Nutr Cycl Agroecosyst (2015) 101:55–82
DOI 10.1007/s10705-014-9662-5

ORIGINAL ARTICLE

Modeling of soil nutrient balances, flows and stocks revealed effects of management on soil fertility in south Ecuadorian smallholder farming systems

Etienne Bahr · Diego Chamba-Zaragocin · Natacha Fierro-Jaramillo · Anke Witt · Franz Makeschin

Received: 6 June 2014 / Accepted: 21 November 2014 / Published online: 29 November 2014

Abstract Linking nutrient balances and flows to soil nutrient stocks creates a valuable indicator for sustainability assessment in agricultural land-use systems. Therefore, we investigated the impact of management on soil fertility at farm/field scale using the Nutmon approach. A detailed methodology for the adaptation of the difficult-to-quantify flows to the local conditions is described. Research was carried out in the three farming systems of Yantzaza (low-external-input), El Tambo (irrigated cash crops) and San Lucas (integrated nutrient management) in southern Ecuador. For each land-use within a farm (annual and perennial crops, pasture, forest), soil nutrient balances and flows were modeled with Nutmon and soil nutrient stocks were calculated for NPK. Soil nutrient balances were evaluated using potential socio-economic and soil fertility explanatory variables. Balances for the different land-uses in the three research areas varied between −151 to 66 kg ha^{-1} a^{-1} for N, −4 to 33 kg ha^{-1} a^{-1} for P and −346 to 39 kg ha^{-1} a^{-1} for K and were mainly negative. Up to 70 % of the balances' variability was explained by soil fertility variables and financial flows. Highest external inputs existed in land-uses with a strong market orientation. Land-uses benefiting from a surplus of within-farm flows had the highest soil nutrient stocks. The focus on N fertilization induced highly negative PK balances in annual crops of El Tambo. In contrast, the application of organic fertilizers and nutrient recycling in San Lucas resulted in positive NP balances particularly for perennial crops. NP balances in annual crops of Yantzaza were most negative due to nonexistent fertilization, leaching and burning of crop residues. A non-sustainable land-use of annual crops in Yantzaza was illustrated by total N stock decreases of 4.9 % a^{-1} and decreased soil organic carbon stocks to 85 % of adjacent forest sites. Results indicated a potential risk regarding sustainable management of soils in the research area and provide a basis for policy and decision makers to develop appropriate management strategies.

Keywords Nutmon · Agricultural soil · Soil nutrient depletion · Sustainable land-use · Within-farm flows

E. Bahr (✉) · F. Makeschin
Institute of Soil Science and Site Ecology, Dresden University of Technology, Pienner Str. 19, 01737 Tharandt, Germany
e-mail: etienne.bahr@tu-dresden.de

D. Chamba-Zaragocin · N. Fierro-Jaramillo
Departamento de Ciencias Agropecuarias y Alimentos, Universidad Técnica Particular de Loja, San Cayetano Alto, Loja, Ecuador

A. Witt
Ringstr. 16, 01968 Brieske, Germany

Introduction

More than 560 million ha of agricultural land are globally threatened by soil degradation (Oldeman et al. 1990). This is a particular problem in land-use systems of developing countries due to nutrient mining and subsequent soil fertility decline (Stoorvogel and Smaling 1998) often caused by low resource endowment (Shepherd and Soule 1998). The calculation of soil nutrient balances and flows is known to be a powerful indicator for the determination of soil fertility decline and nutrient use optimization and proved to be a pragmatic approach in the assessment of natural resource management (Hartemink 2006). The Nutrient Monitoring model (Nutmon) is the most frequently used tool for the calculation of soil nutrient balances and flows (Cobo et al. 2010) and was recently released within a new framework called Monqi (www.monqi.org). Nutmon is based on nutrient inputs and outputs (Smaling and Fresco 1993) and has been widely adopted in African (van Beek et al. 2008; Onduru et al. 2007; Hengsdijk et al. 2005) and Asian (Phong et al. 2011; Surendran and Murugappan 2006) land-use systems. In contrast, South America was only regarded in a single study on a national scale (de Koning et al. 1997) although 50 % of the world's nutrient depleted soils are located in South America (Tan et al. 2005). Nutrient balances should not be used without consideration of soil nutrient stocks when fertilizer requirements or sustainability of the land-use system are investigated. For agricultural land-use systems a stock decline for total nitrogen (TN) of more than 1 % was considered not sustainable (Hilhorst et al. 2000). It was stated that nutrient balance studies need to be combined with field measurement (Vanlauwe and Giller 2006; Janssen 1999); yet, only few studies exist which calculated the rate of change in soil chemical properties (Hartemink 2006). Issues of concern and criticism have been expressed about Nutmon studies for not including all essential flows, using inappropriate transfer functions or failing to link soil nutrient balances and/or flows to soil nutrient stocks (Cobo et al. 2010; Færge and Magid 2004).

It is generally agreed that nutrient management is an important factor to secure sustainability in agriculture (Oenema et al. 2006) among other biophysical, economic and social factors (Smith and McDonald 1998). However, diversity in plot management can also be responsible for considerable differences in soil nutrient stocks causing positive and negative balances within the same farm (Esilaba et al. 2005; Vanlauwe and Giller 2006). Generally, within-farm soil fertility is characterized by decreasing soil fertility from the homestead to remote areas (Tittonell et al. 2007) which in the end also affect crop yields (Vanlauwe et al. 2006). Moreover, it is well known that farmers' decisions on fertility management, which are mainly driven by resource endowment and management aim, are highly influenced by both socio-economic and biophysical environments (Haileslassie et al. 2007; Berkhout et al. 2011). Yet, quantitative data, to what extent management in terms of socio-economic and biophysical issues affects nutrient balances or flows and thus soil fertility, are scarce, but play an essential role when considering the adaptation of management strategies (Vanlauwe et al. 2010).

In the Ecuadorian Andes large areas have been converted into agricultural land at the expense of natural forest caused by the quickly growing population (Barbier 2004; de Koning et al. 1998). The Andes feature an enormous heterogeneity of biophysical conditions, mainly due to high relief intensity, causing multifaceted land-use systems within a relatively small area (Cañadas Cruz 1983). These land-use systems are characterized by a mixture of different ethnic, socio-cultural and socio-economic structures. Agricultural management in the Andean highlands, where the indigenous Saraguro have been farming for several hundred years, is characterized by integrated nutrient management (Pohle et al. 2010). This is defined as the reasonable manipulation of soil nutrient stocks and flows to an optimum level for sustaining crop productivity. Adding a balanced quantity of chemical fertilizers in combination with organic manures and the recycling of crop residues are the main tools of integrated nutrient management (Smaling et al. 1999). In contrast, the eastern escarpments of the Andes facing the Amazon are dominated by low-external-input agriculture with lacking nutrient recycling due to burning of crop residues (Bahr et al. 2014). Climatic conditions in the western Andean cordillera and the inter-Andean valleys are rather dry which induced the implementation of irrigation agriculture (Richter 2003). Particularly the southern inter-Andean valleys are intensively managed with cash crop production using large amounts of urea fertilizer (Bahr et al. 2013). Although land-use systems of the Ecuadorian Andes have been described extensively (Stoorvogel et al. 2004; Borbor-Cordova et al. 2006; Dercon et al. 2006), little is known about the extent to which the relevant agricultural management affects soil fertility.

Hence, the objective of the study was to investigate the impact of agricultural management in three South Ecuadorian farming systems on soil fertility. Therefore, regression equations of inputs and outputs were adjusted to the local conditions for nutrient balance modeling with Nutmon. Soil nutrient balances for NPK were modeled on a field/farm scale and compared to soil nutrient stocks. Soil nutrient balances were evaluated using potential socio-economic and biophysical explanatory factors.

The following hypotheses were put forward:

1. Agricultural management based on low-external-input without nutrient recycling induces non-sustainable land-use due to severe soil nutrient mining.
2. Mixed farming systems with nutrient recycling have a soil nutrient balance in equilibrium since nutrient losses are reduced to a minimum.
3. Different land-uses within the same farming system may have very contrasting soil nutrient balances. The main driver is the management aim causing different nutrient inputs, outputs and flows within the same farm.
4. Financial flows rather than the initial soil fertility have a greater impact on the soil nutrient balance in the intensively managed cash crop area of the inter-Andean valleys. The contrary is expected for the low-external-input system in the transition zone of Andes and Amazon.

Methodology

Research area

The present study was conducted in the southern Andes of Ecuador where agricultural area increased over the last decades. Especially valley bottoms have been cleared to install pastures and cropland (Ochoa-Cueva et al. 2013). In contrast, yields remained on the same level especially in smallholder farming systems (de Koning et al. 1998) where Andean crops such as white corn, bean and potato still prevail (Cueva and Chalán 2010). Therefore, structural changes occurred recently towards larger, more commercial agriculture (Mulligan et al. 2010). Geological, soil, climate and agro-ecological maps were reviewed and field observations with local experts as well as farm interviews were performed before choosing the areas for research. Finally, three research areas were selected which show a clear distinction in biogeochemical, socio-economic and land-use characteristics (see Table 1 for a comprehensive description of the research areas). The research areas represent much of the variability of land-use systems in the southern Ecuadorian Andes in conformity with previous investigation (Pohle 2008).

Farm selection and monitoring

Farms were selected involving multi-disciplinary stakeholders e.g. experts from the local university (UTPL), scientists (TU Dresden), governmental decision makers and local farmers using participatory techniques. Criteria for the selection were the representativeness of the farm with respect to the research area, accessibility of the farm, the keeping of written records by the farmer and the willingness to participate and cooperate. The land-use history was obtained by interviewing the respective landowners. Additionally, farm households participated in the characterization of the current farm nutrient management by preparing maps of the farm which indicated and allocated soil characteristics, cultivation of crops and resource flows. Within each of the three research areas seven different farms were selected (totalling 21) for investigation in 2008. The year of investigation showed deviations from an average year in terms of precipitation (Table 1). Inputs and outputs were monitored in each farm on a 3 month basis over a period of 1 year using the structured questionnaire provided by the Nutmon tool (Van den Bosch et al. 1998). For this purpose farms were visited every 3 months by scientists and maintained farmers' records helped to collect the data. Farm walks were performed after each interview in order to get a better understanding of the processes occurring in the farm and to verify questionnaires by asking the same questions again.

Nutmon approach

Farms were subdivided into various compartments according to the Nutmon approach which are referred to as farm section unit (FSU) and primary production unit (PPU) (for a full description see Van den Bosch et al. 1998; De Jager et al. 1998). FSUs possess homogeneous characteristics in terms of soil

Table 1 Biogeochemical, socioeconomic and land-use characteristics of the research areas and the investigated farms in Yantzaza, El Tambo and San Lucas

	Research area		
	Yantzaza	El Tambo	San Lucas
Biogeochemical characteristics			
Coordinates	3°47′S–3°56′S; 78°43′W–48°46′W	4°01′S–4°06′S; 79°20′W–79°21′W	3°42′S–3°45′S; 79°15′W–79°16′W
Altitude (m a.s.l.)	1,000	1,400	2,500
Annual mean temperature[a] (°C)	22.1	23.7	15.1
Annual mean precipitation (mm) 2008/40 year average[a]	2,295/1,940	605/383	1,641/778
Rainfall distribution	Small peak from March to May	85 % from October to April	Peak from February to April
Parent material	Granite	Dacite	Granite
Dominant soil type[b]	Haplic Cambisol (humic)	Haplic Cambisol (colluvic, eutric)	Mollic Umbrisol (humic)
Topography	Steep slopes and level floodplains	Moderately undulating	Plateaus and steep slopes
Socioeconomic characteristics			
Ethnic group	Mestizos	Mestizos	Saraguro
Land-use distribution (%)[d]			
Forest	46	13	35
Annual crops	1	7	2
Perennial crops	4	15	1
Pasture	45	11	54
Others	4	54	8
Characteristics of the investigated farms			
Farm type	Extensive grazing management with subsistence crops	Intensive irrigated agriculture wish cash crops	Indigenous livestock farming with a mixture of subsistence agriculture and cash crop production
Average farm size (ha)[e]	37.6	1.8	3.3
Average off-farm income (%)[e]	35	0	65
Production activities			
Subsistence crops	Maize, cassava	Maize, beans, cassava	Maize, potato
Cash crops	Coffee, cocoa	Tomato, pepper, cucumber	Blackberry, apple, peach
Farm animals	Cattle	Small farm animals	Cattle and sheep

Table 1 continued

	Research area		
	Yantzaza	El Tambo	San Lucas
Livestock density (TLU ha^{-1})[c]	1.6	0.4	4.1
Crop rotation	None	3–4 times annually	Irregularly
Harvest residue management	Burning of residues	Burning of residues	Incorporation into soil
Ploughing	None	Mechanized to a depth of 30 cm	Animal driven plough
Irrigation	None	Open channels	None

[a] According to Richter (2003)
[b] According to FAO et al. (2006)
[c] Based on TLU per total farm land
[d] Calculated with GIS land-use cover of NCI 2010
[e] n = 7

properties, slope and land tenure. PPUs are situated in one or several FSUs and describe crop activities of one or various crops grown in a distinct field over a specific period of time (Fig. 1). Additionally, a farm usually contains secondary production units (SPUs) and redistribution units (RUs) which refer to a group of animals of the same species and locations where nutrients are collected or accumulated respectively. Farm animals are assigned to tropical livestock units (TLUs) where one TLU corresponds to 250 kg live weight.

For the current research the soil-system-budget approach was implemented which calculates all nutrient inputs and outputs along with nutrient enrichment and depletion within and from the soil surface to a depth of 30 cm of the mineral soil (Oenema et al. 2003). The Nutmon standard flows and sedimentation from erosion were considered of importance after examination of the possible paths for nutrients into and out of the farms. These flows were employed to calculate the soil nutrient balance for NPK. Inputs comprised IN1 (mineral fertilizer [inorganic and synthetic]), IN2 (organic materials and manure), IN3 (atmospheric deposition), IN4 (biological N fixation), IN5 (sedimentation from flooding) and IN6 (sedimentation from erosion). Outputs consisted of OUT1 (harvested products), OUT2 (crop residues and grazing), OUT3 (leaching), OUT4 (gaseous losses) and OUT5 (erosion). Besides nutrient flows, economic flows such as expenses for fertilizers, seeds and pesticides, wages for labor and income from sold products were also evaluated in the present approach. Information gathered from the Nutmon questionnaire for the calculation of these flows was quantitative (amount of fertilizers/harvested products/animals/paid wages among others) and qualitative (type of crops/animals/fertilizers/pesticides, existence of crop residue burning, construction characteristics of RUs among others). Additionally, quantitative information was collected for transfer functions (e.g. leaching) by determination of specific parameters of soil samples. The background database, provided by the Nutmon tool, stores non-farm-specific information on crops, crop residues, animals, inputs and outputs. It provides an essential support for the modeling of inputs, outputs and balances particularly for the calculation of NPK nutrient losses from harvest and plant residues. To increase quality of the data in the Nutmon background database, commonly planted

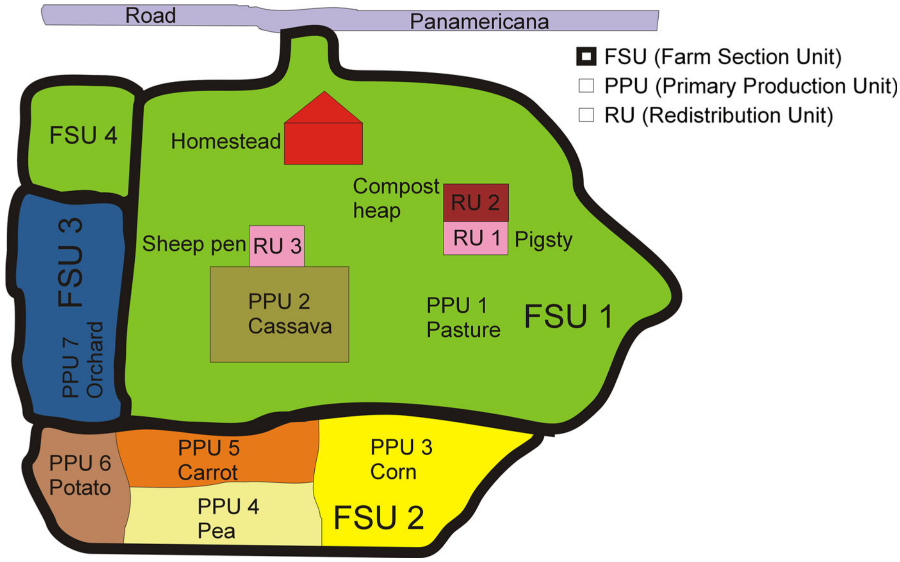

Fig. 1 Outline of an example farm in San Lucas

crops in the research area were sampled and investigated in the laboratory for TN, total phosphorus (TP) and total potassium (TK) contents (see "Soil and plant sampling and laboratory analysis" section for detailed description). Remaining background data was checked thoroughly and modified if literature values from South America (Scrimshaw 1997; International Network of Food Data Systems (INFOODS) 2014) were available. It was intended to target the soil nutrient balance for the year of the investigation as accurately as possible in order to assess the current farm management. Therefore, only input data of the year of the investigation was applied (e.g. precipitation, soil cover, soil chemical and physical data, fertilizer use, harvested products). It was deliberately decided not to make use of long term medium values to take into account that farmers adjust their management strategies to the current socio-economic and natural conditions.

Adapting Nutmon to Ecuador

Nutmon did not require an adaptation of easy-to-quantify flows, since data acquisition of these is universal. However, the assessment of difficult-to-quantify flows beyond the borders of Africa necessitated a thorough review due to different inherent conditions. Up-scaling was not required since the scale of application (field/farm) was the same as the models' scale.

Wet and dry atmospheric deposition (IN3)

Most studies dealing with Nutmon applied the transfer function of Stoorvogel and Smaling (1990) for the calculation of wet and dry deposition. Comparison of the transfer function with results from a study close (3°58′S and 79°04′W) to the three areas of the current investigation revealed an underestimation for wet and dry atmospheric deposition (Wilcke et al. 2008). Therefore, the transfer function of Stoorvogel and Smaling (1990) was adapted to the local conditions using the following equations:

$$IN3_N = 0.32 \times Prec^{0.5} \quad (1)$$

$$IN3_P = 0.034 \times Prec^{0.5} \quad (2)$$

$$IN3_K = 0.28 \times Prec^{0.5} \quad (3)$$

in which $IN3_N$, $IN3_P$ and $IN3_K$ is the input of N, P and K via wet and dry atmospheric deposition (kg ha^{-1} a^{-1}) and Prec is the annual precipitation (mm).

Biological N fixation (IN4)

Non-symbiotic N fixation was calculated according to Stoorvogel and Smaling (1990). The two major contributors of symbiotic N fixation in the research area are beans (*Phaseolus* spp.) usually intercropped with maize and clover (*Trifolium* spp.) which was partly found in association with pasture grass. For beans a symbiotic N_2 fixation rate between 0.2 and 0.75 (kg N fixed kg^{-1} N in crop) was reported (Graham et al. 2003) and hence a value of 0.5 (kg N fixed kg^{-1} N in crop) was used in the present study. For clover the symbiotic N_2 fixation rate was 0.25 (kg N fixed kg^{-1} N in crop) according to Hansen and Vinther (2001).

Sedimentation and addition of dissolved nutrients from flooding and irrigation (IN5)

Input of dissolved nutrients and sediments from irrigation water took place in the semi-arid research area of El Tambo. Water samples were taken at five different sub-locations and element concentrations for NPK were measured and fluxes were calculated. The quantity of irrigated water was obtained from farm surveys. However, calculated NPK inputs never exceeded 1 kg ha^{-1} a^{-1} (data not shown) and were not considered in this study. For naturally flooded land (one farm in Yantzaza) a sediment accumulation rate of 0.5 mm a^{-1} was adopted as was found for the Rio Napo and Rio Yasuni in lowland Amazonian Ecuador (Weng et al. 2002). Nutrient input by sedimentation was then calculated using the topsoil nutrient contents and bulk densities of the flooded farm sections.

Sedimentation (IN6) and soil loss (OUT5) from water erosion

Soil loss from erosion as well as sedimentation from erosion was calculated using the universal soil loss equation (USLE). According to Wischmeier and Smith (1978), yearly soil loss (t ha^{-1} a^{-1}) is estimated as a function of rainfall erosivity (R), soil erodibility (K), topographic factor (LS), soil cover and management (C) and support practices (P) as follows:

$$\textit{Annual soil loss} = R \times K \times LS \times C \times P \quad (4)$$

The calculation of sedimentation and soil loss from water erosion was based on GIS modeling using a digital elevation model (DEM) with grid cells of 50 × 50 m. The basis for the calculation of R, K and C was a thorough literature review. Particularly for R different regression models were used due to the distinct climate characteristics of each area (Table 2). A K factor, which was calculated according to Renard et al. (1997), and a C factor were assigned to each PPU. For each crop literature values were used to determine the C-factor. Visual impressions from farm walks and of photos from the year of the investigation were compiled for every single crop in the research area. The C-factor was then adjusted upwards or downwards within a range of 0.1 in case of deviations from the average soil cover of the crop. If one grid cell contained more than one PPU, a medium value for the respective USLE factors was calculated. To determine the LS factor for each grid cell, a raster-based determination of the flow accumulation using the multiple flow direction algorithm described by Quinn et al. (1991) was implemented. Modeling was performed with ArcGIS 9.2 using the hydrology tools "flow accumulation", "flow direction" and "flow length" in the spatial analyst. Consideration of the surface run-off and the quantification of the flow (flow accumulation) were fundamental for the raster-based calculation of the L factor using the multiple flow direction algorithm. The altitude derived from the DEM was the basis for the calculation of the S factor for each grid cell. Depending on slope gradient and slope length for each of the eight surrounding grid cells, their proportional contribution of the flow into (sedimentation) and out of a central grid cell (erosion) was calculated. Based on this procedure, sedimentation and soil loss from erosion was calculated for each grid cell of the farm separately. Due to the fact that the nutrient rich topsoil is selectively removed by erosion, an enrichment factor for eroded sediments of 1.5 was assumed for all nutrients (Smaling et al. 1993).

Table 2 Calculation of the R factor for the three research areas

Research area	Literature source for calculation	Rainfall erosivity (R) (MJ mm ha^{-1} h^{-1} a^{-1})
Yantzaza	da Silva (2004), Sonder (2002)	11,279
El Tambo	Yu and Rosewell (1996)	2,592
San Lucas	Beskow et al. (2009), da Silva (2004), Sonder (2002)	7,057

Leaching (OUT3)

A regression model based on an extensive literature review with the validity for a wide range of soils and climates in the tropics was used to calculate leaching of N (de Willigen 2000) as follows:

$$OUT3_N = (21.37 + 0.00374) \times \frac{Prec}{C \times L} \times (F + D \times TN - U) \quad (5)$$

with Prec for annual precipitation (mm), C for clay (%), L for rooting depth (m), F for mineral and organic fertilizer N (kg N ha^{-1}), D for decomposition rate (%), TN for amount of nitrogen in the soil (kg N ha^{-1}) and U for N-uptake by crops (kg N ha^{-1}). The N-decomposition rate was adjusted to the local conditions using literature data from soils in the Ecuadorian Andes and tropical Amazon based on different land-uses (Table 3). Since temperature has an effect on N turnover rates, the Q_{10} relationship (Kirschbaum 1995) was used to fit literature values for the decomposition rate in the event of deviating mean annual temperatures from the research area. Leaching losses for potassium were calculated as a function of the clay content, exchangeable K and annual precipitation according to Smaling et al. (1993). P budgets from a tropical watershed in Ecuador affected by agriculture showed that P exports into the river were mainly driven by runoff and erosion (Borbor-Cordova et al. 2006). This was confirmed in a study of Wilcke et al. (2008) near the present research area who did not detect P in the soil solution at 0.15 and 0.30 cm depth indicating a high P sorption which is often found in tropical soils of South America (Sato and Comerford 2008). Therefore, leaching of P was not considered in this study.

Table 3 Nitrogen decomposition rates for the three research areas and corresponding land-uses

Research area	Decomposition rate (% TN a^{-1})			Literature source
Land-use	Yantzaza	El Tambo	San Lucas	
Annual crops	7.1	7.9	4.4	Hughes et al. (2002)
Perennial crops	5.0	5.7	2.6	Rhoades and Coleman (1999)
Pasture	2.2	2.6	1.0	Potthast et al. (2012a, b)
Forest	3.1	3.6	1.6	Rhoades and Coleman (1999)

Gaseous losses (OUT4)

Denitrification and volatilization are the two processes which cause the bulk of nitrogen losses to the atmosphere. The Nutmon toolbox only calculates denitrification (Van den Bosch et al. 1998). Therefore, a transfer function derived from literature data for tropical environments was used which considered both processes (FAO 2004) as follows:

$$OUT4 = (0.025 + 0.000855Prec + 0.01725F + 0.117SOC) + 0.113F \quad (6)$$

with Prec for annual precipitation (mm), F for mineral and organic fertilizer N (kg N ha^{-1} a^{-1}) and SOC for soil organic carbon content (%).

Losses of NPK by burning of crop residues were taken into account on the basis of special flows for each PPU. The return fractions per nutrient were set to 0.2, 0.8 and 0.8 for NPK, respectively, since losses for N are higher due to higher volatilization temperatures of P and K (Thy et al. 2006; Raison et al. 1985).

Soil and plant sampling and laboratory analysis

In total, the soil was sampled in 9–20 different plots in each farm depending on farm size. For each sampling plot a composite soil sample consisting of five subsamples was taken randomly to a depth of 30 cm of the mineral soil using a soil corer (diameter: 5.5 cm). Roots were removed cautiously directly after sampling. The soil moisture content was determined after oven-drying of an aliquot at 105 °C. Volumetric dried samples served for the calculation of the fine soil density (FSD) after sieving at 2 mm mesh size and the bulk density (BD), by considering that some portion of the soil did not pass 2 mm. A combination of sieving and sedimentation was used for the determination of the soil texture (Schlichting et al. 1995). The pH was measured potentiometrically in deionized water at a 1:2.5 soil/water ratio. An aliquot of each sample was dried at 40 °C and finely ground for the determination of soil organic carbon (SOC) and TN using a CNS-analyser (Vario EL, Heraeus). Ground samples were also used to analyze TP, TK and total S (TS) by means of strong acid digestion with HNO_3/HF/$HClO_4$ in a microwave (Kingston and Jassie 1986) and subsequent measurement with ICP-OES (Ciros, Spectro). For the determination of total inorganic nitrogen (TIN:

NH_4-N + NO_3-N) and dissolved organic carbon (DOC) soil samples were extracted with 0.1 M KCl and filtrated (folded filter, grade 292 Munktell Germany). The amount of TIN and DOC in the extracts was subsequently measured by a continuous-flow auto analyzer (Skalar Analytik GmbH, Erkelenz, Germany). For the determination of inorganic P, which is available for plants (PO_4-P), extraction with NH_4-F (Bray and Kurtz 1945) was performed on the acid soils of Yantzaza and San Lucas and extraction with $NaHCO_3$ was carried out for the alkaline soils of El Tambo (Olsen et al. 1954). The cation exchange capacity (CEC), including exchangeable potassium (K_{exch}), was analyzed with 0.5 M NH_4Cl solution (Lüer and Böhmer 2000) in the acid soils of Yantzaza and San Lucas and 0.1 M $BaCl_2$-TEA (Bascomb 1964) in the alkaline soils of El Tambo.

Additionally, plant samples were taken for species which either were grown widespread in the research area or where the database did not provide information at five different PPUs of the same research area to consider variability. All plant samples were dried at 60 °C. TN was determined as described for the mineral soil. TP and TK were studied by acid digestion with HNO_3 at 180 °C (Miller 1998). An aliquot of the plant samples was dried at 105 °C for the determination of the dry matter (DM) weight.

Calculation of soil nutrient balances, flows and stocks

Soil nutrient balances were calculated for all 21 farms of the research area. Additionally, soil nutrient balances, flows and stocks were calculated individually for each PPU of a single farm and then grouped according to land-use into annual crops, perennial crops, pasture and forest. The total soil nutrient balance was calculated as the difference of all inputs and outputs for NPK. Nutrient flows between different farm units were determined for NPK using the data from the Nutmon modeling. Nutrient flows from the external and household into the PPUs of annual crops, perennial crops, pastures and vice versa were identified as well as nutrient flows from SPUs and RUs into PPUs and vice versa. The soil nutrient stock of NPK and SOC was defined as the quantity of nutrients present in all soil components <2 mm in the top 30 cm of the mineral soil. Soil nutrient stocks were calculated for the total (TN, TP, TK and SOC) and plant available amount (TIN, PO_4-P and K_{exch}) using the corresponding fine soil density (Guo et al. 2008).

Statistics

Statistical analyses were carried out with Statistica 10.0. The normal distribution was tested with the Kolmogorov–Smirnov test. Values are reported as means including the standard error. Significant differences at $p < 0.05$ were tested with Tukey's HSD unless stated otherwise. Pearson correlation coefficients were calculated to test the relationships between variables. Inputs and outputs of the nutrient balance for NPK were tested with the two-way factorial Anova using the factors "location" and "land-use". The investigated farms usually included several sites or PPUs for the same land-use respectively. Therefore, the total of investigated sites or PPUs in each research area was as follows: 7 annual crops, 22 perennial crops, 25 pastures, 8 forests in Yantzaza; 21 annual crops, 22 perennial crops, 5 pastures in El Tambo; and 27 annual crops, 9 perennial crops, 17 pastures, 1 forest in San Lucas. However, if several values for one land-use existed in a single farm, a medium value for the specific land-use was calculated prior to statistical analysis. Thus, statistics were carried out on the basis of seven values for each land-use of a specific research area due to the total number of seven farms in each research area. This procedure was applied for the calculation of in- and outputs, soil nutrient balances, nutrient flows between different farm units and soil nutrient stocks.

A redundancy analysis (RDA) was performed to find out to which extent the variability of the independent variables (N inputs and outputs) was explained by financial flows (Fig. 4a–d) and soil fertility variables (Fig. 5a–d). Results were only shown for inputs and outputs of N since they were comparable for P and K. Differences in N inputs and outputs due to financial flows and soil fertility variables and their explained variance were shown for the first two axes of the respective land-uses and research areas. Financial flows were recorded using the Nutmon questionnaire or modeled with Nutmon and comprised expenses for mineral fertilizer, organic fertilizer, pesticides, seeds, hired labour and revenues by sold harvested products. Revenues by sold livestock were not accounted for since they were not assigned to a specific PPU. Monetary values were normalized into ha^{-1} a^{-1} for each PPU. Soil fertility variables consisted of 19 different variables [BD, concentration of H_3O^+, sand, silt, clay, SOC, TN, C/N ratio, TP, TS, exchangeable cations (Mg, Ca, K, Al, Mn), DOC, NO_3-N, NH_4-N, PO_4-P]. For reasons of clarity, only the eight soil fertility variables explaining the highest amount of variance of N inputs and outputs were included in the RDA.

Results

Farm management and soil characteristics of the research area

Physical and chemical soil properties differed widely between the three research areas (Table 4). The pH values in semi-arid El Tambo were more than one unit above those of Yantzaza and San Lucas owing to less leaching of basic cations. SOC stocks in San Lucas were highest for all land-uses and were more than twofold the amount compared to annual and perennial crops of El Tambo. Lowest SOC stocks were generally found in the annual crops of all research areas. C/N ratios were wider in higher altitude locations of El Tambo and San Lucas compared to Yantzaza. The CEC was in the same order of magnitude for the different land-uses of each research unit. Annual crops of Yantzaza had the highest base saturation whereas there was no differentiation between land-use in San Lucas. Soils in the research area had comparable site conditions with respect to the pedogenesis. This was indicated by soil textures in the same order of magnitude for all land-uses of a respective research area except for annual crops in Yantzaza (Table 4). Most annual crops in Yantzaza were located close to the farmyard which was generally near the riverbed causing the addition of sandy sediments whereas the other land-uses were distributed widely within a farm. Highest fine soil densities in each research area were found in annual crops with the exception of El Tambo which might be due to regular plowing with machinery in contrast to the other research areas.

Agriculture in Yantzaza was mainly focused on livestock production with extensive grazing management. Stables only existed for pigs and guinea pigs, whereas poultry was kept in free-range near the farmyard and cattle remained on pastures throughout

Table 4 Soil physical and soil chemical characteristics of annual crops, perennial crops, pastures and forests in the three research areas

Research area	Land-use	Sand (%)	Silt (%)	Fine soil density (g cm^{-3})	pH (H_2O)	SOC stock (Mg ha^{-1})	C/N	CEC ($cmol_c$ kg^{-1})	Base saturation (%)
Yantzaza	Annual crops	43.4 (10.5)	31.0 (1.0)	0.90 (0.17)	5.4 (0.1)	45.6 (6.2)	11.5 (0.2)	6.2 (2.2)	84.2 (6.6)
	Perennial crops	34.1 (4.9)	33.4 (5.6)	0.83 (0.04)	5.2 (0.1)	51.4 (5.5)	11.9 (0.3)	6.2 (0.5)	76.1 (4.2)
	Pasture	33.6 (4.7)	30.2 (2.5)	0.80 (0.05)	5.2 (0.1)	50.4 (3.8)	12.1 (0.2)	6.0 (0.7)	64.9 (7.3)
	Forest	28.3 (6.4)	36.7 (4.1)	0.76 (0.08)	5.0 (0.2)	53.5 (6.2)	12.1 (0.4)	7.2 (1.2)	58.3 (19.4)
El Tambo	Annual crops	35.9 (4.1)	33.6 (4.1)	0.88 (0.07)	7.0 (0.2)	31.5 (6.9)	13.5 (0.7)	41.5 (4.7)	n.d.
	Perennial crops	39.9 (4.5)	25.1 (1.2)	0.93 (0.04)	7.0 (0.2)	32.4 (6.3)	14.7 (1.4)	37.7 (4.1)	n.d.
	Pasture	35.2 (5.8)	32.4 (4.0)	0.93 (0.10)	7.1 (0.4)	47.8 (8.3)	13.1 (0.8)	38.0 (7.6)	n.d.
San Lucas	Annual crops	28.8 (7.1)	43.1 (3.9)	0.97 (0.07)	5.3 (0.2)	80.2 (19.7)	13.6 (1.0)	8.3 (1.0)	65.8 (7.4)
	Perennial crops	27.7 (6.3)	44.8 (3.8)	0.94 (0.08)	5.4 (0.2)	88.5 (17.4)	13.3 (1.1)	8.2 (1.1)	59.0 (9.5)
	Pasture	32.9 (8.1)	40.5 (4.9)	0.93 (0.06)	5.4 (0.1)	78.7 (15.3)	12.5 (0.4)	8.4 (1.1)	66.8 (5.3)
	Forest	24.6	52.1	0.63	5.9	32.6	10.8	7.1	67.6

Means with SE in parenthesis, n = 7 except for annual crops (n = 3) and forest (n = 5) of Yantzaza and pastures (n = 4) of El Tambo the year. Compost heaps were not common and hence, manure from the stables was usually applied directly to the field. Subsistence crops such as maize, banana, plantain and cassava were produced close to the homestead. Integrated nutrient management was the prevailing management system in the indigenous San Lucas where livestock and cash crop production was combined with crops for self-consumption. Animals were kept in stables for fodder purposes at all times (pigs, guinea pigs) or at night (cattle, sheep, poultry) and compost heaps were present in all farms. In El Tambo all family income was generated by cash crop production. Fields were irrigated through open channels which transported water from the mountains to the farmers' fields every 10 days. Livestock was based on small farm animals (poultry, guinea pigs) which were kept in stables in three out of seven farms and a compost heap was found in only one farm. Hence, the three research areas differed considerably in terms of farm management.

Especially in San Lucas farmers adapted their management due to increased precipitation compared to an average year (Table 1). They installed drainage systems by digging small channels at the field edge and planted crops which were able to cope with the wet conditions. Maize was planted at the beginning of the rainy season whereas potatoes were planted at its end to prevent tuber damage. In El Tambo farmers reported that the present procedure of irrigating fields every 10 days might not sufficiently fulfil the requirements of the crops in terms of water supply. Therefore, crop growth was expected to benefit from additional precipitation. Yet, farm management remained unchanged just as in Yantzaza where farmers managed livestock in pastures with steep slopes facilitating the run-off of additional water. The dominant crops such as banana and plantain were well resistant to humid conditions.

Soil nutrient balances

Soil nutrient balances at farm scale

Farm nutrient balances varied widely depending on research area and nutrient (Fig. 2). Highly positive farm balances were found for N in El Tambo and P in San Lucas. For K only Yantzaza had a slightly positive balance whereas it was highly negative for El Tambo. Highest quantities in inputs and outputs were found in farms of El Tambo for NPK whereas farms in Yantzaza had the lowest quantities for all nutrients (Fig. 2). Mineral fertilizer was the dominant source of inputs for all nutrients in El Tambo whereas for San Lucas organic materials and manure prevailed. Erosion was the main source for P and K outputs in all research areas. In contrast, outputs for crop residue and grazing accounted for highest N losses in San Lucas and leaching was the major contributor for N losses in Yantzaza and El Tambo (Fig. 2).

Inputs and outputs for different land-uses

Inputs and outputs fluctuated considerably between different land-uses of the three research areas (Table 5). For a better understanding of the respective inputs and outputs in relation to land-use, they were graphically displayed as independent variables of the RDA in Figs. 4 and 5.

Largest sources for nutrient inputs in Yantzaza were manure in pastures, atmospheric deposition and deposition by water erosion. Mineral fertilizer was not applied owing to the management system of low-external inputs (Table 5). Nutrient outputs were dominated by grazing in pastures, leaching and soil loss by water erosion.

Land-use in El Tambo was characterized by high nutrient inputs from mineral fertilizer in annual crops where those for N clearly outbalanced P and K inputs. Outputs in annual crops were dominated by leaching, losses by water erosion and harvest. More than 75 % of the total losses in pastures originated from grazing. Highest gaseous losses for N were found in the annual crops of El Tambo which was attributed to urea fertilization and subsequent denitrification as well as burning of crop residues.

For all land-uses in San Lucas the main source of nutrient inputs was organic material/manure. They were more than tenfold the amount for N compared to the other research areas (Table 5). Outputs by water erosion prevailed in annual and perennial crops. Nutrient losses due to grazing (OUT2) were most negative in San Lucas which was traced back to highest livestock densities (Table 1) compared to the other research areas. These losses were in turn compensated partly by manure inputs (IN2). Larger losses for OUT2 in annual and perennial crops originated from harvest residues usually used for fodder purposes or removed to compost heaps.

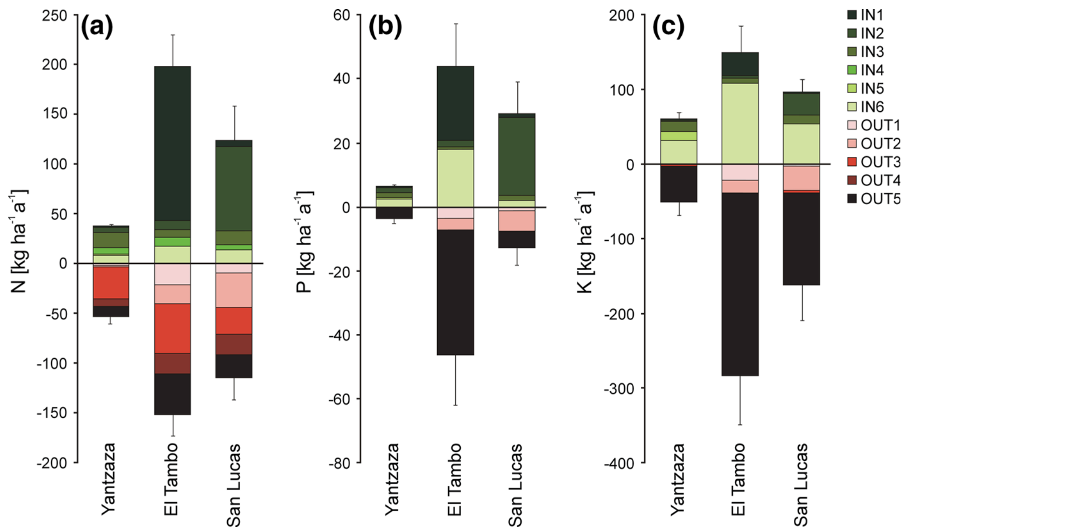

Fig. 2 Nutrient inputs and outputs for nitrogen (**a**), phosphorus (**b**) and potassium (**c**) for farms in Yantzaza, El Tambo and San Lucas (mean, SE is indicated for the sum of all inputs or outputs respectively, n = 7). Inputs include IN1 (mineral fertilizers), IN2 (organic materials and manure), IN3 (atmospheric deposition), IN4 (Biological N fixation) IN5 (sedimentation from flooding), IN6 (sedimentation from erosion) and outputs consist of OUT1 (harvested products), OUT2 (crop residues and grazing), OUT3 (leaching), OUT4 (gaseous losses), OUT5 (erosion)

Effects of adapted transfer functions and background database

The adaptation induced substantial changes in the calculation methods for several flows compared to the transfer functions used in the original Nutmon.

Wet and dry atmospheric deposition (IN3) showed a clear distinction between the three research areas due to different amounts of precipitation (Table 5). GIS based modeling of sedimentation (IN6) and soil loss (OUT5) from water erosion revealed that sedimentation was a major contributor to inputs of the soil nutrient balance. In some cases it even compensated losses from erosion e.g. in annuals of Yantzaza (Table 5) which were mainly situated in concave lower slope positions. Highest transport activities due to erosion were found in annual crops of all three research areas. The calculation of leaching resulted in differences between research areas and land-uses which were highly significant (Table 6). Besides various levels of precipitation in each research area, this was reduced to specific decomposition rates for each land-use which was a crucial element of the leaching transfer function.

Especially laboratory determined nutrient contents of many domestic plants were different from those of the original Nutmon background database (data not shown) or had not existed at all before. Therefore, updating of the background database resulted in a modeling of nutrient flows and balances which should be orientated as close as possible to the natural conditions of the research area.

Impact of location and land-use on inputs and outputs

Different management on mineral N fertilization (IN1) between the three research areas was indicated by the highly significant effect of location in contrast to P and K (Table 6). For organic inputs (IN2) a highly significant effect of location was found for all nutrients (NPK). Highest NPK losses for harvested products were consistently found in the annual crops of all research areas which was illustrated by the highly significant effect of land-use. In contrast, N losses for harvested products in perennial crops amounted only between 15 and 25 % from those of the annual crops (Table 5).

Soil nutrient balances for different land-uses

The high diversity in inputs and outputs caused a wide range of NPK balances in the different land-uses of the three research areas (Fig. 3). Total soil nutrient balances were between −151 to 66, −8 to 33 and

Table 5 Average inputs and outputs of the N, P and K soil nutrient balance depending on research area and land-use

Nutrient element	Research area	Land-use	Inputs (kg ha^{-1} a^{-1})						Outputs (kg ha^{-1} a^{-1})				
			IN1	IN2	IN3	IN4	IN5	IN6	OUT1	OUT2	OUT3	OUT4	OUT5
Nitrogen	Yantzaza	Annual crops	0 (0)	2 (2)	15 (0)	7 (0)	2 (2)	94 (87)	−29 (23)	−1 (1)	−130 (24)	−2 (0)	−109 (109)
		Perennial crops	0 (0)	16 (5)	15 (0)	7 (0)	1 (1)	35 (13)	−7 (3)	−5 (3)	−87 (21)	−4 (0)	−51 (19)
		Forest	0 (0)	5 (4)	15 (0)	7 (0)	1 (1)	0 (0)	−1 (0)	0 (0)	−42 (2)	−3 (0)	0 (0)
		Pasture	0 (0)	49 (14)	15 (0)	7 (0)	0 (0)	7 (2)	0 (0)	−60 (16)	−18 (1)	−9 (2)	−8 (2)
	El Tambo	Annual crops	211 (56)	11 (4)	6 (0)	10 (10)	0 (0)	32 (12)	−34 (12)	−20 (5)	−61 (16)	−25 (6)	−64 (22)
		Perennial crops	29 (27)	32 (11)	6 (0)	0 (0)	0 (0)	10 (4)	−5 (2)	−21 (13)	−28 (4)	−9 (3)	−10 (3)
		Pasture	28 (28)	105 (82)	6 (0)	0 (0)	0 (0)	2 (2)	0 (0)	−140 (110)	−23 (3)	−18 (14)	−1 (0)
	San Lucas	Annual crops	2 (1)	134 (51)	13 (0)	16 (7)	0 (0)	84 (26)	−41 (11)	−31 (24)	−64 (4)	−18 (5)	−132 (32)
		Perennial crops	5 (5)	166 (64)	13 (0)	3 (1)	0 (0)	79 (32)	−14 (9)	−20 (13)	−54 (4)	−17 (6)	−103 (32)
		Forest	0	0	13	3	0	1	−67	0	−18	−2	−1
		Pasture	4 (3)	157 (42)	13 (0)	3 (0)	0 (0)	8 (2)	0 (0)	−181 (49)	−18 (6)	−21 (5)	−8 (2)
Phosphorus	Yantzaza	Annual crops	0 (0)	0 (0)	2 (0)		1 (1)	28 (25)	−7 (6)	0 (0)			−33 (33)
		Perennial crops	0 (0)	4 (1)	2 (0)		0 (0)	10 (4)	−1 (1)	−1 (0)			−14 (6)
		Forest	0 (0)	1 (0)	2 (0)		0 (0)	0 (0)	0 (0)	0 (0)			0 (0)
		Pasture	0 (0)	6 (2)	2 (0)		0 (0)	2 (1)	0 (0)	−7 (2)			−2 (1)
	El Tambo	Annual crops	36 (17)	4 (1)	1 (0)		0 (0)	33 (15)	−7 (2)	−5 (1)			−64 (22)
		Perennial crops	3 (3)	5 (2)	1 (0)		0 (0)	10 (4)	−1 (0)	−3 (2)			−10 (3)
		Pasture	0 (0)	16 (13)	1 (0)		0 (0)	1 (1)	0 (0)	−17 (14)			−1 (0)
	San Lucas	Annual crops	2 (2)	31 (10)	1 (0)		0 (0)	15 (4)	−8 (2)	−3 (2)			−31 (7)
		Perennial crops	6 (6)	36 (16)	1 (0)		0 (0)	14 (6)	−2 (1)	−2 (2)			−20 (6)
		Forest	0	0	1		0	0	−1	0			0
		Pasture	0 (0)	23 (7)	1 (0)		0 (0)	2 (1)	0 (0)	−18 (5)			−2 (1)
Potassium	Yantzaza	Annual crops	0 (0)	0 (0)	13 (0)		29 (29)	461 (422)	−10 (6)	0 (0)	0 (0)		−469 (465)

Table 5 continued

Nutrient element	Research area	Land-use	Inputs (kg ha^{-1} a^{-1})						Outputs (kg ha^{-1} a^{-1})				
			IN1	IN2	IN3	IN4	IN5	IN6	OUT1	OUT2	OUT3	OUT4	OUT5
		Perennial crops	0 (0)	10 (3)	13 (0)		13 (13)	169 (57)	−12 (5)	−7 (3)	0 (0)		−263 (117)
		Forest	0 (0)	5 (4)	13 (0)		16 (16)	1 (0)	0 (0)	0 (0)	0 (0)		0 (0)
		Pasture	0 (0)	36 (19)	13 (0)		12 (12)	25 (7)	0 (0)	−45 (23)	0 (0)		−28 (7)
	El Tambo	Annual crops	50 (29)	26 (9)	5 (0)		0 (0)	208 (106)	−31 (10)	−34 (9)	0 (0)		−492 (190)
		Perennial crops	2 (2)	32 (11)	5 (0)		0 (0)	122 (67)	−8 (3)	−23 (14)	0 (0)		−92 (32)
		Pasture	0 (0)	104 (80)	5 (0)		0 (0)	8 (5)	0 (0)	−152 (120)	−1 (1)		−5 (3)
	San Lucas	Annual crops	2 (1)	49 (19)	11 (0)		0 (0)	362 (115)	−19 (5)	−20 (16)	0 (0)		−730 (159)
		Perennial crops	4 (4)	101 (39)	11 (0)		0 (0)	348 (133)	−17 (10)	−22 (14)	−1 (0)		−548 (183)
		Forest	0	0	11		0	8	−27	0	0		−8
		Pasture	0 (0)	136 (30)	11 (0)		0 (0)	39 (11)	0 (0)	−187 (50)	−1 (0)		−43 (16)

Means with SE in parenthesis, n = 7 except for annual crops (n = 3) and forest (n = 5) of Yantzaza and pastures (n = 4) of El Tambo. Inputs and outputs are defined as follows: IN1 (mineral fertilizers), IN2 (organic materials and manure), IN3 (atmospheric deposition), IN4 (Biological N fixation), IN5 (sedimentation from flooding), IN6 (sedimentation from erosion), OUT1 (harvested products), OUT2 (crop residues and grazing), OUT3 (leaching), OUT4 (gaseous losses), OUT5 (erosion)

Table 6 Two-way factorial ANOVA showing the influence of location (Yantzaza, El Tambo, San Lucas) and land-use (annual crops, perennial crops, pastures) on inputs and outputs of the N, P and K balance

Nutrient element	*DF*	F values										
		IN 1	IN 2	IN 3	IN 4	IN 5	IN 6	OUT 1	OUT 2	OUT 3	OUT 4	OUT 5
Nitrogen												
Location	2	11.8***	9.1***	246.1***	0.6	3.9*	3.0	0.6	2.1	9.5***	5.5**	3.6*
Land-use	2	5.1*	1.2	1.1	2.5	0.5	5.9**	13.1***	10.9***	21.9***	1.3	8.9***
Location × land-use	4	6.1***	0.3	1.4	0.6	0.5	0.9	0.2	0.9	3.3*	0.9	0.7
Phosphorus												
Location	2	2.5	8.3***	246.1***		4.3*	0.3	0.2	1.7			0.5
Land-use	2	2.3	0.1	1.1		0.4	6.1**	13.8***	9.7***			9.9***
Location × land-use	4	2.9*	0.6	1.4		0.3	0.6	0.1	0.6			1.4
Potassium												
Location	2	1.9	6.0**	246.1***		4.5*	1.4	0.6	2.4	4.4*		2.5
Land-use	2	1.7	4.0*	1.1		0.5	6.1**	7.2**	9.9***	3.8*		9.0***
Location × land-use	4	2.1	0.4	1.4		0.4	0.6	1.3	1.3	0.8		0.6

Inputs and outputs are defined as follows: IN1 (mineral fertilizers), IN2 (organic materials and manure), IN3 (atmospheric deposition), IN4 (Biological N fixation), IN5 (sedimentation from flooding), IN6 (sedimentation from erosion), OUT1 (harvested products), OUT2 (crop residues and grazing), OUT3 (leaching), OUT4 (gaseous losses), OUT5 (erosion)

*, **, *** Statistical significance at the 0.05, 0.01 and 0.001 level, respectively

−346 to 39 kg K ha^{-1} a^{-1}. For pastures, total balances for N, P and K were in the same order of magnitude for all research areas. Highest total N and P losses were found in annual crops of Yantzaza due to leaching. Owing to high mineral and organic fertilizer inputs, highest N gains occurred in annual crops of El Tambo and perennial crops of San Lucas, respectively which however, had very negative K balances. Generally, balances for NPK were not consistent within a land-use of a specific research area and only perennial crops of El Tambo had a positive total balance for all three nutrients (Fig. 3).

Nutrient flows between different farm units

Nutrient flows enabled the detection of distinct patterns in each research area. Highest absolute flows were external inputs into annual crops of El Tambo and flows from pastures into the SPUs and vice versa in all research areas (Table 7).

Nutrient flows into annual crops of El Tambo pointed to a large surplus of external inputs for N and P which were more than fivefold the amount compared to the respective outputs (Table 7). However, for K external inputs into annual crops were in the same order of magnitude as outputs. External inputs into annual crops, perennial crops and pastures of San Lucas exceeded those of the outputs, yet, at a lower level compared to annual crops of El Tambo. In Yantzaza external inputs into annual crops, perennial crops or pastures were either very low or did not exist at all. Nutrient inputs from organic household waste were only of minor importance in all research areas and were highest in the perennial crops of El Tambo. Grazing and/or harvest residue export for livestock took place in annual and perennial crops of all research areas. Yet, only perennial crops in San Lucas had a large surplus of nutrients they received from SPUs compared to nutrients lost to SPUs. Flows from pastures into SPUs and vice versa played an important role in all research areas and were most negative for NPK in San Lucas. Nutrient flows from RUs were only of importance in San Lucas with perennial crops receiving the greatest proportion. External inputs into SPUs and flows vice versa were tenfold the amount in San Lucas compared to Yantzaza and El Tambo which illustrates the production target on livestock with a rather high productivity per hectare. In contrast,

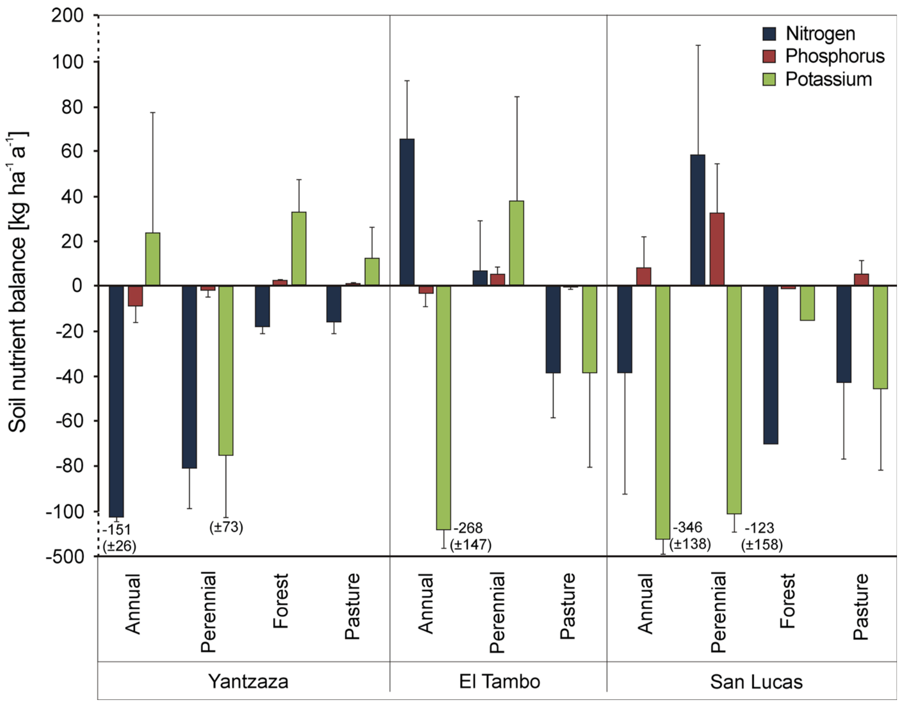

Fig. 3 Soil nutrient balances for NPK in annual crops, perennial crops, forest and pastures of Yantzaza, El Tambo and San Lucas [scale of y axis is compressed for values above 100 and below −100, mean, SE, n = 7 except for annual crops (n = 3) and forest (n = 5) of Yantzaza, pastures (n = 4) of El Tambo and forest (n = 1) of San Lucas]

farming in Yantzaza also focused on livestock production; however, productivity per hectare was low due to extensive pasture grazing in large farms.

Soil nutrient stocks

Total and plant available stocks for NPK showed a greater variation depending on research area than depending on land-use (Table 8). N balances had the largest impact on total nutrient stock change a^{-1} whereas the effect of the P and K balance was only moderate.

Highest TN stocks were found in San Lucas which was 1.5-fold above those of Yantzaza and El Tambo (Table 8). Generally, annual crops had the lowest TN stocks in all research areas. Highest N losses per year (Fig. 3) and relatively low TN stocks induced a yearly TN loss of almost 5 % in the annual crops of Yantzaza. The contrary was found in the annual crops of El Tambo due to a strongly positive N balance. El Tambo had the lowest mineral N stocks despite highest mineral N fertilizer application (Table 5). TP stocks were highest in El Tambo, and only for the annual and perennial crops of San Lucas a stock change of more than 1 % a^{-1} was calculated. Annual crops had the highest stocks for PO_4-P in all research areas which were twofold the amount compared to the other land-uses in El Tambo and San Lucas. Stocks for TK were lowest in El Tambo and exchangeable K stocks in the perennial crops of El Tambo were almost twofold and fivefold the amount compared to San Lucas and Yantzaza, respectively.

Impact of financial flows and soil fertility on the nutrient balance

The multivariate RDA was used to plot the distribution of independent variables (N inputs and N outputs) as a function of financial flows for N (Fig. 4) and soil fertility variables (Fig. 5) in annual crops, perennial crops and pastures of the three research areas.

Different land-uses of the same research area plotted close to each other with regard to financial flows for N (Fig. 4a). This effect was even more pronounced for soil fertility variables (Fig. 5a) indicating a greater effect of location than land-use. Therefore, RDAs were also presented for the three research areas separately to show differences between the land-uses of the same research area depending on financial flows (Fig. 4b–d) and soil fertility variables

Table 7 Nutrient flows for N, P and K in Yantzaza, El Tambo and San Lucas from the external (Ext), household (HH), secondary production unit (SPU), redistribution unit (RU) into PPUs (primary production units) separated into annual crops (Ann), perennial crops (Per), pastures (Pas) and vice versa

	Yantzaza (kg ha^{-1} a^{-1})			El Tambo (kg ha^{-1} a^{-1})			San Lucas (kg ha^{-1} a^{-1})		
	N	P	K	N	P	K	N	P	K
Ann-Ext	3.6 (3.6)	0.9 (0.9)	1.1 (1.1)a	47.2 (12.8)	8.2 (2.1)	47.5 (12.3)b	17.7 (5.9)	3.3 (1.3)	10.2 (4.1)a
Ext-Ann	0.0a	0.0	0.0	247.3 (42.2)c	45.4 (17.6)	55.7 (28.2)	75.4 (32.3)b	21.7 (8.1)	20.9 (7.9)
Per-Ext	3.7 (1.4)	0.8 (0.3)	7.4 (2.2)	3.4 (1.4)	0.7 (0.2)	4.0 (1.6)	4.7 (3.5)	1.0 (0.9)	7.5 (6.2)
Ext-Per	1.3 (1.3)	0.3 (0.3)	0.3 (0.3)	38.8 (36.4)	2.8 (2.8)	1.8 (1.8)	83.7 (64.3)	27.1 (21.7)	24.7 (18.8)
Pas-Ext	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ext-Pas	0.1 (0.1)	0.2 (0.2)	0.1 (0.1)	28.0 (28.0)	0.0	0.0	25.7 (16.5)	5.7 (4.2)	6.3 (4.8)
Ann-HH	10.3 (5.9)	2.4 (1.5)	4.7 (2.1)	8.4 (6.5)	1.9 (1.6)	3.2 (1.9)	21.9 (6.2)	4.1 (1.4)	10.2 (2.9)
HH-Ann	1.6 (1.6)	0.4 (0.4)	0.3 (0.3)	0.9 (0.7)	0.2 (0.1)	1.2 (0.9)	0.3 (0.3)	0.1 (0.1)	0.4 (0.4)
Per-HH	1.3 (0.7)	0.2 (0.1)	2.7 (1.3)	2.9 (1.0)	0.6 (0.2)	5.7 (2.3)	3.1 (2.2)	0.4 (0.2)	3.7 (2.3)
HH-Per	1.4 (0.5)	0.3 (0.1)	1.9 (0.7)	8.3 (6.7)	1.9 (1.6)	8.0 (5.8)	0.0	0.0	0.0
Pas-HH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HH-Pas	0.2 (0.1)	0.1 (0.0)	0.2 (0.2)	0.0	0.0	0.0	0.6 (0.4)	0.1 (0.1)	0.8 (0.6)
Ann-SPU	1.2 (0.7)	0.3 (0.2)	0.3 (0.2)	3.1 (1.4)	0.5 (0.2)	2.7 (1.5)	8.4 (2.9)	1.1 (0.4)	4.6 (1.7)
SPU-Ann	0.0	0.0	0.0	5.1 (2.9)	0.9 (0.5)	4.1 (2.5)	0.0	0.0	0.0
Per-SPU	6.8 (3.1)	1.4 (0.6)	8.8 (4.1)	20.6 (13.1)	2.5 (1.6)	22.2 (14.2)	20.1 (13.3)	2.5 (1.7)	21.8 (14.5)
SPU-Per	6.5 (2.4)	1.1 (0.4)	5.0 (2.4)	22.2 (9.8)	3.3 (1.2)	20.5 (10.9)	60.8 (24.3)	10.2 (4.3)	42.0 (17.7)
Pas-SPU	59.9 (16.7)	7.3 (2.1)	44.8 (22.9)	140.0 (110.6)	17.5 (13.8)	151.7 (119.8)	182.7 (49.7)	18.6 (5.1)	188.6 (50.3)
SPU-Pas	47.9 (13.7)	6.1 (1.7)	35.0 (18.3)	104.6 (81.6)	16.1 (13.0)	103.8 (80.0)	120.9 (30.3)	13.5 (3.3)	120.4 (28.3)
Ann-RU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RU-Ann	0.4 (0.2)	0.1 (0.0)	0.1 (0.0)	1.0 (1.0)	0.2 (0.2)	1.6 (1.6)	11.8 (5.3)	2.5 (1.3)	8.6 84.6)
Per-RU	0.0	0.0	0.0	0.0	0.0	0.0	5.5 (5.5)	0.6 (0.6)	5.0 (5.0)
RU-Per	6.2 (3.7)	1.7 (1.0)	3.0 (1.3)	2.2 (2.1)	0.4 (0.4)	3.9 (3.7)	25.9 (19.4)	4.8 (3.9)	38.0 (34.1
Pas-RU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RU-Pas	0.7 (0.4)a	0.2 (0.1)a	1.0 (0.7)	0.0a	0.0a	0.0	17.0 (5.4)b	3.9 (1.2)b	9.7 (4.4)
Ext-SPU	4.9 (1.4)	1.6 (0.4)	1.6 (0.4)	5.7 (2.7)	1.5 (0.7)	2.8 (1.9)	55.3 (27.5)	16.6 (8.5)	20.4 (10.1)
SPU-Ext	6.0 (1.0)	1.4 (0.3)	1.3 (0.5)	2.6 (1.8)	0.6 (0.4)	1.4 (1.4)	61.2 (25.3)	6.6 (2.8)	29.3 (21.4)

Means with SE in parenthesis, n = 7 except for nutrient flows involving annual crops (n = 3) of Yantzaza and pastures (n = 4) of El Tambo

Lowercase letters (a<b<c) indicate significant differences between nutrient flows of the same nutrient within the three research areas

Table 8 Soil nutrient stocks for total and plant available N, P and K and yearly total stock change based on results for the soil nutrient balance

Research area	Land-use	Stocks						Stock change		
		TN (Mg ha^{-1})	TIN (kg ha^{-1})	TP (Mg ha^{-1})	PO_4-P (kg ha^{-1})	TK (Mg ha^{-1})	K_{exch} (kg ha^{-1})	TN (% a^{-1})	TP (% a^{-1})	TK (% a^{-1})
Yantzaza	Annual crops	3.5 (0.6)	143.0 (23.8)	1.5 (0.1)	18.8 (13.6)	38.5 (10.0)	211.4 (29.3)	−4.9 (1.8)	−0.7 (0.5)	0.0 (0.2)
	Perennial crops	4.3 (0.4)	185.0 (8.7)	1.4 (0.1)	14.6 (6.1)	31.4 (4.4)	210.6 (20.9)	−1.9 (0.5)	−0.1 (0.2)	−0.3 (0.2)
	Pasture	4.2 (0.3)	184.6 (14.8)	1.4 (0.1)	12.7 (6.2)	30.9 (4.3)	317.7 (85.1)	−0.4 (0.1)	0.1 (0.1)	0.0 (0.0)
	Forest	4.5 (0.5)	174.5 (15.5)	1.5 (0.2)	14.2 (7.9)	30.5 (6.6)	226.5 (43.5)	−0.4 (0.1)	0.1 (0.2)	0.1 (0.0)
El Tambo	Annual crops	2.5 (0.5)	42.2 (19.0)	2.5 (0.4)	59.4 (8.4)	20.4 (3.7)	661.6 (105.7)	3.6 (1.5)	−0.3 (0.2)	−1.5 (0.8)
	Perennial crops	2.5 (0.4)	34.2 (13.7)	2.2 (0.3)	41.7 (5.8)	24.2 (5.0)	1,093.4 (305.2)	0.6 (1.1)	0.2 (0.2)	0.2 (0.2)
	Pasture	3.9 (0.6)	43.0 (19.0)	2.2 (0.1)	42.4 (12.2)	17.6 (4.5)	679.2 (201.9)	−0.9 (0.4)	0.0 (0.1)	−0.2 (0.2)
San Lucas	Annual crops	5.7 (1.0)	191.0 (63.8)	1.4 (0.2)	69.8 (33.2)	38.4 (6.6)	693.4 (92.7)	−0.3 (1.2)	1.1 (1.1)	−1.1 (0.4)
	Perennial crops	6.6 (1.0)	219.2 (70.0)	1.5 (0.3)	36.7 (10.4)	39.2 (7.2)	641.2 (129.1)	1.4 (1.6)	2.3 (1.6)	−0.1 (0.4)
	Pasture	6.2 (1.0)	237.5 (68.5)	1.5 (0.2)	34.3 (6.6)	38.9 (4.2)	602.9 (52.0)	−1.1 (0.7)	0.5 (0.5)	−0.1 (0.1)
	Forest	3.0	390.1	0.7	7.4	23.9	98.9	−2.3	0.0	−0.1

Means with SE in parenthesis, n = 7 except for annual crops (n = 3) and forest (n = 5) of Yantzaza and pastures (n = 4) of El Tambo

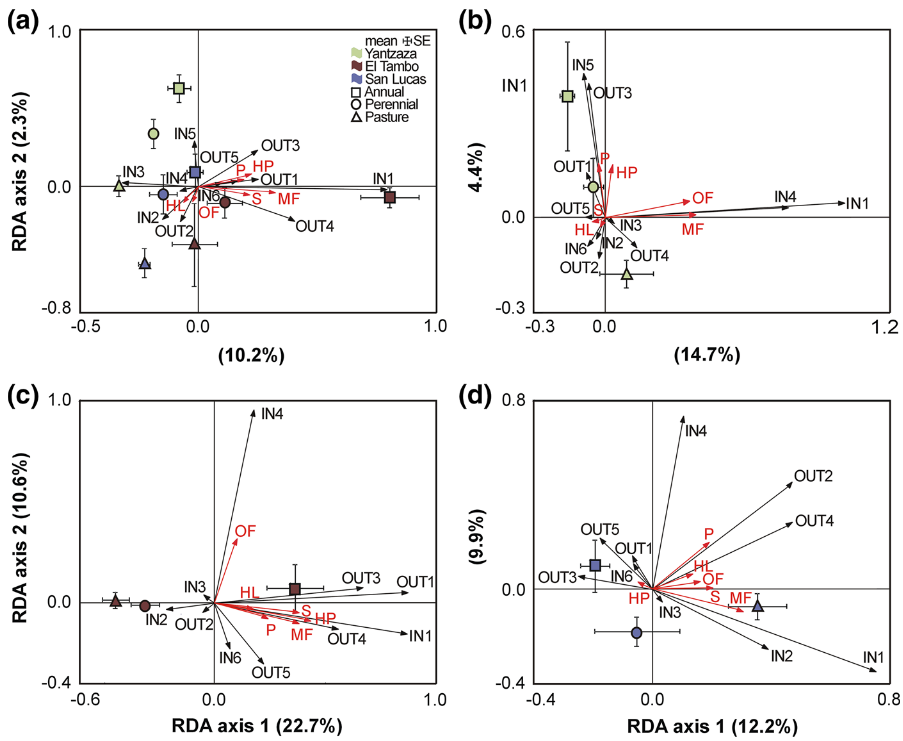

Fig. 4 Ordination biplots of a redundancy analysis for inputs [IN1 (mineral fertilizers), IN2 (organic materials and manure), IN3 (atmospheric deposition), IN4 (Biological N fixation) IN5 (sedimentation from flooding), IN6 (sedimentation from erosion)] and outputs [OUT1 (harvested products), OUT2 (crop residues and grazing), OUT3 (leaching), OUT4 (gaseous losses), OUT5 (erosion)] of the N balance with financial flows [expenses for MF (mineral fertilizer), OM (organic fertilizer), P (pesticides), HL (hired labour), S (seeds) and revenues by HP (harvested products)]. Biplots show the separation along the first and second axis of annual crops, perennial crops and pastures for **a** all three research areas, **b** Yantzaza, **c** El Tambo and **d** San Lucas (mean, SE)

(Fig. 5b–d). Expenses for mineral fertilizer, pesticides, seeds and revenues by harvested products dominated the land-uses in El Tambo whereas investments into organic fertilizer and hired labor prevailed in San Lucas (Fig. 4a). Regarding soil fertility variables, high values for most nutrient elements pointed into the direction of the different land-uses in El Tambo whereas high contents of NH_4-N were associated with agricultural land-use in San Lucas and Yantzaza (Fig. 5a).

21.9, 38.1 and 27.4 % of the variability in N inputs and outputs in Yantzaza, El Tambo and San Lucas was explained by the six investigated financial flows respectively. The wide angles between the three land-uses and financial inputs for mineral fertilizer and organic material corroborate the predominant management practice of low-external inputs for Yantzaza (Fig. 4b). Monetary inputs by mineral fertilizer, pesticides, seeds, hired labor and revenues by harvested products were highly associated with N inputs and outputs in annual crops of El Tambo. For all land-uses in El Tambo, a low correlation was found for expenses on organic fertilizer with N inputs and outputs (Fig. 4c). In San Lucas all considered expenses were related to N inputs and outputs of pastures (Fig. 4d) in contrast to pastures in Yantzaza and El Tambo.

With respect to the inputs and outputs of the N-balance, the total variance explained by soil fertility variables was 41.5, 31.8 and 35.4 % for Yantzaza, El Tambo and San Lucas respectively. Wider C/N ratios and higher contents of exchangeable K pointed into the direction of pastures in Yantzaza (Fig. 5b). High contents of TP, exchangeable Mg and NO_3-N plotted close to annual crops in El Tambo whereas high bulk densities and DOC concentrations were associated with pastures and perennial crops, respectively (Fig. 5c). In San Lucas annual crops were dominated

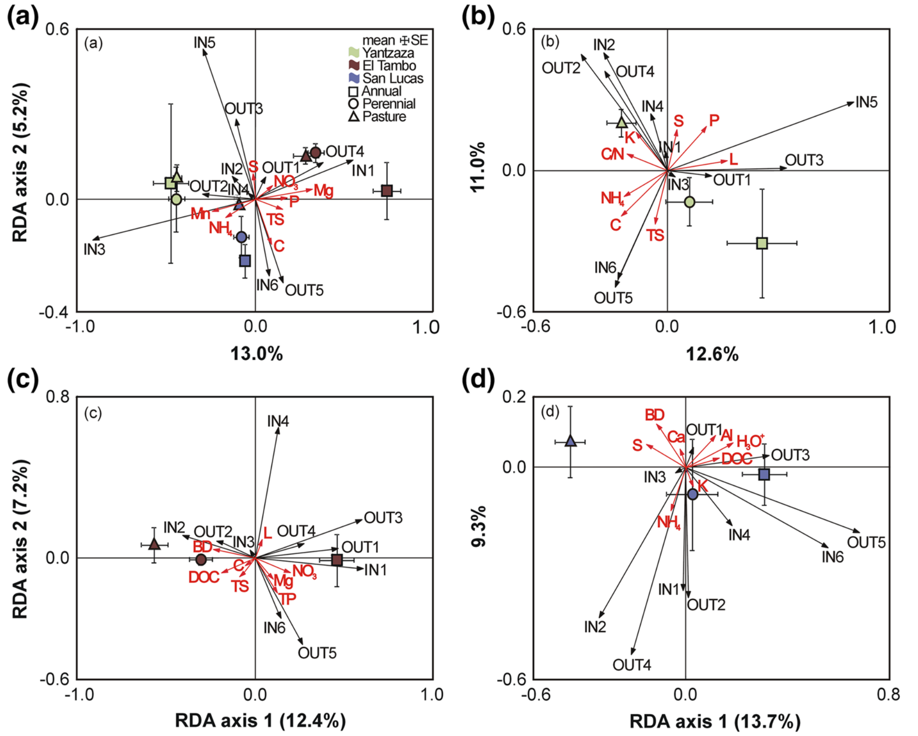

Fig. 5 Ordination biplots of a redundancy analysis for inputs [IN1 (mineral fertilizers), IN2 (organic materials and manure), IN3 (atmospheric deposition), IN4 (Biological N fixation) IN5 (sedimentation from flooding), IN6 (sedimentation from erosion)] and outputs [OUT1 (harvested products), OUT2 (crop residues and grazing), OUT3 (leaching), OUT4 (gaseous losses), OUT5 (erosion)] of the N balance with soil fertility variables [bulk density (BD), concentration of H_3O^+ (H_3O^+), sand (S), silt (L), clay (C), soil organic carbon (SOC), total nitrogen (TN), C/N ratio (C/N), total phosphorus (TP), total sulphur (TS), dissolved organic carbon (DOC), nitrate (NO_3), ammonium (NH_4), plant available phosphorus (P), exchangeable cations of magnesium, calcium, potassium, aluminium, manganese (Mg, Ca, K, Al, Mn)]. For reasons of clarity, only the eight soil fertility variables explaining the highest amount of variance of N inputs and N outputs are shown. Biplots show the separation along the first and second axis of annual crops, perennial crops and pastures for (a) all three research areas, (b) Yantzaza, (c) El Tambo and (d) San Lucas (mean, SE)

by soil variables indicating acidification (Fig. 5d) while N inputs and outputs of the perennial crops pointed to long arrows for NH_4-N and exchangeable K.

Discussion

Adaptation of Nutmon to Ecuador

Adaptation of Nutmon was essential to map difficult-to-quantify inputs and outputs in the south Ecuadorian research area comprehensively based on the prevailing biogeochemical conditions. As was done for erosion in the present study, the Nutmon follow-up Monqi is already able to link GIS data to empirical relationships and transfer functions (Lesschen et al. 2007). However, weaknesses in the evaluation of N related difficult-to-quantify flows still exist in Monqi (Abdulkadir et al. 2013).

The applied transfer functions for leaching and erosion were not validated site specifically and therefore, contain an unknown level of uncertainty regarding the soil nutrient balance. Yet a detailed validation or measurement of all difficult-to-quantify flows is impossible in practical terms. Additionally, it does not serve the aim of a rather pragmatic approach to quickly estimate the soil nutrient balance, localize problematic areas and adapt management strategies. Moreover, it should be noted that precipitation during the year of the research in 2008 was above long-term average values (Table 1), in particular for San Lucas it more than doubled. This induced higher values for leaching, erosion and wet atmospheric deposition compared to an average year. Moreover, higher precipitation in the year of the research also induced changes in crop production as indicated from yields in 2009 where annual precipitation was according to the long-term average. Despite more precipitation in 2008, yield increases, as expected by the farmers in El Tambo, were not detected for the major cash crops tomato, cucumber and pepper when compared to yields in 2009. In contrast, a different pattern was found in Yantzaza and San Lucas where yields for the main crops were about 20 % higher in 2008 than in 2009 (ESPAC 2014). The authors were aware that this also influences the discussion about long-term management strategy adaptation. However, it was shown that short-term management decisions of the farmers are highly influenced by the present weather conditions e.g. sowing period and time of fertilizer application among others (Aubry et al. 1998). Therefore it was decided to model the soil nutrient balance based on current weather data and not on long-term average data taking into account that nutrient balances may vary between different years (Sheldrick et al. 2003).

Stoorvogel (1993) reported that dry atmospheric deposition is negligible in humid regions with large quantities of rainfall. In contrast, considerable amount of dry deposition due to increased anthropogenic activity (slash and burn) was proved for southern Ecuador (Wilcke et al. 2008) and hence necessitated the adaptation of the transfer function for wet and dry atmospheric deposition.

For the calculation of leaching, land-use specific values for each research area were used for the decomposition rate employing data from the Andes in Ecuador and tropical Amazon (Table 3). This reflects natural conditions in particular of Yantzaza and San Lucas better than applying the fixed value of 3 % as proposed by Nutmon. The decomposition rate is the crucial factor in the calculation of nitrogen leaching using transfer functions which strongly depend on available N in the soil (Færge and Magid 2004) and can vary in the same area depending on land-use (Neill et al. 1995). Measured data for leaching in tropical agroecosystems is scarce. In a tropical montane forest of Ecuador leaching losses amounted between 12 and 22 kg N ha^{-1} a^{-1} (Wilcke et al. 2009) which is between 25 and 50 % of the amount leached in forest sites of Yantzaza (Table 5). However, when adjusting the N-leaching transfer function according to the Q_{10} relationship (Kirschbaum 1995), results for the montane forest and the transition zone of Andes and Amazon were in the same order of magnitude. This can be explained by a larger pool of potentially available N for leaching due to faster N mineralization rates at lower altitudes (Marrs et al. 1988). In a tropical sandy soil in Zimbabwe up to 56 kg N ha^{-1} a^{-1} were leached after application of 120 kg of mineral N-fertilizer (Nyamangara et al. 2003). This was in accordance with the modeled leaching of 61 kg N ha^{-1} a^{-1} for annual crops on loamy soils in El Tambo where even 210 kg of mineral N-fertilizer were applied. Nyamangara et al. (2003) reported that leaching after manure application was clearly reduced compared to mineral fertilizer in soils of Zimbabwe. This exposes a shortcoming of the implemented transfer function in the present research where mineral and organic fertilizers were treated equally.

Results of the present study illustrated the importance of including sedimentation by erosion (IN6) which was neither incorporated into the original Nutmon nor the revised Monqi model (Table 5). The reason for this is that considerable amounts of eroded sediments in cropland remained close to its origin and were deposited as colluvial soil at the bottom of the slopes as was shown by Vandenbygaart et al. (2012). Therefore, it was stressed that Nutmon has a strong tendency to overestimate erosion losses by up to one order of magnitude (Cobo et al. 2010; Færge and Magid 2004). Sedimentation by erosion (IN6) amounted to 52 % of losses by erosion (OUT5) for N in all research areas (Fig. 2). It was even more relevant in annual crops of Yantzaza where it accounted for 87 % of losses by erosion (OUT5) due to their nearby location to households at the foot of the slope (Table 5). Hence, results proved that excluding sedimentation by erosion from the soil nutrient balance would have led to overestimation of erosion losses which might induce misleading conclusions in particular with regard to management adaptation.

Impact of nutrient management on soil nutrient balances and flows

Results of the soil nutrient balances and flows indicated that hypotheses 1 and 2 must be rejected (Figs. 2, 3; Tables 5, 7). Neither did land-use based on low-external inputs in Yantzaza induce non-sustainable land-use throughout the entire land-use system, nor did mixed farming systems with nutrient recycling in San Lucas have nutrient balances in equilibrium. Therefore, an assessment of the respective land-use system should rather take place on the basis of individual land-uses and nutrients within each research area. Large losses for N were found in Yantzaza for annual and perennial crops (Fig. 3) as was also characteristic for nutrient balances on a sub-national scale in the Amazon of Ecuador (de Koning et al. 1997). Annual crops of San Lucas had moderate N losses like on a sub-national scale for the Andes. In contrast, the other land-uses of El Tambo and San Lucas showed deviating N balances which were either above or below from those of the sub-national scale (Fig. 3). The range of P balances in the present study showed a large variability between −4 and 33 kg P ha^{-1} a^{-1} with most land-uses fluctuating around even balances (Fig. 3). Similar ranges were found for P balances on a sub-national scale where, however, P-erosion was not calculated (de Koning et al. 1997). Higher losses for erosion in the present study often resulted in more negative K balances when compared to those of the sub-national scale where balances did not drop below −40 kg K ha^{-1} a^{-1}. A high variability of soil nutrient balances (Table 5; Figs. 2, 3) compared to average values on the sub-national scale was obvious. On the one hand, this illustrated the large diversity between and within south Ecuadorian smallholder land-use systems of the Andes. Characteristic for these systems were erosion for NPK and/or leaching for N which were often outnumbering losses for harvested products in annual crops of the research area (Table 5). On the other hand, the large variability can also be caused by comparing different spatial scales where the same nutrient flows can be of less or no relevance at higher scales (Veldkamp et al. 2001). At farm scale nutrient flows due to erosion, organic fertilizer inputs, external grazing or selling of harvested products play an important role as inputs or outputs whereas they have to be at least partially internalized at the sub-national scale. The tracking of specific flows gave a detailed insight into the management of the respective research area. It clearly showed that nutrient flows were directed to that land-use which was the essential component in generating farm income for a respective research area (Table 7). Despite the same production focus on livestock in Yantzaza and San Lucas, management characteristics were contrary. Due to smaller pastures sizes (2.5 vs. 25.4 ha) and higher livestock densities (1.6 and 4.1 TLU ha^{-1}) in San Lucas, large quantities of external nutrients and feeds were imported into pastures and SPUs (Table 7). Manure management and storage enabled the recycling of nutrients via RUs with subsequent application to annual and perennial crops in San Lucas (Table 7). This was also found in Kenyan farms with high external inputs and regarded responsible for increased crop production (van Beek et al. 2008). For pastures in the Yantzaza area a livestock density of 1.0 animals ha^{-1} was considered appropriate (Potthast et al. 2012a) since cows only produce 5.6 l of milk per day due to poor nutritional value of the planted pasture grass (UGT 2011). Therefore, a TLU of 1.6 ha^{-1} seemed to be at the upper end of an acceptable livestock density since external inputs to pastures and SPUs in Yantzaza were scarce (Table 7).

Management decisions due to different production targets and soil inherent conditions were particularly attributed to explain a large quantity of the variability in nutrient inputs and outputs (Figs. 4, 5). Hence, the hypothesis, that varying inputs and outputs due to specific management aims cause contrasting soil nutrient balances within the same farm was agreed on. High fertilizer application in cash crops of El Tambo was mainly focused on N (Table 5) which is common for developing countries with nutrient replenishment dominated by N fertilization (van der Velde et al. 2012) or inappropriate fertilizer combinations (Vanlauwe and Giller 2006). This process was enhanced by governmental urea subsidies leading to the depletion of other essential nutrients (Oenema et al. 2006). As a consequence, soil nutrient balances for P and K in annual crops of El Tambo were strongly negative (Fig. 3). In contrast, fertilizer inputs in annual and perennial crops of San Lucas were mostly organic originating either from external inputs or RUs (Table 7) resulting in a positive balance for P.

A decreasing gradient regarding explained variability of nutrient inputs and outputs by financial farm flows was found from the area with highest external inputs in El Tambo towards Yantzaza with low-external-input agriculture (Fig. 4). Using additional management variables such as planting date or plant density could have even increased the explained variability as was indicated by a study on maize yields where management factors explained between 40 and 60 % of its variability (Tittonell et al. 2007). The arrows for the financial farm flows pointed into the direction of the land-use with the dominant production focus with Yantzaza being the only exception (Fig. 4b–d). Of particular importance for agricultural management in San Lucas was the positive and negative significant correlation ($r = 0.41$ and -0.40) of expenses for hired labor and pesticides to the nutrient balance, respectively. In contrast, in El Tambo the nutrient balance was significantly positively affected by expenses for pesticides ($r = 0.35$). These diverging results can be traced back to different production aims of cash and subsistence crops in San Lucas and El Tambo respectively. However, they also indicate that the management was well adjusted to the local conditions of the respective research area since indigenous knowledge of farmers often considers soil quality while managing their soils (Barrios and Trejo 2003).

Consequences on soil fertility and sustainability of the agroecosystems

The hypothesis that financial farm flows have a greater impact on the soil nutrient balance than soil fertility variables in high-external input agriculture was confirmed for El Tambo. In contrast, for the low-external-input system of Yantzaza soil fertility variables explained the highest proportion of the variability of inputs and outputs reaching almost 50 % and decreased with increasing management intensity in San Lucas and El Tambo (Figs. 4, 5). Results showed that not a single but a combination of soil variables was responsible for the variability in inflows and outflows (Fig. 5) indicating the importance of including soil variables in their entirety. This is in compliance with a study from Kenya where regression models explained the variability in maize yields after combining soil variables instead of using them separately (Tittonell et al. 2007).

Nutrient flows indicated the dislocation of nutrients depending on management strategies especially in San Lucas and El Tambo (Table 7) which affected the soil fertility of the respective area. A redistribution of nutrients within the farm particularly took place from RUs and SPUs to perennial crops of San Lucas (Table 7) inducing higher SOC and TN stocks (Tables 4 and 8). In contrast, negative effects of nutrient redistribution were found for pastures of San Lucas which lost large quantities of nutrients to SPUs (Table 7) resulting in decreased SOC and TN stocks compared to perennial crops. Similar effects of within-farm nutrient redistribution, which were usually based on management aim, were found in smallholder farms of Ethiopia (Haileslassie et al. 2006) and Kenya (De Jager et al. 2001). Within-farm nutrient redistribution in El Tambo was of minor importance since it mainly involved external inflows (Table 7). However nutrient stocks of SOC and TN in annual and perennial crops (Table 8) were clearly below those of other semiarid agricultural areas of the tropics (Onduru et al. 2007; Elias et al. 1998) despite receiving large amounts of urea. This could be due to an intensified mineralization of soil organic matter triggered by an application of 200 kg urea-N in El Tambo which caused a loss of 23 kg NO_3-N ha^{-1} (Bahr et al. 2013). The mineralization of soil-derived N due to urea fertilization was not included as an output into the soil nutrient balance and therefore, might be a reason for the strongly positive N balance in annual crops of El Tambo (Fig. 3).

Although soil nutrient balances for NPK were rather negative than positive for most land-uses (Fig. 3), the effect on the respective nutrient stock change was often negligible. This followed from the fact that either soil nutrient balances were only slightly negative or large nutrient stocks were able to buffer strongly negative soil nutrient balances. This was also shown by Bindraban et al. (2000) who concluded that negative soil nutrient balances not necessarily imply the threat of soil nutrient depletion by nutrient mining. Hilhorst et al. (2000) regarded yearly TN stock declines of more than 1 %, which were found in annual and perennial crops of Yantzaza and pastures of San Lucas (Table 8), not sustainable. For additional verification of yearly nutrient stock changes, the chronosequence approach is a valuable tool for the assessment of the long-term impact on soil fertility and sustainability (Walker et al. 2010). A chronosequence research in Yantzaza showed that annual crops were abandoned after 5 years due to a severe soil nutrient decline which averaged 170 kg N a^{-1} or a TN stock decline of 3.6 % a^{-1} (Bahr et al. 2014). This corresponds well to strongly negative N and P balances (Fig. 3) as well as the most negative TN and TP stock change of all land-uses (Table 8) in the present study. Additional losses by leaching or harvested products caused by the a-typical climate in 2008 might be responsible for a higher yearly TN stock decline when comparing soil nutrient balance to chronosequence results. Hence, a yearly TN loss of more than 3 % served as a valuable indication for non-sustainable land-use in the research area causing land abandonment even in the short-term. In contrast, moderately negative stock changes of up to 2 % a^{-1} still enabled agricultural land-use for several decades in the research area, e.g. perennial crops of Yantzaza and pastures of San Lucas (Table 8).

SOC stocks of the respective land-use in each research area showed a clear trend of nutrient mining or accumulation (Table 4) as was also found for farming systems in Senegal (Manlay et al. 2004). For annual crops of Yantzaza SOC stocks were more than 15 % below those of the forest sites pointing to a non-sustainable land-use according to the fertility capability assessment in tropical soils (Sanchez et al. 2003). There the authors concluded that a value of 80 % for topsoil SOC stocks compared to nearby undisturbed sites was the threshold to maintain most of the productive functions in the soil. On the contrary, SOC stocks of perennial crops in San Lucas were highest due to nutrient accumulation by organic inputs (Table 7) indicated by strongly positive soil nutrient balances for N and P (Fig. 3). Besides total soil nutrient stocks it should also be regarded whether nutrients are quickly available (Vanlauwe and Giller 2006). TP stocks in Yantzaza were on an average level; however, a deficiency in the short-term availability was indicated by very low PO_4-P stocks (Table 8). This was also found for tropical African soils (Nwoke et al. 2004) and is mainly caused by high P fixation due to iron and aluminum oxides (Nziguheba et al. 1998) or a reduced mineralization of organic P by microorganisms (Vincent et al. 2010).

Conclusion

We showed that adapted equations for transfer functions to the Ecuadorian conditions induced an area and land-use specific calculation of difficult-to-quantify flows. GIS based modeling of sedimentation and soil loss from water erosion illustrated the large influence of both variables on the soil nutrient balance. It facilitated the identification of areas and land-uses benefiting from inputs by sedimentation and hence, nutrient addition and those suffering from nutrient losses. Therefore, we recommend using the adapted method for soil fertility assessment on a farm/field scale in south Ecuadorian land-use systems.

The majority of the NPK balances were negative in all research areas. However, this did not necessarily imply soil nutrient depletion since yearly nutrient stock changes were often negligible. Yearly nutrient stock losses of up to 2 % enabled agriculture for at least several decades whereas for annual crops in Yantzaza a yearly TN stock loss of almost 5 % indicated a non-sustainable land-use. We therefore recommend introducing harvest residue recycling and manure collection in the low-external-input system of Yantzaza to avoid soil nutrient depletion. Highest mineral fertilizer inputs were found in land-uses which contributed the most to crop production for market sale, e.g. annuals of El Tambo. Yet, they focused on N fertilization inducing negative soil nutrient balances for P and K which indicated a potential risk for a sustainable management. Financial farm flows and soil fertility variables were helpful tools to explain variability in inputs and outputs and showed a clear pattern depending on management focus.

Future studies should investigate whether soil nutrient balances are comparable over several yearly cycles. On this basis, the present research supports policy and decision makers to develop alternative or to adapt existing land-use for a sustainable agroecological management in southern Ecuador.

Acknowledgments The study was funded by the German Research Foundation (DFG) and was conducted within the Research Unit 816. We are grateful to the laboratory team for the accurate performance and to our Ecuadorian co-workers for actively supporting our field work. We thank Fernando Oñate-Valdivieso of the UTPL for the provision of a DEM for erosion modeling. Special thanks are given to Alexander Tischer, Susanne Frank and Lars Koschke for helpful comments and revising the manuscript. We are grateful to the three anonymous reviewers for their valuable comments.

References

Abdulkadir A, Leffelaar PA, Agbenin JO, Giller KE (2013) Nutrient flows and balances in urban and peri-urban agroecosystems of Kano, Nigeria. Nutr Cycl Agroecosyst 95(2):231–254. doi:10.1007/s10705-013-9560-2

Aubry C, Papy F, Capillon A (1998) Modelling decision-making processes for annual crop management. Agric Syst 56(1):45–65. doi:10.1016/S0308-521X(97)00034-6

Bahr E, Hamer U, Zaragocin DC, Makeschin F (2013) Different fertilizer types affected nitrogen and carbon cycling in

eroded and colluvial soils of Southern Ecuador. Agric Sci 4(12A):19–32. doi:10.4236/as.2013.412A002
Bahr E, Chamba Zaragocin D, Makeschin F (2014) Soil nutrient stock dynamics and land-use management of annuals, perennials and pastures after slash-and-burn in the Southern Ecuadorian Andes. Agric Ecosyst Environ 188:275–288. doi:10.1016/j.agee.2014.03.005
Barbier EB (2004) Agricultural, expansion, resource booms and growth in Latin America: implications for long-run economic development. World Dev 32(1):137–157. doi:10.1016/j.worlddev.2003.07.005
Barrios E, Trejo MT (2003) Implications of local soil knowledge for integrated soil management in Latin America. Geoderma 111(3–4):217–231. doi:10.1016/S0016-7061(02)00265-3
Bascomb CL (1964) Rapid method for determination of cation-exchange capacity of calcareous and non-calcareous soils. J Sci Food Agric 15(12):821–823. doi:10.1002/jsfa.2740151201
Berkhout ED, Schipper RA, Van Keulen H, Coulibaly O (2011) Heterogeneity in farmers' production decisions and its impact on soil nutrient use: results and implications from northern Nigeria. Agric Syst 104(1):63–74. doi:10.1016/j.agsy.2010.09.006
Beskow S, Mello CR, Norton LD, Curi N, Viola MR, Avanzi JC (2009) Soil erosion prediction in the Grande River Basin, Brazil using distributed modeling. Catena 79(1):49–59. doi:10.1016/j.catena.2009.05.010
Bindraban PS, Stoorvogel JJ, Jansen DM, Vlaming J, Groot JJR (2000) Land quality indicators for sustainable land management: proposed method for yield gap and soil nutrient balance. Agric Ecosyst Environ 81(2):103–112. doi:10.1016/S0167-8809(00)00184-5
Borbor-Cordova MJ, Boyer EW, McDowell WH, Hall CA (2006) Nitrogen and phosphorus budgets for a tropical watershed impacted by agricultural land use: Guayas, Ecuador. Biogeochemistry 79(1–2):135–161. doi:10.1007/s10533-006-9009-7
Bray RH, Kurtz LT (1945) Determination of total, organic, and available forms of phosphorus in soil. Soil Sci 59:39–45. doi:10.1097/00010694-194501000-00006
Cañadas Cruz L (1983) Mapa bioclimático y ecológico del Ecuador. Ministerio de Agricultura y Ganadería/Programa Nacional de Regionalización, Quito
Cobo JG, Dercon G, Cadisch G (2010) Nutrient balances in African land use systems across different spatial scales: A review of approaches, challenges and progress. Agric Ecosyst Environ 136(1–2):1–15. doi:10.1016/j.agee.2009.11.006
Cueva J, Chalán L (2010) Cobertura Vegetal y Uso Actual del Suelo de la Provincia de Loja. Technical report. Departamento de Sistemas de Información Geográfica de Naturaleza & Cultura Internacional. Gráficas Amazonas. Loja, Ecuador. Available at: http://www.naturalezaycultura.org/docs/Informe%20Cobertura%20Vegetal.pdf
da Silva AM (2004) Rainfall erosivity map for Brazil. Catena 57(3):251–259. doi:10.1016/j.catena.2003.11.006
De Jager A, Nandwa SM, Okoth PF (1998) Monitoring nutrient flows and economic performance in African farming systems (NUTMON) I. Concepts and methodologies. Agric Ecosyst Environ 71(1–3):37–48. doi:10.1016/S0167-8809(98)00130-3
De Jager A, Onduru D, van Wijk MS, Vlaming J, Gachini GN (2001) Assessing sustainability of low-external-input farm management systems with the nutrient monitoring approach: a case study in Kenya. Agric Syst 69(1–2):99–118. doi:10.1016/S0308-521X(01)00020-8
de Koning GHJ, van de Kop PJ, Fresco LO (1997) Estimates of sub-national nutrient balances as sustainability indicators for agro-ecosystems in Ecuador. Agric Ecosyst Environ 65(2):127–139. doi:10.1016/S0167-8809(97)00059-5
de Koning GHJ, Veldkamp A, Fresco LO (1998) Land use in Ecuador: a statistical analysis at different aggregation levels. Agric Ecosyst Environ 70(2–3):231–247. doi:10.1016/S0167-8809(98)00151-0
de Willigen P (2000) An analysis of the calculation of leaching and denitrification losses as practised in the NUTMON approach. Plant research international BV, Wageningen, Report 18
Dercon G, Deckers J, Poesen J, Govers G, Sanchez H, Ramirez M, Vanegas R, Tacuri E, Loaiza G (2006) Spatial variability in crop response under contour hedgerow systems in the Andes region of Ecuador. Soil Till Res 86(1):15–26. doi:10.1016/j.still.2005.01.017
Elias E, Morse S, Belshaw DGR (1998) Nitrogen and phosphorus balances of Kindo Koisha farms in southern Ethiopia. Agric Ecosyst Environ 71(1–3):93–113. doi:10.1016/S0167-8809(98)00134-0
Esilaba AO, Nyende P, Nalukenge G, Byalebeka JB, Delve RJ, Ssali H (2005) Resource flows and nutrient balances for crop and animal production in smallholder farming systems in eastern Uganda. Agric Ecosyst Environ 109(3–4):192–201. doi:10.1016/j.agee.2005.03.013
ESPAC (2014) Visualizador de estadísticas agropecuarias del Ecuador. http://www.inec.gob.ec/estadisticas/?option=com_content&view=article&id=103&Itemid=75. Accessed 06/08/2014
Færge J, Magid J (2004) Evaluating NUTMON nutrient balancing in sub-Saharan Africa. Nutr Cycl Agroecosyst 69(2):101–110. doi:10.1023/B:FRES.0000029680.97610.51
FAO (2004) Scaling soil nutrient balances—enabling mesolevel applications for African realities. FAO, Rome
FAO, IUSS, ISRIC (2006) World reference base for soil resources 2006. World soil resources reports no. 103. Food and Agriculture Organization of the United Nations, Rome
Graham PH, Rosas JC, de Jensen CE, Peralta E, Tlusty B, Acosta-Gallegos J, Pereira PAA (2003) Addressing edaphic constraints to bean production: the bean/cowpea CRSP project in perspective. Field Crop Res 82(2–3):179–192. doi:10.1016/s0378-4290(03)00037-6
Guo LB, Cowie AL, Montagu KD, Gifford RM (2008) Carbon and nitrogen stocks in a native pasture and an adjacent 16-year-old *Pinus radiata* D. Don. plantation in Australia. Agric Ecosyst Environ 124(3–4):205–218. doi:10.1016/j.agee.2007.09.013
Haileslassie A, Priess JA, Veldkamp E, Lesschen JP (2006) Smallholders' soil fertility management in the central highlands of Ethiopia: implications for nutrient stocks, balances and sustainability of agroecosystems. Nutr Cycl

Agroecosyst 75(1–3):135–146. doi:10.1007/s10705-006-9017-y

Haileslassie A, Priess JA, Veldkamp E, Lesschen JP (2007) Nutrient flows and balances at the field and farm scale: exploring effects of land-use strategies and access to resources. Agric Syst 94(2):459–470. doi:10.1016/j.agsy.2006.11.013

Hansen JP, Vinther FP (2001) Spatial variability of symbiotic N-2 fixation in grass-white clover pastures estimated by the N-15 isotope dilution method and the natural N-15 abundance method. Plant Soil 230(2):257–266. doi:10.1023/a:1010390901845

Hartemink AE (2006) Assessing soil fertility decline in the tropics using soil chemical data. In: Advances in agronomy, vol 89. Elsevier Academic Press, San Diego, pp 179–225. doi:10.1016/s0065-2113(05)89004-2

Hengsdijk H, Meijerink GW, Mosugu ME (2005) Modeling the effect of three soil and water conservation practices in Tigray, Ethiopia. Agric Ecosyst Environ 105(1–2):29–40. doi:10.1016/j.agee.2004.06.002

Hilhorst T, Muchena FN, Defoer T, Hassink J, De Jager A, Smaling EMA, Toulmin C (2000) Managing soil fertility in Africa: diverse settings and changing practice. In: Hilhorst T, Muchena F (eds) Nutrients on the move: Soil fertility dynamics in African farming systems. International Institute for Environment and Development, London, pp 1–25

Hughes RF, Kauffman JB, Cummings DL (2002) Dynamics of aboveground and soil carbon and nitrogen stocks and cycling of available nitrogen along a land-use gradient in Rondonia, Brazil. Ecosystems 5(3):244–259. doi:10.1007/s10021-001-0069-1

International Network of Food Data Systems (INFOODS) (2014) FAO. http://www.fao.org/infoods/infoods/tables-and-databases/latin-america/en/. Accessed 29/07/2014

Janssen BH (1999) Basic of budgets, buffers, abd balances of nutrients in relation to sustainability of agroecosystems. In: Smaling EMA, Oenema O, Fresco LO (eds) Nutrient disequilibria in agroecosystems: concepts and case studies. CABI Publishing, Wallingford, pp 27–56

Kingston HM, Jassie LB (1986) Microwave-energy for acid decomposition at elevated-temperatures and pressures using biological and botanical samples. Anal Chem 58(12):2534–2541. doi:10.1021/ac00125a038

Kirschbaum MUF (1995) The temperature-dependence of soil organic-matter decomposition, and the effect of global warming on soil organic-C storage. Soil Biol Biochem 27(6):753–760. doi:10.1016/0038-0717(94)00242-s

Lesschen JP, Stoorvogel JJ, Smaling EMA, Heuvelink GBM, Veldkamp A (2007) A spatially explicit methodology to quantify soil nutrient balances and their uncertainties at the national level. Nutr Cycl Agroecosyst 78(2):111–131. doi:10.1007/s10705-006-9078-y

Lüer B, Böhmer A (2000) Comparison between percolation and extraction with 1 M NH4Cl solution to determine the effective cation exchange capacity (CECeff) of soils. J Plant Nutr Soil Sci 163(5):555–557. doi:10.1002/1522-2624(200010)163:5<555:aid-jpln555>3.3.co;2-r

Manlay RLJ, Ickowicz A, Masse D, Floret C, Richard D, Feller C (2004) Spatial carbon, nitrogen and phosphorus budget of a village in the West African savanna—I. Element pools and structure of a mixed-farming system. Agric Syst 79(1):55–81. doi:10.1016/s0308-521x(03)00053-2

Marrs R, Proctor J, Heaney A, Mountford M (1988) Changes in soil nitrogen-mineralization and nitrification along an altitudinal transect in tropical rain forest in Costa Rica. J Ecol 76(2):466–482. doi:10.2307/2260606

Miller RO (1998) Nitric-perchloric acid wet digestion in an open vessel. In: Kalra Y (ed) Handbook of reference methods for plant analysis. CRC Press LLC, Boca Raton, pp 57–61

Mulligan M, Rubiano J, Hyman G, White D, Garcia J, Saravia M, Gabriel LJ, Selvaraj JJ, Guttierez T, Saenz-Cruz LL (2010) The Andes basins: biophysical and developmental diversity in a climate of change. Water Int 35(5):472–492. doi:10.1080/02508060.2010.516330

Neill C, Piccolo MC, Steudler PA, Melillo JM, Feigl BJ, Cerri CC (1995) Nitrogen dynamics in soils of forests and active pastures in the western Brazilian Amazon Basin. Soil Biol Biochem 27(9):1167–1175. doi:10.1016/0038-0717(95)00036-e

Nwoke OC, Vanlauwe B, Diels J, Sanginga N, Osonubi O (2004) The distribution of phosphorus fractions and desorption characteristics of some soils in the moist savanna zone of West Africa. Nutr Cycl Agroecosyst 69(2):127–141. doi:10.1023/B:FRES.0000029677.09424.ef

Nyamangara J, Bergström L, Piha M, Giller K (2003) Fertilizer use efficiency and nitrate leaching in a tropical sandy soil. J Environ Qual 32(2):599–606. doi:10.2134/jeq2003.0599

Nziguheba G, Palm CA, Buresh RJ, Smithson PC (1998) Soil phosphorus fractions and adsorption as affected by organic and inorganic sources. Plant Soil 198(2):159–168. doi:10.1023/a:1004389704235

Ochoa-Cueva P, Fries A, Montesinos P, Rodríguez-Díaz JA, Boll J (2013) Spatial estimation of soil erosion risk by land-cover change in the Andes of southern Ecuador. Land Degrad Dev. doi:10.1002/ldr.2219

Oenema O, Kros H, de Vries W (2003) Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. Eur J Agron 20(1–2):3–16. doi:10.1016/s1161-0301(03)00067-4

Oenema O, Janssen BH, Smaling E, Hoffland E (2006) Nutrient management in tropical agroecosystems. Agric Ecosyst Environ 116(1–2):1–3. doi:10.1016/j.agee.2006.03.008

Oldeman L, Hakkeling Ru, Sombroek WG (1990) World map of the status of human-induced soil degradation: an explanatory note. Global assessment of soil degradation. International Soil Reference and Information Centre, Wageningen

Olsen SR, Cole CV, Wanatabe FS, Dean LA (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Washington DC

Onduru DD, De Jager A, Muchena FN, Gachimbi L, Gachini GN (2007) Socio-economic factors, soil fertility management and cropping practices in mixed farming systems of sub-saharan Africa: a study in Kiambu, central highlands of Kenya. Int J Agric Res 2(5):426–439. doi:10.3923/ijar.2007.426.439

Phong LT, Stoorvogel JJ, van Mensvoort MEF, Udo HMJ (2011) Modeling the soil nutrient balance of integrated agriculture–aquaculture systems in the Mekong Delta, Vietnam. Nutr Cycl Agroecosyst 90(1):33–49. doi:10.1007/s10705-010-9410-4

Pohle P (2008) The people settled around Podocarpus National Park. In: Beck E, Bendix J, Kottke I, Makeschin F, Mosandl R (eds) Gradients in a tropical mountain ecosystem of Ecuador. Ecological studies: analysis and synthesis, vol 198. Springer, Berlin, pp 25–36. doi:10.1007/978-3-540-73526-7_3

Pohle P, Gerique A, Park M, Lopez Sandoval MF (2010) Human ecological dimensions in sustainable utilization and conservation of tropical mountain rain forests under global change in southern Ecuador. In: Tscharntke T, Leuschner C, Veldkamp E, Faust H, Guhardja E, Bidin A (eds) Tropical rainforests and agroforests under global change: ecological and socio-economic valuations. Environmental science and engineering:environmental engineering. Springer, Heidelberg, pp 477–509. doi:10.1007/978-3-642-00493-3_23

Potthast K, Hamer U, Makeschin F (2012a) In an Ecuadorian pasture soil the growth of Setaria sphacelata, but not of soil microorganisms, is co-limited by N and P. Appl Soil Ecol 62:103–114. doi:10.1016/j.apsoil.2012.08.003

Potthast K, Hamer U, Makeschin F (2012b) Land-use change in a tropical mountain rainforest region of southern Ecuador affects soil microorganisms and nutrient cycling. Biogeochemistry 111(1–3):151–167. doi:10.1007/s10533-011-9626-7

Quinn P, Beven K, Chevallier P, Planchon O (1991) The prediction of hillslope flow paths for distributed hydrological modeling using digital terrain models. Hydrol Process 5(1):59–79. doi:10.1002/hyp.3360050106

Raison RJ, Khanna PK, Woods PV (1985) Mechanisms of element transfer to the atmosphere during vegetation fires. Can J For Res 15(1):132–140. doi:10.1139/x85-022

Renard KG, Foster GR, Weesies GA, McCool DK, Yoder DC (1997) Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). Agriculture handbook no. 703. Washington

Rhoades CC, Coleman DC (1999) Nitrogen mineralization and nitrification following land conversion in montane Ecuador. Soil Biol Biochem 31(10):1347–1354. doi:10.1016/S0038-0717(99)00037-1

Richter M (2003) Using epiphytes and soil temperatures for eco-climatic interpretations in southern Ecuador. Erdkunde 57(3):161–181. doi:10.3112/erdkunde.2003.03.01

Sanchez PA, Palm CA, Buol SW (2003) Fertility capability soil classification: a tool to help assess soil quality in the tropics. Geoderma 114(3–4):157–185. doi:10.1016/s0016-7061(03)00040-5

Sato S, Comerford NB (2008) The non-recoverable phosphorus following sorption onto a Brazilian Ultisol. Biol Fertil Soils 44(4):649–652. doi:10.1007/s00374-007-0255-1

Schlichting E, Blume H-P, Stahr K (1995) Bodenkundliches Praktikum. Blackwell Wissenschaftsverlag, Berlin

Scrimshaw NS (1997) INFOODS: the international network of food data systems. Am J Clin Nutr 65(4):1190S–1193S

Sheldrick WF, Syers JK, Lingard J (2003) Soil nutrient audits for China to estimate nutrient balances and output/input relationships. Agric Ecosyst Environ 94(3):341–354. doi:10.1016/s0167-8809(02)00038-5

Shepherd KD, Soule MJ (1998) Soil fertility management in west Kenya: dynamic simulation of productivity, profitability and sustainability at different resource endowment levels. Agric Ecosyst Environ 71(1–3):131–145. doi:10.1016/S0167-8809(98)00136-4

Smaling EMA, Fresco LO (1993) A decision-support model for monitoring nutrient balances under agricultural land use (NUTMON). Geoderma 60(1–4):235–256. doi:10.1016/0016-7061(93)90029-K

Smaling EMA, Stoorvogel JJ, Windmeijer PN (1993) Calculating soil nutrient balances in Africa at different scales. Fertil Res 35(3):237–250. doi:10.1007/BF00750642

Smaling EMA, Oenema O, Fresco LO (1999) Nutrient disequilibria in agroecosystems: concepts and case studies. CABI Publishing, Wallingford

Smith CS, McDonald GT (1998) Assessing the sustainability of agriculture at the planning stage. J Environ Manag 52(1):15–37. doi:10.1006/jema.1997.0162

Sonder K (2002) Soil erosion in andean cropping systems: the impact of rainfall erosivity. Dissertation, Hohenheim, Hohenheim

Stoorvogel JJ (1993) Optimizing land-use distribution to minimize nutrient depletion—a case-study for the Atlantic zone of Costa-Rica. Geoderma 60(1–4):277–292. doi:10.1016/0016-7061(93)90031-F

Stoorvogel JJ, Smaling EMA (1990) Assessment of soil nutrient depletion in sub-Saharan Africa: 1983–2000. Vol. II: nutrient balances per crop and per land use systems. DLO-Winand Staring Centre, Report 28, Wageningen

Stoorvogel JJ, Smaling EMA (1998) Research on soil fertility decline in tropical environments: integration of spatial scales. Nutr Cycl Agroecosyst 50(1–3):151–158. doi:10.1023/A:1009732126336

Stoorvogel JJ, Antle JM, Crissman CC (2004) Trade-off analysis in the Northern Andes to study the dynamics in agricultural land use. J Environ Manag 72(1–2):23–33. doi:10.1016/j.jenvman.2004.03.012

Surendran U, Murugappan V (2006) A micro- and meso-level modeling study for assessing sustainability in semi-arid tropical agro ecosystem using NUTMON-toolbox. J Sustain Agric 29(2):151–179. doi:10.1300/J064v29n02_10

Tan ZX, Lal R, Wiebe KD (2005) Global soil nutrient depletion and yield reduction. J Sustain Agric 26(1):123–146. doi:10.1300/J064v26n01_10

Thy P, Jenkins BM, Lesher CE, Grundvig S (2006) Compositional constraints on slag formation and potassium volatilization from rice straw blended wood fuel. Fuel Process Technol 87(5):383–408. doi:10.1016/j.fuproc.2005.08.015

Tittonell P, Vanlauwe B, de Ridder N, Giller KE (2007) Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: soil fertility gradients or management intensity gradients? Agric Syst 94(2):376–390. doi:10.1016/j.agsy.2006.10.012

UGT (2011) Sistema Económico Productivo. Gobierno Provincial de Zamora Chinchipe, Zamora

van Beek CL, Onduro DD, Gachimbi LN, de Jager A (2008) Farm nitrogen flows of four farmer field schools in Kenya. Nutr Cycl Agroecosyst 83(1):63–72. doi:10.1007/s10705-008-9199-6

Van den Bosch H, De Jager A, Vlaming J (1998) Monitoring nutrient flows and economic performance in African farming systems (NUTMON) II. Tool development. Agric Ecosyst Environ 71(1–3):49–62. doi:10.1016/S0167-8809(98)00131-5 van der Velde M, See L, Fritz S (2012) Agriculture: soil remedies for small-scale farming. Nature 484(7394):318. doi:10.1038/484318c

Vandenbygaart AJ, Kroetsch D, Gregorich EG, Lobb D (2012) Soil C erosion and burial in cropland. Glob Change Biol 18(4):1441–1452. doi:10.1111/j.1365-2486.2011.02604.x

Vanlauwe B, Giller KE (2006) Popular myths around soil fertility management in sub-Saharan Africa. Agric Ecosyst Environ 116(1–2):34–46. doi:10.1016/j.agee.2006.03.016

Vanlauwe B, Tittonell P, Mukalama J (2006) Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. Nutr Cycl Agroecosyst 76(2–3):171–182. doi:10.1007/s10705-005-8314-1

Vanlauwe B, Bationo A, Chianu J, Giller K, Merckx R, Mokwunye U, Ohiokpehai O, Pypers P, Tabo R, Shepherd K (2010) Integrated soil fertility management operational definition and consequences for implementation and dissemination. Outlook Agric 39(1):17–24. doi:10.5367/000000010791169998

Veldkamp A, Kok K, De Koning GHJ, Schoorl JM, Sonneveld MPW, Verburg PH (2001) Multi-scale system approaches in agronomic research at the landscape level. Soil Till Res 58(3–4):129–140. doi:10.1016/s0167-1987(00)00163-x

Vincent AG, Turner BL, Tanner EV (2010) Soil organic phosphorus dynamics following perturbation of litter cycling in a tropical moist forest. Eur J Soil Sci 61(1):48–57. doi:10.1111/j.1365-2389.2009.01200.x

Walker LR, Wardle DA, Bardgett RD, Clarkson BD (2010) The use of chronosequences in studies of ecological succession and soil development. J Ecol 98(4):725–736. doi:10.1111/j.1365-2745.2010.01664.x

Weng CY, Bush MB, Athens JS (2002) Holocene climate change and hydrarch succession in lowland Amazonian Ecuador. Rev Palaeobot Palyno 120(1–2):73–90

Wilcke W, Yasin S, Fleischbein K, Goller R, Boy J, Knuth J, Valarezo C, Zech W (2008) Nutrient status and fluxes at the field and catchment scale. In: Beck E, Bendix J, Kottke I, Makeschin F, Mosandl R (eds) Gradients in a tropical mountain ecosystem of ecuador. Ecological studies: analysis and synthesis. Springer, Berlin, pp 203–216. doi:10.1007/978-3-540-73526-7_20

Wilcke W, Günter S, Alt F, Geißler C, Boy J, Knuth J, Oelmann Y, Weber M, Valarezo C, Mosandl R (2009) Response of water and nutrient fluxes to improvement fellings in a tropical montane forest in Ecuador. For Ecol Manag 257(4):1292–1304. doi:10.1016/j.foreco.2008.11.036

Wischmeier WH, Smith DD (1978) Predicting rainfall erosion losses: a guide to conservation planning. Agricultural handbook, 537. United States department of agriculture, Washington

Yu B, Rosewell CJ (1996) A robust estimator of the R-factor for the universal soil loss equation. Trans ASAE 39(2):559–561