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Are partial nutrient balances suitable to evaluate nutrient sustainability of land use systems? Results from a case study in Central Sulawesi, Indonesia

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Abstract

Nutrient input–output balances are often used as indicators for the sustainability of land use systems. In a case study on plot scale in Central Sulawesi, Indonesia, we measured nutrient input–output balances of natural rainforest and two unfertilized land use systems (maize, and coffee/cacao agroforestry). These are the two major land use systems on converted rainforest sites in this part of Sulawesi. We wanted to test if (a) plant nutrient balances are negative, (b) which pathway is most important for losses of plant nutrients, and (c) if partial plant nutrient balances are suitable to evaluate sustainability of the land use systems. We measured nutrient inputs by precipitation and nutrient outputs by harvest export and leaching. We selected two locations, the first was situated on a fertile Cambisol developed on alluvial sediment soil, and the second on a less fertile Cambisol developed on weathered phyllite substrate. Nutrient losses through leaching were higher on sites with higher soil fertility. Nutrient balances in natural forest on fertile soils were negative for N, Ca, K and Mg. Inputs of P by precipitation and outputs by leaching were below detection limit. On less fertile soils, leaching of N and K in natural forest was lower than inputs by precipitation. As net nutrient losses were highest in agroforestry, followed by maize and natural forest stands, forest conversion into agricultural land will result in increased nutrient losses. Main output pathway of N, P and K was harvest, whereas main output pathway for Ca and Mg was through leaching. The annual losses of nutrients we measured were higher than in comparable studies on nutrient poor soils; however losses were only small fractions of available nutrient stocks. Our results showed negative partial nutrient balances in both agricultural systems. Nutrient balances in this study were more influenced by native soil fertility than by land use. Because we found indirect evidence that some nutrient pathways, which were not measured, may have significantly changed the overall balance (biological N fixation, weathering), we conclude that partial nutrient balances are no good indicators for sustainability of land use systems.

Introduction

In many rainforest margins of the tropics, land use systems (e.g. slash-and-burn systems) receive no or low nutrient inputs through fertilization, and nutrients exported from the system through harvest are therefore not replaced (Hölscher et al. 1997; Sommer et al. 2004). Clear cutting of natural forest leads to the quick mineralization of large amounts of nutrients from slashed biomass and the soil (Bruijnzeel 1991; Mackensen et al. 2003). Also the timing and rate at which nutrients are released and taken up may differ considerably, as is the case for young crop plants which have a low nutrient uptake. This, combined with intense rain showers and reduced interception on cleared sites, often result in nutrient losses through leaching (e.g. Bruijnzeel 1995; Klinge et al. 2004). Erosion and runoff on slopes, and volatilization by regular burning of weed- or harvest-residues on agricultural sites add to losses of nutrients (e.g. Hölscher et al. 1997; Bationo et al. 1998; Sommer et al. 2004). If agricultural management results in continuously negative nutrient balances, we expect these land use systems to be unsustainable and to degrade with time. This has already been shown in the 1960s by the studies of Nye and Greenland (1965) in tropical areas with acidic, deeply weathered soils, where during cultivation after forest conversion harvests declined rapidly. More recent studies in the Brazilian Amazon on similar soils showed that in slash-and-burn cropping systems with fallow periods, large nutrient losses per cultivation cycle occurred (Hölscher et al. 1997).

Contrary to agricultural land use systems, late successional vegetation types like natural tropical rain forests have reduced nutrient losses and are close to a steady state with inputs close or equal to outputs. The tight nutrient cycling between the ecosystem compartments stabilizes these vegetation forms over long periods of time (Brouwer 1996). However, Vitousek and Sanford (1986) and Bruijnzeel (1991) differentiated between forests on poor and rich substrates, and cite evidence that under fertile soil conditions nutrient cycling is less conserving than under nutrient poor conditions. Most successful nutrient balancing studies in agricultural systems have been conducted on deeply weathered soils with nutrient poor conditions. It is however unclear whether this approach can be used on nutrient rich soils.

The present study was conducted in an area around Lore Lindu National park, Central Sulawesi, Indonesia, where relatively young and fertile soils predominate. In this area deforestation rates have increased in recent years and forest clearing is mainly done by smallholders who use the cleared areas for agriculture (Van Rheenen et al. 2004). Dominant land use systems on converted sites are unfertilized continuous maize cultivation without fallow periods, and unfertilized agroforestry systems with cacao and coffee.

With the present study we wanted to answer the question whether these agricultural land use systems with annual or perennial crops on relatively fertile soils have negative nutrient balances for N, P, K, Ca and Mg. We also wanted to find out which nutrient pathway was the most important for nutrient loss of the major plant nutrients. Our final question was whether partial nutrient balances are good indicators of the sustainability of these agricultural systems. To answer these questions we conducted a case study at plot scale at two locations. Two sites of continuous maize, one site of cacao/coffee agroforestry, and two natural forest sites as a reference were selected. The system boundaries were the upper surface of the vegetation, soil at 1.20 m depth, and the site borders. We measured only nutrients that entered or left these system boundaries: inputs by precipitation, outputs by leaching below 1.20 m depth, and export of harvest from the site. Nutrient fluxes between nutrient pools within the system (e.g. litterfall, nutrient uptake) were not investigated. Our measured nutrient fluxes were used to calculate partial nutrient balances. Other nutrient pathways like inputs by mineral weathering, deep soil exploitation, biological N fixation, and outputs like volatilization by biomass-burning or denitrification, were not measured. Outputs by erosion or runoff were avoided by selection of flat sites.

Materials and methods

Site selection and soil parameters

Two locations were selected which had different land use systems close to each other on relatively homogenous soil to enable comparison of nutrient input and output fluxes under different agricultural management. Both locations were about 1100 m above sea level, close to the north-eastern border of the Lore Lindu National Park, Sulawesi. Location 1 was south-east of the village Wuasa (lat. −01°25′37″ 08, long. 120°18′21″ 69) on deep, alluvial sediments with sandy loam texture (Table 1). Three land use systems were selected here: forest, agroforestry and maize; soil type was fluvic Cambisol (FAO 1998). Location 2 was north-east of the village Wanga (lat. −01°29′27″ 59, long. 120°19′21″ 96) on deeply weathered phyllite as parent material and a clay texture (Table 1). Two land use systems were selected here: forest and maize; soil type was dystric Cambisol. The maize fields on both locations had been cultivated continuously with maize for at least 2–3 years; the agroforestry site in location 1 was established from natural forest 6 years before, with a 2 year period of maize cultivation directly after forest clearing when coffee plants were still small. In both managed systems of location 1, coarse woody debris from the originally cleared forest could still be observed. The forest reference in both locations had been disturbed by selective removal of individual trees of species with valuable wood, but both sites still had a high density and coverage of large trees. In both locations, areas with different land use systems were not further than 50 m apart. The size of the maize plot in location 1 was 50 m × 75 m, the agroforestry plot was 50 m × 80 m, and the maize plot in location 2 was 25 m × 30 m. All research sites were flat to exclude erosion or runoff effects.

Maize was planted on February 28, 2002 in location 1 and March 4 in location 2, and harvested on June 6 and June 1, respectively. Second replanting took place on July 27 and July 12, respectively. The second harvest in the year was October 30, and November 7, respectively. Planting density of maize was between 40,000 and 50,000 plants per hectare. The agroforestry site was a mixed stand of coffee (60%), cacao (40%), and shade trees (*Erythrina fusca* and *Gliricidia sepium*). Cacao and coffee was planted approximately at 2×2 m spacing (2000–3000 plants per hectare), and shade trees at about 5×5 m. Cacao was often younger than coffee, inter-planted between larger coffee plants, so that the cacao was at the center of the open space between 4 coffee plants.

To characterize soil conditions for all study sites, soil samples were taken from 0 to 10 and 30 to 40 cm depth (per site: three composite samples from five subsamples each) and analyzed for pH, bulk density, texture and CEC (cation exchange capacity). Total concentrations of C and N were analyzed with CNS Elemental Analyzer. Total concentrations of P, K, Ca and Mg were determined after digestion with HNO_3 under pressure following the method described in Heinrichs (1989). Additionally samples were analyzed for exchangeable cations (K, Ca and Mg) by percolation with 1 M NH_4Cl following the method described in Meiwes et al. (1984). Soil nutrient stocks 0–40 cm depth were calculated by using nutrient concentration and bulk density data from samples of 0–10 cm depth for 0–20 cm depth and data from samples of 30–40 cm depth for 20–40 cm depth. Results are presented in Table 1.

All selected agricultural sites had been established by local farmers, and management during the measurements continued according to the local farmers' management practice. Farmers did not apply fertilizer or manure on the research sites. Forest sites were studied as reference representing the undisturbed situation.

Table 1. Soil texture (0–10 cm), soil parameters (0–10 cm), total nutrient stocks (digestion method, 0–40 cm), and exchangeable base cation stocks (percolation method, 0–40 cm).

Site	Clay (%)	Sand (%)	Silt (%)	BS (%)	pH in KCl	Bulk density (g cm^{-3})	Total stocks (t ha^{-1}, 0–40 cm)						Exchangeable stocks (t ha^{-1}, 0–40 cm)		
							C	N	P	Ca	K	Mg	Ca	K	Mg
Location 1, fluvic Cambisol															
NF	22.8	51.3	25.9	98.9	5.8	1.1	109.0	10.6	2.9	14.4	40.2	26.0	23.4	0.5	1.6
AF	18.0	58.1	24.0	99.4	5.7	1.1	97.4	9.9	2.6	13.3	34.8	24.5	20.1	0.5	1.4
MF	15.2	45.2	39.6	99.6	6.5	1.0	134.6	11.8	2.7	21.7	35.6	22.4	35.2	1.0	5.1
Location 2, dystric Cambisol															
NF	59.6	13.6	26.8	76.7	4.4	0.8	134.8	9.3	2.1	9.0	0.6	6.4	5.6	0.3	1.5
MF	63.0	8.5	28.3	85.9	4.6	0.9	134.4	11.0	4.6	8.0	0.3	5.7	7.6	0.2	1.6

NF = natural forest, AF = agroforestry, MF = maize field.

Instrumentation

On all sites of location 1 and the maize site of location 2 a total of 16 lysimeters (plastic pipes 2 cm diameter with ceramic suction cups at the end) were installed in 1.20 m depth to collect soil-water samples. In location 2 on the forest site eight lysimeters were installed. We assumed that soil water samples from this depth were taken below the main rooting zone. Suction cups had been washed with acid and distilled water before use to remove possible traces of nutrients, especially N. Four lysimeters were placed at the corners of a square of approximately 1 m^2; two lysimeters each were connected to one brown 0.5 l glass bottle to collect the soil water, so that eight bottles per site were collecting soil water samples. Glass bottles were placed in plastic buckets with lids, which were dug into the soil to protect them and allow work to continue on the managed sites. From the two bottles of one set of four lysimeters one composite soil water sample was taken weekly, four samples per site. In the forest site of location 2 only two sets of four lysimeters were installed. On each glass bottle a vacuum of 200–300 kPa was applied with a portable vacuum pump. Soil water samples were collected in PE-bottles of 100 ml, 14–20 h after application of the vacuum.

At both locations a set of five rain water samplers were installed on open areas 2 m above ground level to collect samples of gross precipitation. The rain water samplers consisted of funnels of 0.1 m diameter covered with a 0.5 mm plastic netting to prevent insects or leaves from entering, fixed to a 1 l PE-bottle with a rubber stopper which had an opening in the middle. Bottles were covered with reflective silver tape to avoid heating up of the rain water sample and development of algae. At each location, one composite sample of rain water was collected weekly. Soil and rain water samples were taken to the laboratory and were frozen within 24 h after collection. Analysis of the soil water and rain water samples was conducted in the laboratory unit at Tadulako University, Palu. Samples were analyzed for P, K, Mg, Al, and Ca, using ICP-OEC, for total N using a TOC-analyzer, and for pH. Both Al and P were analyzed only in the first batch of about 100 samples, but because all of these samples had values under detection limit these elements were not analyzed further in the following samples.

Water balance and leaching

A water balance was calculated using climatic data obtained from meteorological stations closest to the experimental site to estimate drainage from the soil profile. For location 1 the distance to the climatic station was approximately 2–3 km, and for location 2 only 60 m. The data set of the climatic stations included mean daily temperature, humidity, precipitation, global radiation, and wind speed. The water balance was calculated using Expert-N software version 2.6.0 EE (Engel and Priesack 1993). This program calculates actual transpiration, actual evaporation, and drainage based on the climatic data, soil texture, and vegetation data (LAI natural forest: 7, agroforestry 3, maize 2.5), and simulates growth of annual crop vegetation for the maize sites between sowing and harvest (Figure 1). From daily data weekly sums were calculated of both precipitation and drainage.

Soil and rain water were collected weekly from March to October 2002. These 8 months included the rainy season, when most of drainage occurred. Leaching of nutrients per area was calculated from data of nutrient concentration in soil water and the amount of water draining per week. We did not find differences between mean nutrient concentrations during the wet period (March–June) and mean concentrations during the dry period (July–September). Therefore we used mean concentration data from the whole period March–October to calculate leaching for months where no concentration data were available (January–March and October–December). Nutrient fluxes were calculated as kg ha^{-1} a^{-1}.

It should be noted that nutrient balances in agroforestry sites may vary depending on proportions of coffee and cacao, and planting densities. These parameters varied across the research region.

Harvest

On the agricultural sites we measured nutrient export through harvest. Maize was harvested by taking only the maize cob, following the general practice of farmers in the area. The maize-plant residuals were left on the field to rot or burned in small piles scattered across the field. Maize harvest was measured by harvesting five subplots of 4 m^2,

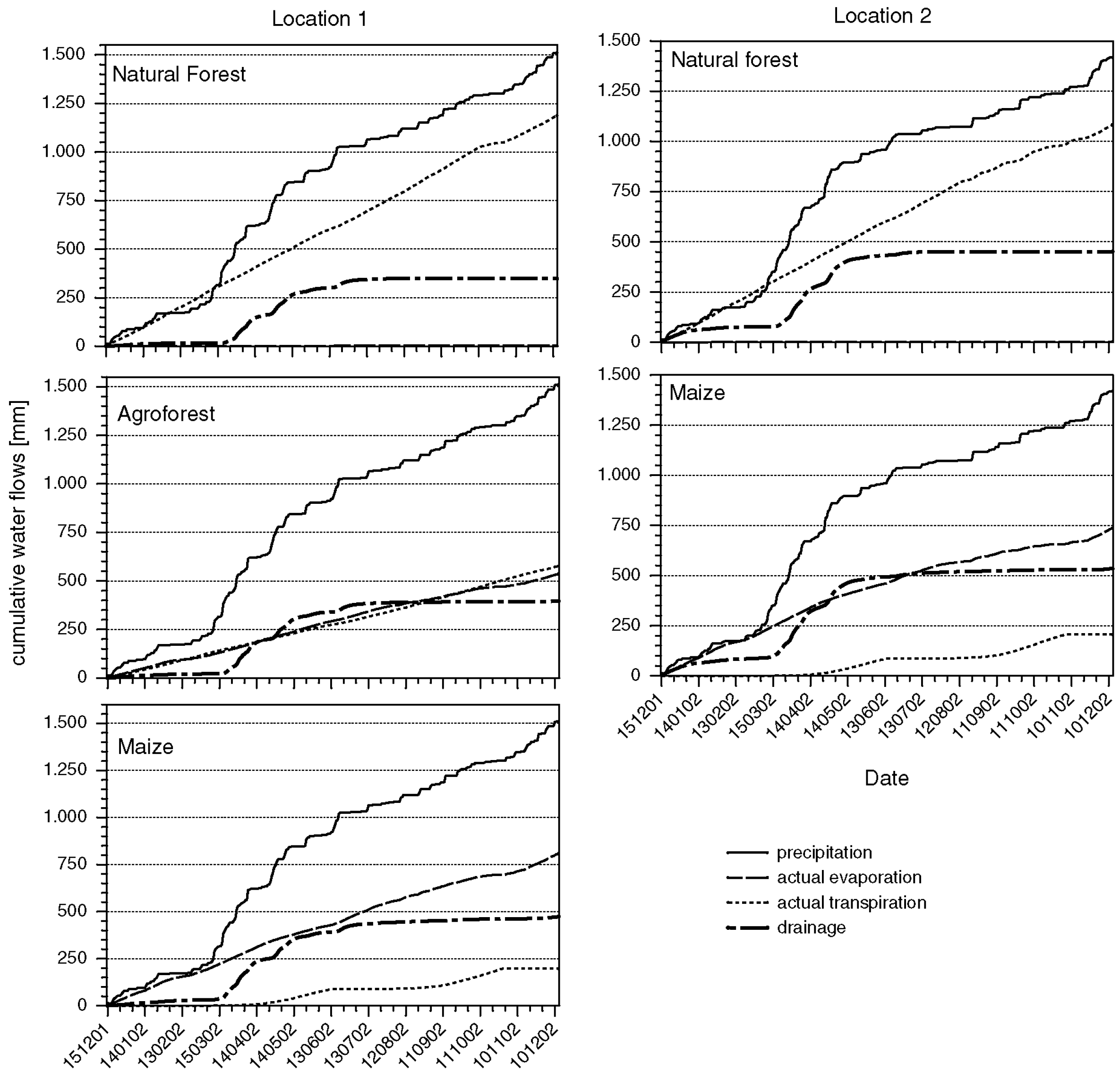

Figure 1. Cumulative precipitation, evaporation, transpiration, and water drainage, in 2002 for location 1 and location 2 (mm).

drying of the maize-cobs for 24 h at 105 °C and calculating the total harvest of maize cobs (separated into seeds and cob-residues) dry matter per site. The harvest was analyzed for concentrations of macronutrients N, P, Ca, K and Mg. Planting frequency in the research area varied, but according to observations maize cultivation was done continuously without distinct fallow periods or planting seasons, and many growth stages were present at one time. Time between sowing and harvesting of maize was approximately 4.5 months. Including a short period of 1–2 months where weeds are controlled and harvest is processed, an average of 2 harvests of maize per year was estimated. Export of nutrients per area and year were calculated from harvest data, number of harvests per year and nutrient concentrations in maize harvest.

On agroforestry sites harvesting was a continuous process with weekly or bi-weekly harvests of coffee or cacao. We regularly sampled coffee or cacao fruits and analyzed them for nutrient concentrations. Total export was estimated by interviewing the farmer every week about the harvest (in kg) of the week before. Farmers export the ripe coffee-berries from the site, while the cacao fruits are opened and only the beans are exported from the site. Most agroforestry sites are mixed stands with a high variety of fruits, nuts vegetables or other cultivated plants. On the research site these other crops (e.g. cassava, sweet potato, banana, chili, pineapple, cucumber and pumpkin) were of negligible amounts and were not included into this study. Apart from coffee and cacao one other crop was included: Candle Nut (Indonesian: Kemiri), *Aleurites mollucana*, of which about 1 t ha^{-1} a^{-1} was harvested. This fast-growing tree yields fruits that contain nuts of which the fatty kernels are mostly sold and used to produce oil. Fruits are collected after they drop from the tree, they are opened and only the dried nuts are removed from the site. Some candle nut trees were planted within the agroforestry system, replacing some of the shade trees, but most occurred along the border of the field.

Results

Water balance

Annual precipitation was 1525 mm (location 1) and 1427 mm (location 2). Cumulative simulated drainage in location 1 was 349 mm a^{-1} in natural forest, 396 mm a^{-1} in agroforestry, and 473 mm a^{-1} in the maize site. Cumulative simulated drainage in location 2 was 451 mm a^{-1} in natural forest, and 535 mm a^{-1} in the maize site (Figure 1). The wet season was between March and June (46% of annual precipitation), and the dry season from July until October (Figure 1). Evapotranspiration was between 66 and 83% of annual precipitation. Temperature (21.1 and 21.4 °C), humidity (81.4 and 80.2%), and wind speed (annual mean 1.0 m s^{-1}) did not vary much during the year, daily average amplitude of maximum and minimum temperature was about 8 °C. Water balance calculations showed highest drainage of water from March until May. During this time about 85% of the annual amount of draining was calculated, whereas during July and August drainage was very low (Figure 1).

Nutrient inputs

Nutrient input by rain differed between both locations. In location 2, inputs by rain were lower for N, Ca, and K because of lower nutrient concentrations in rain water (Table 2). In both agricultural land use systems N, Ca and Mg inputs by rain were small compared to leaching and harvest exports. However, precipitation replaced 76% of K losses in maize of location 1 and 37% of K in maize of location 2, and 29% of K losses in agroforestry (Table 3). In natural forest, rain replaced 52% (location 1) and 183% (location 2) of N leaching losses. In the forest of location 2, N and K input by rain exceeded outputs, resulting in positive N and K balance (Table 3). Concentrations of P in rain water were below detection limit.

Nutrient outputs

In general, leaching losses on less fertile soils on weathered phyllite (location 2) were considerably lower than on more fertile alluvial soils (location

Table 2. Nutrient concentrations in rain and soil water, mean (SE), at 120 cm depth.

Land use	pH	N (mg l^{-1})	Ca (mg l^{-1})	K (mg l^{-1})	Mg (mg l^{-1})
Soil water location 1, fluvic Cambisol					
Forest	6.8 (0.3)	1.2 (0.5)	7.7 (2.6)	4.4 (0.7)	1.5 (0.5)
Agroforest	6.8 (0.5)	3.2 (1.9)	16.6 (4.9)	4.5 (1.0)	2.7 (0.8)
Maize	6.7 (0.5)	2.7 (0.9)	6.3 (1.0)	2.4 (0.6)	1.5 (0.2)
Soil water location 2, dystric Cambisol					
Forest	6.5 (0.7)	0.4 (0.5)	2.1 (2.2)	1.0 (1.0)	1.1 (0.7)
Maize	5.8 (0.9)	0.8 (0.7)	1.2 (0.9)	0.7 (0.4)	0.4 (0.3)
Rain water					
Location 1	7.0 (0.8)	0.18 (0.1)	0.43 (0.2)	1.05 (0.5)	0.02 (0.1)
Location 2	6.5 (0.8)	0.17 (0.1)	0.40 (0.1)	0.60 (0.2)	0.07 (0.1)

Table 3. Annual input–output balance of nutrients (kg ha^{-1}).

	N	P	Ca	K	Mg
Location 1, fluvic Cambisol					
Forest					
In: Rain	2.6	n.d.	6.3	18.0	0.1
Out: Leaching	5.0	n.d.	33.7	18.7	6.2
Balance	−2.4	0	−27.4	−0.7	−6.1
Agroforest					
In: Rain	2.6	n.d.	6.3	18.0	0.1
Out: Leaching	16.2	n.d.	74.3	20.4	12.3
Out: Harvest	57.0	9.1	12.2	41.8	6.4
Balance	−70.9	−9.1	−80.2	−44.2	−18.6
Maize					
In: Rain	2.6	n.d.	6.3	18.0	0.1
Out: Leaching	10.3	n.d.	26.0	10.0	6.3
Out: Harvest	38.0	5.9	0.4	13.8	2.2
Balance	−45.7	−5.9	−20.1	−5.8	−8.4
Location 2, dystric Cambisol					
Forest					
In: Rain	2.2	n.d.	5.6	8.5	1.2
Out: Leaching	1.2	n.d.	9.7	4.3	5.1
Balance	1.0	0	−4.1	4.2	−3.9
Maize					
In: Rain	2.2	n.d.	5.6	8.5	1.2
Out: Leaching	5.5	n.d.	8.4	3.6	2.8
Out: Harvest	44.0	12.7	0.5	19.7	4.1
Balance	−47.3	−12.7	−3.3	−14.8	−5.7

1). Leaching losses of N and K in forest were about four times higher in location 1 than in location 2, leaching losses of Ca were three times higher in location 1 compared to location 2 (Table 3). This was mainly due to lower nutrient concentrations in soil water of location 2 (Table 2). Concentrations of Al and P in soil water were below detection limit; therefore P balances in natural forest without harvest export were calculated as zero. Leaching losses in agroforestry were highest for N, Ca and Mg compared to forest and maize.

Harvest export of nutrients was higher in the agroforestry system for all elements compared to maize (Table 3 and Figure 2). Especially N, K, Mg and Ca exports were substantially higher in the agroforestry system. The high K-export was caused by the high potassium content of coffee beans, Ca-export by harvest was mainly caused by the shells of the Candle nuts and the coffee-harvest. Although dry weight of the maize harvest is similar in both locations, harvest export of P, K and Mg differed between the two locations, because the concentration of P, K and Mg in maize seeds was substantially higher in location 2 compared to location 1.

Maize yields were about 2.0 t ha^{-1} per harvest, and 4.0–4.3 t ha^{-1} per year (grain dry matter, Table 4). Although the dry weight biomass export was substantially higher in maize culture than in the agroforestry system, fresh weight biomass export was similar in both systems. This was caused by the higher water content of coffee beans, which was the major crop in the mixed agroforestry system in our study.

Nutrient balances

In general lowest net nutrient losses were found under forest, highest losses in agroforestry. Only Ca losses in maize were lower compared to the forest sites. In both agroforestry and maize, leaching was the major output pathway for Ca, and Mg ($>50\%$ of total losses). The main output pathway for N, P and K was harvest export. Annual net losses of total N, total P and exchangeable Ca in all agricultural systems were below 1% of total soil stocks of each element in 0–40 cm depth. In agroforestry of location 1, K losses were 8.8% and Mg losses were 1.3% of exchangeable stocks.

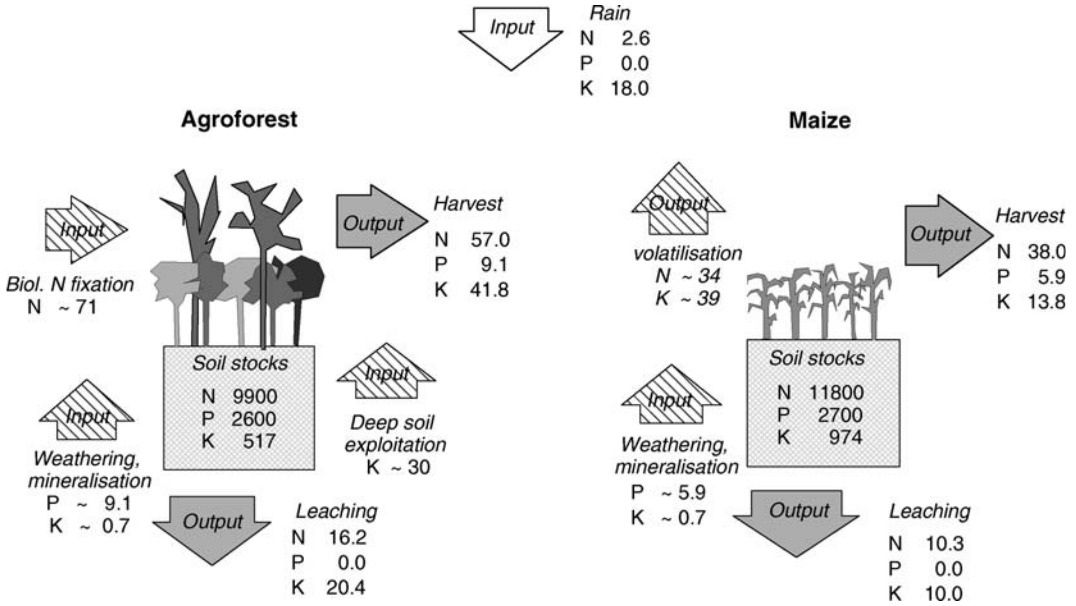

Figure 2. Nutrient balance of agroforestry and maize, location 1. Solid arrows indicate measured fluxes, hatched arrows indicate nutrient fluxes that were not measured, but estimated based on indirect evidence (see text). Soil stocks (0–40 cm, total N and P, exchangeable K) are in kg ha^{-1}, all fluxes in kg ha^{-1} a^{-1}.

Table 4. Removal of biomass by harvest, dry weight (DW), kg ha^{-1}.

	Location	Per harvest (kg ha^{-1} DW)	Per year (kg ha^{-1} DW)
Maize, total[1]	1	2010	4020
Maize seeds[1]	1	1660	3320
Cob-residue[1]	1	350	700
Maize, total	2	2130	4260
Maize seeds[1]	2	1720	3440
Cob-residue[1]	2	410	820
Agroforestry, total	1		2680
Coffee[2]	1		1140
Cacao[2]	1		540
Candle Nut[2]	1		900
Shells[2]	1		405
Kernels[2]	1		495

[1] Measured.
[2] Information provided by farmer.

K losses in maize of location 2 were 7.4% of exchangeable stocks (Table 5).

Discussion

Partial nutrient balances

Although nutrient losses in the natural forest systems were low compared to agricultural systems, the overall partial nutrient balance of the forest site in location 1 with more fertile soils was still negative. This is in contrast with other studies that also report net nutrient accumulation in rainforest systems, e.g. Forti and Moreira-Nordemann (1998), who report lower outputs of ions than inputs in watershed-scale on soils with low fertility in Amazonia. Other examples are studies by Lesack and Melack (1996) and Mackensen et al. (2003). Bruijnzeel (1991) also reported accumulation of P in most studies in tropical moist forests, whereas this study did not detect P-inputs by rain, and therefore our calculations resulted in unchanged P stocks in natural forest. However, these studies were all conducted on soils with a relatively low fertility. Given the high fertility of soils in location 1, it is not surprising that nutrient cycles were more open and natural forest sites lost nutrients. This has been shown before for nutrient balances of natural forests on relatively fertile soils (Vitousek and Sanford 1986). In our case study the natural forest site on poorer soils in location 2 (lower soil pH and lower base cation stocks) also showed lower nutrient losses, and even accumulation of N and K.

Partial nutrient balances in maize and agroforestry were negative for all major plant nutrients. The annual net nutrient losses that were calculated

Table 5. Annual losses (–) or gains (+) of nutrients, given as percentage of total soil stocks (N, P, Ca, K and Mg), and of exchangeable soil stocks (Ca, K and Mg), 0–40 cm depth.

Site	% of total stocks					% of exchangeable stocks		
	N	P	Ca	K	Mg	Ca	K	Mg
Location 1, fluvic Cambisol								
NF	–0.02	0.0	–0.2	0.0	–0.02	–0.1	–0.1	–0.4
AF	–0.7	–0.4	–0.6	–0.1	–0.1	–0.4	–8.8	–1.3
MF	–0.4	–0.2	–0.1	–0.02	–0.04	–0.1	–0.6	–0.2
Location 2, dystric Cambisol								
NF	+**0.01**	0.0	–0.1	+**0.7**	–0.1	–0.1	+**1.4**	–0.3
MF	–0.4	–0.3	–0.04	–4.9	–0.1	–0.04	–7.4	–0.4

in this study were much higher than the net nutrient losses reported for shifting cultivation systems on acidic weathered tropical soils in Brazil, reflecting the high native soil fertility in this study. Annual net nutrient losses in this study were between 25 and 100% of nutrient exports during complete rotation cycles (of 7–9 years) in the Eastern Amazon, which included fallow periods and regular burning of fallow vegetation (Hölscher et al. 1997; Sommer et al. 2004). Studies on different land use systems in Ethiopia showed similar or higher losses of N in annual crops compared to our results, but lower losses or even accumulation of P (Elias et al. 1998). It must be noted that in our research area no manure input occurred. Results of nutrient balance studies are often difficult to compare, because of different scales used (e.g. plot, farm, regional, or watershed scale). Additionally, different sets of input and output pathways are used, and some pathways are estimated, not measured. However, relative to the available (exchangeable) nutrient stocks, the high annual losses in this study on relatively fertile soils accounted only for small fractions. This emphasizes the importance of native soil fertility when comparing nutrient budgets between sites.

Only in location 1, nutrient loss of annual crops (maize) could be directly compared with the perennial (agroforestry) system. Surprisingly, higher nutrient losses were found in the agroforestry systems, not only because nutrient export in harvested products was higher, but also because leaching losses were higher. This is in contrast with the review by Schroth et al. (2001) who report that most studies found lower leaching of nutrients in multistrata perennial cropping systems compared to annual crops. We consider calculated drainage water of agricultural sites in this study a conservative estimate, because other studies report conversion of forest into agricultural land results in increase in water yield of around 200 mm a^{-1} compared to natural forest (Bruijnzeel 1990), due to reduced interception and transpiration. Additional water draining of this magnitude would increase leaching losses of nutrients by about 10–15%. Our results show higher drainage in location 2 compared to location 1, where precipitation is higher. We suggest that the reason for this are slightly lower average wind speed and global radiation in location 2.

Pathways of nutrient gain and loss in maize and agroforestry

Maize yields in this study (about 2 t maize ha^{-1} per harvest) were relatively high compared with published numbers for unfertilized systems. Hölscher (1997) measured maize yields of 0.6 t ha^{-1} (unfertilized) and 1.2 t ha^{-1} (NPK-fertilized) per harvest from field experiments in Amazonia. In our study, harvests were achieved after several years of continuous cultivation, and the owners of the plots reported even higher yields in the beginning of cultivation on these plots. Low yields were often blamed by the farmers on weed infestation or weather conditions rather than on soil fertility. This underlines the high native soil fertility in the research area. Nutrient exports of P, K and Mg in maize harvest differed between the two locations, even though dry weight harvest was similar. Soil total P stocks were much lower and pH was higher in maize of location 1 (pH 6.5) compared with location 2 (pH 4.6). We therefore assume that low supply is the reason for low P uptake by maize in location 1. However, harvest export of K and Mg were higher in location 2 although soil stocks were lower compared with location 1.

Although concentrations of N, Ca and K in rain water were mostly at the top of the range reported in literature (Brouwer 1996; Mackensen et al. 2003), nutrient input by rain replaced only a small fraction of nutrient losses in agricultural systems, except for K. At the forest sites, rain replaced N and K losses, especially on the poorer soils of location 2. The pH values were also significantly higher than literature values, whereas P and Mg were similar to the median of literature values (Bruijnzeel 1991; Brouwer 1996). Our rain samplers were permanently installed on open sites and we assume that these samplers also collected (at least partly) dry atmospheric deposition of nutrients, which may have contributed to the high K and Ca concentrations and pH in rain water. In the research area frequent and widespread slash-and-burn activity, rice straw fires, etc., release large amounts of ash into the air.

Missing nutrient pathways

The partial nutrient balance in agroforestry shows high net annual N losses of 71 kg ha^{-1}, in contrast with an ancillary chronosequence study in the same area (Dechert et al. 2004), where stable or slightly increasing soil C and N stocks were found during cultivation in agroforestry. We interpret this as indirect evidence of the effect of biological N-fixation by legume shade trees, which contributes N to the system. This was supported by an ancillary study of gross soil N transformations (Dechert et al. unpublished results): in agroforestry, rates of N mineralization and NH_4^+ uptake were higher and turnover of the NH_4^+ pool was much faster than in maize, indicating a sufficient N supply in agroforestry. Based on these results we suggest that that the partial nutrient balances that we measured miss some important nutrient pathways. We estimated these missing pathways by comparing the average annual nutrient losses in the ancillary chronosequence study with actual losses measured in our partial balances, and assumed that the missing pathways account for the difference. Obviously comparisons between general trends on regional scale and studies on plot scale must be treated with great caution, and the following numbers should be interpreted simply as range or magnitude for the missing pathways.

Biological N fixation in agroforestry systems with legume shade trees has been reported to be a major input pathway for N to land use systems, but the amount of N which is contributed to the system remains unclear. Assuming that agroforestry in this case study has stable N stocks (as was shown in the ancillary chronosequence study), and biological N fixation is the additional input which stabilizes soil N, it must contribute at least 71 kg N ha^{-1} annually (added as estimated flux in Figure 2). Other studies also have reported legume shade trees to supply similar amounts of N annually (up to 60 kg N ha^{-1}, Beer et al. 1998), and these inputs were exceeding annual harvest exports. Most studies state that the positive effect of the shade trees is not only biological N-fixation, but also organic matter input, control of water evaporation by shading and prevention of erosion (Fassbender 1998). This may explain the results in the chronosequence study of stable soil C stocks in agroforestry. In a landscape-scale study in Indonesia, increased soil C and aboveground C levels were found in shaded coffee plantations compared to sun exposed coffee without shade trees (Bruijnzeel 2002).

The chronosequence study of maize sites in the same area (Dechert et al. 2004) showed an annual decline of topsoil (0–10 cm) N stocks of 2%, which is about 80 kg ha^{-1} a^{-1} calculated for the N stocks of maize field in location 1. However, the partial nutrient balance in this case study results in an annual net loss of only about 46 kg ha^{-1}. This difference of net outputs suggests that in our plot scale study there are possibly additional N output pathways other than leaching and harvests (volatilization losses, denitrification) of about 34 kg N ha^{-1}, which we did not measure in the partial balance (added as estimated flux in Figure 2). Another explanation for the differences may be that N-losses in maize during the first years following clear cutting have probably been higher than in following years. The nutrient balances in our study represent results from only 1 year in a highly dynamic system, and nutrient balances on recently cleared sites probably differ from nutrient balances on sites which have been cultivated for several years.

Differences between nutrient losses in this case study on plot scale and in the chronosequence study on regional scale were also found for exchangeable K stocks. The chronosequence study (Dechert et al. 2004) showed an annual decline of exchangeable K in the topsoil by 14% in maize and 6.4% in agroforestry, which equals losses of about 45 kg ha^{-1} a^{-1} in maize and 14 kg ha^{-1} a^{-1} in agroforestry. However, the nutrient balance study in location 1 resulted in lower K losses in maize (6 kg ha^{-1} a^{-1}) and higher losses in agroforestry (44 kg ha^{-1} a^{-1}). These differences may be also caused by missing nutrient pathways (added in Figure 2 as estimated fluxes): in maize, volatilization of K by burning harvest residues and weeds may be an additional K-export pathway (estimated as 39 kg ha^{-1} a^{-1} in Figure 2), whereas in agroforestry, shade trees and crop plants can take up nutrients from deeper soil layers (estimated as 30 kg ha^{-1} a^{-1} in Figure 2), and topsoil changes of nutrient stocks alone may not be representative in agroforestry systems. Our approach to estimate missing nutrient pathways results in higher K- than N-volatilization, which is unlikely. These results underline the uncertainties of estimating nutrient pathways and the problem of applying data from studies of regional scale to plot scale.

Given the young age of the soils and the high content of primary minerals, we expect weathering of minerals to supply basic cations to the systems in our study area. Based on the assumption that natural forest vegetation is close to a steady state, we estimated weathering as input pathway of basic cations as being equal to net losses of basic cations under natural forest conditions (e.g. 0.7 kg ha^{-1} a^{-1} of K, Figure 2). Of all nutrients, only net K losses were a significant proportion of exchangeable K stocks, and for K a large non-exchangeable pool remains. In the case of soils in Central Sulawesi, these total stocks may replace losses, as long as export fluxes are not larger than import fluxes.

In both maize and agroforestry P was lost through crop harvest, but no imports were measured and total P stocks did not change significantly in the chronosequence study. We suggest that total P stocks are too large in relation to net losses to detect the decline of stocks. In Figure 2 we assume that mineralization replaces P losses (estimated input equal to harvest loss, Figure 2).

Conclusion

This study highlights the problems with commonly used partial nutrient balances as indicators of sustainability. Balanced nutrient in- and outputs are crucial for long term sustainability of agricultural land use systems. However, nutrient balance studies have so far mainly focused on nutrient pathways which are relatively easy to measure, and these may not be sufficient to evaluate sustainability. These missing nutrient pathways may be critical to understand the observed nutrient losses. Three of the pathways which are almost never measured because of methodological problems are biological N-fixation, deep soil root exploitation, and mineral weathering. Nutrient balances therefore should never be compared directly, but always in the context of site differences, site age, and potentially missing pathways. In our case study the ancillary chronosequence study in the same region made clear that a considerable N source (presumably N-fixation) must compensate the high N-losses measured in agroforestry. Losses of base cations in the forest sites (which is very unusual), together with the high base saturation of the soils, indicate that base cations were not critical nutrients.

Our conclusion is that overall the observed nutrient losses depended more on site conditions than on land use. High fertility of soils in Central Sulawesi creates good conditions for permanent agriculture. The only element that can become critical in time is N, as it is not released during weathering. Management should therefore be directed at maintaining nitrogen levels. As this is done in agroforestry with legume shade trees, this land use system is sustainable from a soil nutrient perspective. In time, permanent maize cultivation cannot be continued without external N inputs and management of soil organic matter.

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References

Bationo A., Lompo F. and Koala S. 1998. Research on nutrient flows and balances in West Africa: state of the art. Agric. Ecosyst. Environ. 71: 19–35.

Beer J., Muschler R., Kass D. and Somarriba E. 1998. Shade management in coffee and cacao plantations. Agroforest. Syst. 38: 139–164.

Brouwer L. 1996. Nutrient cycling in pristine and logged tropical rain forest – a study in Guyana. Tropenbos Guyana Series 1, pp. 42–51.

Bruijnzeel L.A. 1990. Hydrology of moist tropical forests and effects of conversion: a state of knowledge review. UNESCO, Publication of the Humid Tropics Programme. University of Amsterdam, Institute of Earth Science, Amsterdam, Netherlands, pp. 79–100.

Bruijnzeel L.A. 1991. Nutrient input–output budgets of tropical forest ecosystems: a review. J. Trop. Ecol. 7: 1–24.

Bruijnzeel L.A. 1995. Predicting the hydrological impacts of land cover transformation in the humid tropics, the need for integrated research. In: Gash H., Nobre C., Roberts J. and Victoria R. (eds), Amazonian Deforestation and Climate. J. Wiley, New York, pp. 15–56.

Bruijnzeel L.A. October 2002. Carbon stock assessment for a forest-to-coffee conversion landscape in Sumber-Jaya (Lampung, Indonesia): from allometric equations to land use change analysis. Sci. China, Ser. C: Life Sci. 45(suppl.): 75–86.

Dechert G., Veldkamp E. and Anas I. 2004. Is soil degradation unrelated to deforestation? Examining soil parameters of land use systems in upland Central Sulawesi, Indonesia. Plant Soil 265: 197–209.

Elias E., Morse S. and Belshaw D. 1998. Nitrogen and phosphorus balances of Kindo Koisha farms in southern Ethiopia. Agric. Ecosyst. Environ. 71: 93–113.

Engel Th. and Priesack E. 1993. Expert-N, a building-block system of nitrogen models as resource for advice, research, water management and policy. In: Eijsackers H.J.P. and Hamers T. (eds), Integrated Soil and Sediment Research: A Basis for Proper Protection. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 503–507.

FAO 1998. World reference for soil resources. World Soil Resources Reports 84. FAO, Rome.

Fassbender H. 1998. Long term studies of soil fertility in cacao-shade trees agroforestry systems: results of 15 years of organic matter and nutrient research in Costa Rica. In: Schulte A. and Ruhiyat D. (eds), Soils of Tropical Forest Ecosystems. Springer-Verlag, Berlin, Heidelberg, New York, pp. 150–158.

Forti C. and Moreira-Nordemann L. 1998. An ion budget for a terra firma rainforest in Central Amazonia. In: Braga B. and Fernandez-Jauregani C. (eds), Water Management of the Amazon Basin. UNESCO, Paris.

Heinrichs H. 1989. Aufschlussverfahren in der analytischen Geochemie (1). Labor Praxis 12: 1140–1146.

Hölscher D., Möller R., Denich M. and Fölster H. 1997. Nutrient input–output budget of shifting agriculture in Eastern Amazonia. Nutr. Cycl. Agroecosyst. 47: 49–57.

Klinge R., Martins A., Mackensen J. and Fölster H. 2004. Element loss on rain forest conversion in East Amazonia: comparison of balances of stores and fluxes. Biogeochemistry 69(1): 63–82.

Lesack L. and Melack J. 1996. Mass balance of major solutes in a rainforest catchment in the Central Amazon: implications for nutrient budgets in tropical rainforests. Biogeochemistry 32: 115–142.

Mackensen J., Klinge R., Ruhiyat D. and Fölster H. 2003. Assessment of management-dependent nutrient losses in tropical industrial tree plantations. Ambio 32(2): 106–112.

Meiwes K.-J., König N., Khanna P.K., Prenzel J. and und Ulrich B. 1984. Chemische Untersuchungsmethoden für Mineralböden. Ber. Forschungszentrums Waldökosyst. 7: 1–67.

Nye P. and Greenland D. 1965. The soil under shifting cultivation. Technical Communication 51. Commonwealth Bureau of Soils, Harpenden, UK.

Schroth G., Lehmann J., Rodrigues M., Barros E. and Macedo J. 2001. Plant-soil interactions in multistrata agroforestry in the humid tropics. Agrofor. Syst. 53: 85–102.

Sommer R., Vlek P., Sa T., Vielhauer K., Coelho R. and Fölster H. 2004. Nutrient balances by burning or mulching in the Eastern Amazon. Evidence for subsoil nutrient accumulation. Nutr. Cycl. Agroecosyst. 68(3): 257–271.

Van Rheenen T., Elbel C., Schwarze S., Nuryartono N. and Zeller M. 2004. Encroachments into Primary Forests: are they really driven by despair. Land Use, Nature Conservation and the Stability of Rainforest Margins in Southeast Asia. Springer, Berlin, pp. 199–214.

Vitousek P. and Sanford R. 1986. Nutrient cycling in moist tropical forest. Ann. Rev. Ecol. Syst. 17: 137–167.