29 climate zones, on basis of altitude/temperature and yearly total precipitation. This zonation, together with the estimated areas of the zones, is given in Table 3. The climate zones on the map were matched with the base grid by assigning to each grid cell the two dominant climate zones with their respective surface fractions. Similar to the assignment of the soil units, the two dominant climate units were maintained as separate units without averaging.

2.4. Land use / cover data

In Ecuador, yearly agricultural statistics are collected by means of stratified sampling by the National System for Agricultural Statistics (SEAN). SEAN data for 1991 (INEC, 1991) were used, con-

Table 4
SEAN–91 land use items and data

	Land use types	Individual crops		Animal husbandry
		Temporary	Permanent	
Items	Temporary crops	Rice	Banana	Cattle
	Permanent crops	Barley	Plantain	Sheep
	Cultivated grassland	Maize	Cocoa	Goats
	Natural grassland	Wheat	Coffee	Horses
	Páramo[a]	Potato	Sugar cane	Donkeys
	Short fallow (< 1 year)	Bean		Mules
	Long fallow (1–5 years)	Broad bean		Pigs
	Mountains/forests	Soybean		
	Other land use			
Data	Area	Area sown		Number of heads
		Yield		
		Area with organic fertilizer		
		Area with mineral fertilizer		
		Area with organic and mineral		
		Fertilizer		
		Area irrigated		

[a] Páramo: alpine natural grasslands.

taining information on 65415 farmers in 3137 sample sites. Data of sample sites were related to grid cells, thus constructing a land use map. When more than one sample site was found within a grid cell, data of these sites were averaged. The data can be categorised in general land use types, individual crops and animal husbandry. Table 4 shows the items in each category and the data available.

Ecuador can broadly be divided in the eco-regions Coast, Andes and Amazon (Fig. 1). The coastal eco-region consists of the provinces El Oro, Esmeraldas, Guayas, Los Ríos and Manabí, the Andean eco-region of the provinces Azuay, Bolivar, Cañar, Carchi, Cotopaxi, Chimborazo, Imbabura, Loja, Pichincha and Tungurahua, and the Amazonian eco-region of the provinces Morona Santiago, Napo, Pastaza, Zamora Chinchipe and Sucumbíos. A summary of land use for the eco-regions Coast, Andes and Amazon is given in Table 5 (INEC, 1991). The area of agricultural land as percentage of total land

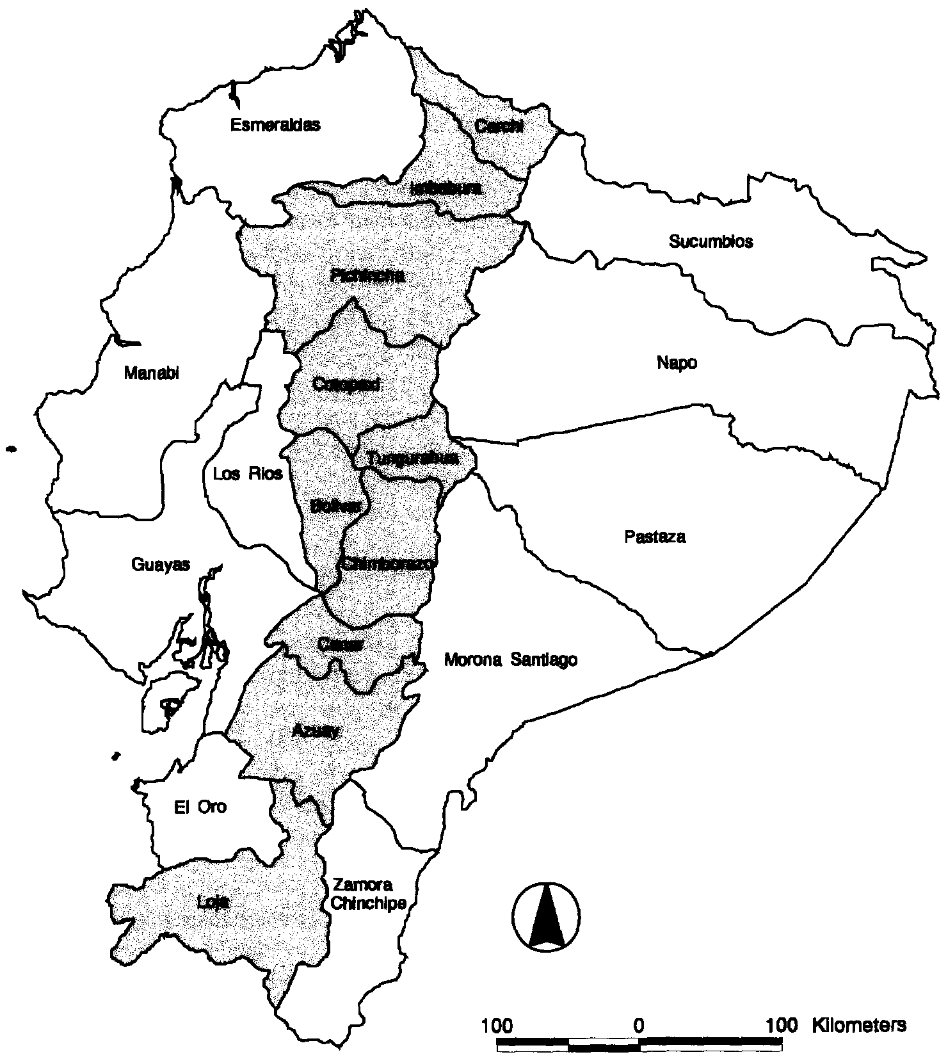

Fig. 1. Provinces of Ecuador. The Andean region is indicated in grey. The coastal provinces are located west of the Andean region, the Amazon provinces are located east of the Andean region.

Table 5
SEAN-91 land use data (×1000 ha). (Calculated from INEC, 1991)

	Coast	Andes	Amazon
Temporary crops + short fallow	685.6	666.5	46.1
Permanent crops	874.0	347.7	128.7
Total grassland	2226.7	1838.1	853.6
Long fallow (1–5 years)	128.2	101.6	16.7
Non-agricultural land	2726.4	3440.0	11996.9
Total land	6641.0	6393.9	13042.1

in 1991 was 59% in the coast, 46% in the Andes and 8% in the Amazon.

3. The nutrient balance model

3.1. Calculation of the nutrient balance

All model calculations were executed per grid cell, the smallest spatial unit. Only the three most important nutrients were considered: nitrogen (N), phosphorus (P) and potassium (K). Per cell the individual inputs and outputs of the nutrient balance were estimated for the land use types temporary crops (including the area short fallow), permanent crops, cultivated and natural grassland, and páramo. For the land use types temporary and permanent crops, specific inputs and outputs (IN1, IN2, IN4, IN5, OUT1, OUT2, OUT4 and OUT5) were assessed for the individual crops and attributed to the total area of temporary and permanent crops. Deposition (IN3) and leaching (OUT3) were directly attributed to the total area of temporary and permanent crops.

It was assumed that organic manure is not entering or leaving a grid cell. However, within a cell nutrients in organic manure do flow from one land use type to another.

For the land use types long fallow, mountains and forest, the inputs and outputs were not assessed separately, but a balanced system was assumed. Other land use was not taken into account.

3.2. Model inputs and outputs

The model will be described on basis of the separate inputs and outputs listed in Table 1.

3.2.1. IN1: Mineral fertilizer

All mineral fertilizers used in Ecuador are imported. In 1991 total fertilizer imports amounted to 45000 ton N, 16815 ton P_2O_5 and 24100 ton K_2O (FAO, 1995). On basis of these total importations for 1991 and the fertilised area per crop in 1991 (SEAN-91 data) the nutrient application rates as estimated by Hammond and Hill (1984) were corrected to obtain the Ecuadorian 1991 application rates for the fertilized area of each crop.

3.2.2. IN2: Organic fertilizer

Within each cell, cattle was allocated to cultivated grassland up to a maximum stocking rate of 2.5 animals ha^{-1}. Remaining cattle was supposed to graze on natural grassland up to 1.5 animal ha^{-1}. Sheep and goats were allocated to natural grassland and paramo, with maximum stocking rates of 4 animals ha^{-1}. Cattle, sheep and goat manure was assumed to be collected at night, when animals are gathered in stables. Amounts of nutrients in collected manure are calculated using average grazing hours, dry matter intake, digestibility of herbage, and nutrient concentrations of manure from literature (Knapp, 1991; Landon, 1991). This amount of nutrients was evenly applied to the area of temporary and permanent crops fertilized with organic manure, taking into account a physical limit to manure application of 5 ton ha^{-1} fresh weight.

Horses, donkeys, mules and pigs graze near the farm house on crop residues, and their manure production was not taken into account, assuming that the nutrients consumed remain in the same land use type, with minor losses.

Nutrients in supplementary feedstuffs like soybean meal and cotton seed cake for cattle were regarded as organic manure on grassland (after removal of part of the manure as organic fertilizer, calculated in OUT1)

3.2.3. IN3: Atmospheric deposition

No specific data were available on wet and dry deposition for Ecuador. Therefore, the equations of Stoorvogel et al. (1993) were used, relating deposition with the square root of average annual rainfall. For the different Ecuadorian rainfall classes calculated depositions are given in Table 6.

Table 6
Estimated deposition of N, P and K (kg ha^{-1} yr^{-1}) per rainfall class (mm yr^{-1})[a]

Rainfall class	N	P	K
< 200	1.4	0.2	0.9
200–500	2.6	0.4	1.7
500–1000	3.8	0.6	2.5
1000–1500	5.0	0.8	3.3
1500–2000	5.9	1.0	3.9
2000–3000	7.0	1.2	4.6
> 3000	8.6	1.4	5.7

[a] After: Stoorvogel et al. (1993).

3.2.4. *IN4: Biological N fixation*

Smaling et al. (1993) have estimated that symbiotic N-fixation by leguminous crops can supply up to 75% of their nitrogen demand. In Ecuador, P-availability in soils is generally low, which limits N-fixation. The supply percentage was set at 50%. On basis of this percentage, symbiotic N-fixation of bean, soybean and broad bean was calculated, taking into account the harvested areas and yields of these crops.

For non-symbiotic N-fixation by *Azotobacter*, *Beyerinckia* and *Clostridium spp*, a small rainfall dependent contribution (3, 4 and 5 kg ha^{-1} yr^{-1} for the rainfall classes < 500 mm, 500–1000 mm, and > 1000 mm, respectively) was taken into account, as derived from Stoorvogel et al. (1993).

Chemo-autotrophic N-fixation (*Azolla* and other algae) was assumed to supply up to a maximum of 30 kg ha^{-1} yr^{-1} in wetland rice.

3.2.5. *IN5: Sedimentation*

Sediment input through irrigation water for irrigated land was calculated from the 1:1000000 map with average annual hydrological deficits (average annual hydrological deficit calculated from monthly differences between precipitation and potential evapotranspiration) determined by Peralta et al. (1978) and average sediment loads of irrigation water on basis of data from INECEL (1992). Nutrient concentrations in the sediment were assumed to be equal to the average nutrient concentrations in the top 20 cm of the soils in the grid cell. Sedimentation was calculated for the irrigated surface given by SEAN-91.

3.2.6. *OUT1: Harvested product; OUT2: Removed crop residues*

Nutrient loss through removal of harvested crop products were calculated from the SEAN-91 data on harvested area and yields, using crop specific data on nutrient concentrations. Most crop residues remain on the field, where they decompose or are grazed on by pigs and mules. Only the straw of cereals was supposed to leave the system through external use.

3.2.7. *OUT3: Leaching*

Leaching of phosphorous was not taken into account because of its minor importance in Ecuadorian soils.

Leaching of nitrogen and potassium was determined with transfer functions from Smaling et al. (1993), that calculate nitrogen leaching as a percentage of total mineral soil N and crop dependent fertilizer N, and potassium leaching as percentage of exchangeable K and crop dependent fertilizer K. The percentage leaching is calculated separately for nitrogen and potassium and for each texture class using regression equations where rainfall is the independent variable. Total mineral soil N was calculated for the 0–20 cm soil layer, from total soil N, bulk density and a fixed annual temperature dependent mineralization rate.

3.2.8. *OUT4: Gaseous losses*

Denitrification of nitrogen was calculated on basis transfer functions of Stoorvogel et al. (1993). A rainfall dependent base denitrification was estimated, that can amount to up to 8 kg ha^{-1} yr^{-1} under the wettest climatic conditions. Additional denitrification was calculated through multiple regression using inherent soil fertility, mineral fertilizer and organic fertilizer as the independent variables.

3.2.9. *OUT5: Erosion*

To estimate soil and nutrient loss by erosion a semi-quantitative approach was used, taking into account rainfall intensity, land use, slope angle and soil type. For each of these factors a rating of 0 (no erosion risk) to 1 (maximum erosion risk) was given on basis of various literature sources. Multiplication of these factors resulted in the total erosion risk.

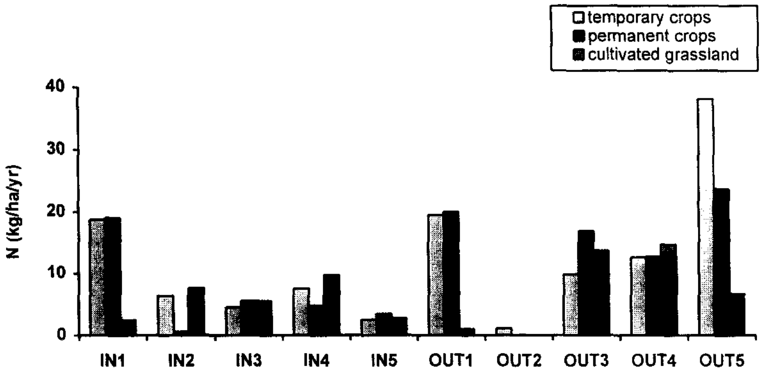

Fig. 2. Average inputs and outputs of N for land use systems at a national scale.

Rain intensity ratings ranging from 0.5 to 1 were derived from a rain intensity map (De Noni and Trujillo, 1986) reflecting the maximum rainfall during 30 min that is expected to occur once every two years. Land use ratings of 1 for bare land, 0.55 for temporary crops, 0.25 for permanent crops and 0.05 for grassland were used, on basis of data from INECEL (1992). Slope ratings were, for a standard slope length, derived from Wischmeier and Smith (1978). Finally soil type specific erodibility ratings were established by grouping the soil units in erodibility rating classes of low, moderate, high and very high erodibility using literature (Restrepo et al., 1993; Custode and Viennot, 1986; González et al., 1986; FAO, 1979)

The maximum soil loss was established on basis of literature on soil loss measurements on Wischmeier plots by Dehn (1995); De Noni et al. (1986); Harden (1988, 1991, 1993) and additional unpublished data. The average maximum soil loss for bare land at field level was estimated at 150 ton ha^{-1} yr^{-1}.

Finally, nutrient loss due to erosion per land use type within a grid, was calculated by multiplying the erosion total risk factor, maximum soil loss, and N and K concentrations in the soil material. As the finest nutrient rich soil particles are eroded most easy, eroded soil has higher nutrients contents than the average top soil. This was being accounted for by an enrichment factor of 1.5, based on Stoorvogel (1993). Of this amount of nutrients lost, 80% is assumed to actually enter the water streams, and leave grid cells (INECEL, 1992).

As data on soil P were not available for Ecuador, it was not possible to calculate P loss by erosion.

4. Results

The separate inputs and outputs of the nutrient balance for the land use types temporary crops, permanent crops and permanent grassland at a national scale are given in Figs. 2–4.

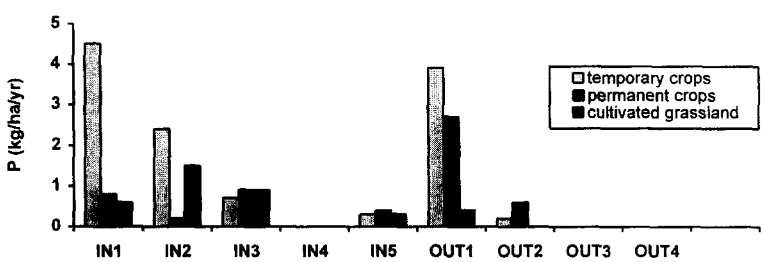

Fig. 3. Average inputs and outputs of P for land use systems at a national scale.

Fig. 4. Average inputs and outputs of K for land use systems at a national scale.

The contribution of erosion (OUT5) to the total balance of nitrogen is to be noted, especially for temporary crops and permanent crops. This finding is strongly related to the land use ratings in the erosion assessment. Also, leaching (OUT3) and gaseous losses (OUT4) contribute significantly to total N output. The output of N through harvested product (OUT1) as well as the mineral fertilizer input is for temporary crops very similar to that of permanent crops, but in temporary crops organic fertilizer (IN2) is more important.

As P loss by erosion was not calculated, the total P balance was not assessed. However, individual inputs and outputs are presented, in order to make comparison between the land use types temporary crops permanent crops and cultivated grassland possible. Both mineral and organic P fertilizer inputs are notably higher for temporary crops than for permanent crops. Output of P through harvest crop product and residues is slightly higher in temporary crops.

As a combined result of high K concentrations in permanent crops and intensive cultivation systems, K removal in harvested product (OUT1) is relatively high for the land use system permanent crops and is the main output of the balance. Due to lower K concentrations in the soil, losses of K through leaching and erosion are much lower than those for N.

National nitrogen and potassium balances were obtained by averaging inputs and outputs calculated per grid cell, for the land use types temporary crops, permanent crops and cultivated grassland, and furthermore for total land use, taking into account the fractions of the land use types temporary crops, permanent crops, cultivated grassland, natural grassland, páramo, fallow, and mountains and forests (Table 7). With the exception of potassium in cultivated grassland, negative total balances were found indicating a depletion of the soil nutrient stock.

Tables 8–10 present inputs, outputs and total nutrient balance for separate land use types and total land use in the 3 eco-regions Coast, Andes and Amazon. The proportion of agricultural land to total area (Table 5) explains why nitrogen and potassium balances for total land use in the Amazon are close to zero, though nitrogen balances for separate land use types, and the potassium balance for permanent crops is strongly negative.

The data in Table 8 indicate that the nitrogen balance for total land is most negative in the Andes. Erosion is an important component of the nitrogen balance, especially for temporary and permanent crops. In the Andes erosion losses are higher then in the coast, but erosion risk is highest in the Amazon eco-region. This is mainly caused by agriculture on the low Eastern footslopes of the Andes where steep slopes, susceptible soils and high rainfall intensity cause unfavourable conditions. Leaching of nitrogen is for most land use types highest in the Andes, reflecting the characteristics of soil types in this eco-region. In the coastal eco-region relatively more mineral fertilizer is used than in the Andes, above all

Table 7
Total national nitrogen and potassium balance (kg ha^{-1} yr^{-1}) for different land use types and total land

Land use type	Nitrogen	Potassium
Temporary crops	−42	−5
Permanent crops	−40	−25
Cultivated grassland	−8	+4
Natural grassland	−10	−2
Total land	−8	−2

Table 8
Nitrogen inputs and outputs and total balance (kg ha^{-1} yr^{-1}) for different land use types and total land, in three regions[a]

Region	Land use type	n	IN1	IN2	IN3	IN4	IN5	OUT1	OUT2	OUT3	OUT4	OUT5	Balance
Coast	Temporary crops	544	25.5	0.3	4.9	11.2	3.7	29.6	1.5	11.2	11.2	19.8	−27.7
	Permanent crops	535	21.9	0.3	5.4	4.7	3.3	15.5	0.0	15.9	13.3	20.0	−29.1
	Cultivated grassland	554	2.4	8.0	5.2	9.7	3.4	0.3	0.0	10.5	14.5	5.9	−2.5
	Natural grassland	297	0.0	0.0	4.1	9.1	0.0	0.1	0.0	4.2	7.4	1.9	−0.4
	Total land												−9.9
Andes	Temporary crops	550	12.8	11.5	4.2	4.3	1.5	10.8	0.8	8.8	13.7	53.4	−53.2
	Permanent crops	385	11.8	1.3	5.9	4.7	3.1	31.4	0.2	23.1	11.3	30.4	−69.6
	Cultivated grassland	485	2.4	7.7	5.9	9.7	1.4	2.8	0.0	20.6	15.3	6.7	−18.3
	Natural grassland	472	0.0	0.0	4.3	9.4	0.0	4.6	0.0	7.0	8.0	6.8	−12.7
	Páramo	259	0.0	0.0	4.5	9.4	0.0	1.2	0.0	5.1	10.1	8.0	−10.5
	Total land												−20.1
Amazon	Temporary crops	126	0.5	0.3	6.9	5.0	0.0	10.8	0.0	20.1	11.8	112.4	−142.4
	Permanent crops	138	0.8	0.8	7.2	5.0	0.0	24.9	0.0	21.3	10.7	38.5	−81.6
	Cultivated grassland	144	2.4	2.2	6.9	10.0	0.3	0.1	0.0	20.1	13.9	10.9	−23.3
	Natural grassland	16	0.0	0.0	6.4	10.0	0.0	0.0	0.0	12.7	11.8	4.7	−12.8
	Total land												−0.6

[a] The meaning of IN1–OUT5 is explained in Table 1. Number of grid cells for each land use type indicated with n.

the result of high application rates in banana plantations and rice. The importance of organic manure in the Andes compared to the coast and the Amazon is remarkable. In the Andes relatively more grazing cattle, sheep and goats are present, and a higher percentage of (mainly temporary) crops is fertilized with organic manure. Under the assumption of the collection of part of the animal manure, this leads to relative high inputs of organic nitrogen, phosphorus and potassium, particularly for temporary crops, at the expense of cultivated and natural grassland and páramo. Furthermore, gaseous losses constitute significantly to the loss of nitrogen in all three regions. In the potassium balance, the output through harvested products of permanent crops is high, due to high potassium concentrations and high yields of

Table 9
Phosphorous inputs and outputs (kg ha^{-1} yr^{-1}) for different land use types in three regions[a]

Region	Land use type	n	IN1	IN2	IN3	IN4	IN5	OUT1	OUT2	OUT3	OUT4	OUT5
Coast	Temporary crops	554	3.9	0.1	0.8	0.0	0.5	5.7	0.3	0.0	0.0	–
	Permanent crops	535	0.8	0.1	0.9	0.0	0.4	1.9	0.2	0.0	0.0	–
	Cultivated grassland	554	0.6	1.6	0.9	0.0	0.4	0.1	0.0	0.0	0.0	–
	Natural grassland	297	0.0	0.0	0.6	0.0	0.0	0.1	0.0	0.0	0.0	–
Andes	Temporary crops	550	5.0	4.5	0.7	0.0	0.2	2.3	0.2	0.0	0.0	–
	Permanent crops	385	0.9	0.5	1.0	0.0	0.4	4.8	1.7	0.0	0.0	–
	Cultivated grassland	485	0.6	1.5	1.0	0.0	0.2	1.1	0.0	0.0	0.0	–
	Natural grassland	472	0.7	0.0	0.7	0.0	0.0	2.4	0.0	0.0	0.0	–
	Páramo	259	0.0	0.0	0.7	0.0	0.0	0.9	0.0	0.0	0.0	–
Amazon	Temporary crops	126	0.2	0.1	1.2	0.0	0.0	3.1	0.0	0.0	0.0	–
	Permanent crops	138	0.1	0.3	1.2	0.0	0.0	3.4	0.1	0.0	0.0	–
	Cultivated grassland	144	0.6	0.4	1.2	0.0	0.0	0.1	0.0	0.0	0.0	–
	Natural grassland	16	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	–

[a] The meaning of IN1–OUT5 is explained in Table 1. Number of grid cells for each land use type indicated with n.

Table 10
Potassium inputs and outputs and total balance (kg ha^{-1} yr^{-1}) for different land use types and total land, in three regions[a]

Region	Land use type	n	IN1	IN2	IN3	IN4	IN5	OUT1	OUT2	OUT3	OUT4	OUT5	Balance
Coast	Temporary crops	544	5.5	0.1	3.2	0.0	1.6	8.2	2.1	3.8	0.0	2.6	−6.3
	Permanent crops	535	16.9	0.2	3.6	0.0	1.4	36.3	0.0	2.0	0.0	1.9	−18.1
	Cultivated grassland	554	1.0	2.4	3.4	0.0	1.5	0.1	0.0	2.8	0.0	0.6	4.8
	Natural grassland	297	0.0	0.0	2.7	0.0	0.0	0.1	0.0	2.3	0.0	0.2	0.1
	Total land												−2.4
Andes	Temporary crops	550	3.7	4.8	2.8	0.0	0.6	5.6	2.0	2.5	0.0	6.2	−4.3
	Permanent crops	385	8.2	0.6	3.9	0.0	1.3	49.6	0.2	1.5	0.0	2.7	−40.0
	Cultivated grassland	485	1.0	2.3	3.9	0.0	0.6	1.3	0.0	2.8	0.0	0.5	3.9
	Natural grassland	472	0.0	0.0	2.8	0.0	0.0	2.7	0.0	2.2	0.0	0.6	−2.7
	Páramo	259	0.0	0	2.9	0.0	0	3.2	0	2.4	0.0	0.4	−3.2
	Total land												−3.3
Amazon	Temporary crops	126	0.1	0.2	4.5	0.0	0.0	2.9	0.1	0.9	0.0	2.2	−1.2
	Permanent crops	138	0.4	0.4	4.7	0.0	0.0	43.3	0.0	0.5	0.0	0.8	−39.1
	Cultivated grassland	144	1.0	0.7	4.5	0.0	0.1	0.1	0.0	0.9	0.0	0.2	5.1
	Natural grassland	16	0.0	0.0	4.2	0.0	0.0	0.0	0.0	0.7	0.0	0.1	3.4
	Total land												0.0

[a] The meaning of IN1–OUT5 is explained in Table 1. Number of grid cells for each land use type indicated with n.

especially banana and to a lesser extent plantain. It seems that especially for permanent crops, fertilizer application is not sufficient to supply the amount of nutrients that is taken up by the crop.

5. Discussion and conclusions

The NUTMON model suggests that, overall, Ecuadorian land use systems display a net depletion of nutrients. The actual degree of depletion depends on the combination of land use, soils, rainfall, fertilizer application, crop yields and animal husbandry.

Current fertilizer application rates appear generally hardly sufficient to supply the nutrients that leave the production system through harvested products and do not compensate additional nutrient losses.

Erosion is an important factor in a negative nutrient balance as it was also in the previous studies by Stoorvogel et al. (1993) and Smaling et al. (1993). This is in line with Quiroz et al. (1995) who used the EPIC model to estimate soil loss through erosion in Peru and stated that "current management of most cultivable land in the Andes threatens the sustainability of the agricultural systems and thus jeopardises the future of the region's inhabitants, because of excessive soil erosion". Our results suggest that not only in the Andes, but also in the coastal zone and the Amazon, serious threats occur due to erosion and leaching. However, in the Amazon this does not yet lead to problems at the regional scale due to the spatial predominance of undisturbed forest. Intensive logging and introduction of agriculture leads to local impoverishment of soils.

In Ecuador, population growth has caused high pressure on the land. This leads to shorter fallow periods and the conversion of non-agricultural land in land for agricultural crops and grassland, often in marginal areas (Southgate and Whitaker, 1994), resulting in stronger nutrient depletion.

In this study, the yearly rates of changing nutrient stock are assessed, based on the 1991 land use data. It is obvious that a negative balance does not necessarily lead to problems in the short term. On some deep volcanic soils of the Andes even soil losses of 100 ton ha^{-1} yr^{-1} do not cause immediate problems. However, if after several years of soil losses the infertile subsoil (often with poor hydraulic properties) is reached, the process is irreversible on a human time scale. The strength of the nutrient balance approach lies in its use as a sustainability indicator that is regularly monitored.

Further improvement of the assessment of soil nutrient balances requires a reduction of data uncertainty. Specific data needs for the Ecuadorian situation first of all relate to erosion which is a key factor. More information on soil loss under different conditions of land use, soils and climate is desirable. Simultaneous studies at field and watershed level will contribute to better estimates of the amount of soil and nutrients lost at field level, that actually enter the river systems. Some of this material is redistributed to lower areas and is therefore not a loss at national level. Furthermore, more detailed data on the spatial variability in fertilizer application rates is desirable. The role of the fallow in nutrient replenishment also needs further consideration, as it has hitherto been treated as a balanced system ignoring grazing of fallow land. The positive contribution of the fallow depends on climate and altitude as well as soils.

The grid approach proved to be suitable for linking input data and performing calculations at a spatial aggregation level that is related to the detail of the input data. By treating different land use types separately, effects of changing land use can be explored. This is especially interesting when the monitoring of nutrient balances will be linked with models that explore possible land use changes under influence of changing land use drivers such as technical improvements, population growth and market changes.

Moving between different hierarchical spatial levels allows the detection of broad zones that seem interesting with regards to sustainability issues. Zooming in to these zones is possible to a level where still enough spatial units (grid cells) contain relevant data. For further detail in areas of interest, a combination with field studies that investigate the relation between land use and nutrient flows at the level of small watersheds is recommendable. An example of such a study has been presented by De Ridder et al. (1996) for West Africa.

We conclude that the monitoring of nutrient regional balances seems to be a useful tool for the support of research and policy measures aiming at sustainable developments in (changing) agricultural land use. In Ecuador, recommendations with respect to erosion control and fertilizer policy are corroborated by this study.

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