Deutscher Tropentag 2003
Göttingen, October 8-10, 2003
Conference on International Agricultural Research for Development

Changes of soil properties and input-output balance of nutrients in land-use systems following rain forest conversion in Central Sulawesi, Indonesia

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Abstract

Indonesia has nearly 50% of Asia's and 10% of the worlds remaining tropical rainforest, but deforestation rates are among the highest worldwide and rainforest area is declining rapidly (FAO 2001). The most important factor for deforestation is agriculture. We wanted to study the sustainability of land-use systems in conversion areas in respect to soil fertility. We studied maize- and cacao/coffee-agroforests, which are the main non-irrigated land-use systems of the upland rainforest margin areas in Central Sulawesi.
The study objective of this study were:

- To quantify changes of soil properties under maize cultivation and agroforestry compared to natural forest and to measure the effect of the duration of cultivation (chronosequence).
- To measure the input-output balance of nutrients in maize and agroforestry compared to natural forest.

Soils were generally fertile, with high base cation saturation, cation exchange capacity and pH-values. Carbon and nitrogen-stocks were highest in natural forest and lower in maize and agroforestry. In maize both C and N decreased with time, whereas in agroforestry they increased slightly. Maize fields had lost on average approximately 25% of the below-ground C-pool compared to natural forest. Soil bulk density was highest in agroforestry, in maize an increase was observed in time and in agroforestry it remained stable on a high level. In both managed systems Ca-saturation of CEC increased and K-saturation decreased during cultivation.
We measured nutrient-input by precipitation, and output by leaching and harvest export on unfertilized maize- and agroforestry-sites. We found low nutrient input through rain, only potassium was imported in considerable amounts. Exports of Mg, Ca was mainly by leaching, whereas N and K was exported mainly by removal of crop harvest. Highest nutrient exports were found in the agroforestry system, maize was intermediate and lowest were found in the forest sites. All systems, including the forest sites, had negative balance of macronutrients, indicating open nutrient cycles on these soils even in natural forests.

Introduction

The uplands of Central Sulwesi have been subject to widespread clear cutting of natural rainforest, mainly by smallholder farmers. The rate of annually cleared land has increased significantly in the last 5 years (Van Rheenen et al. 2003). Main land use systems on converted sites are cacao-coffee agroforestry and maize.

To investigate the causes and driving factors of rainforest conversion, Central Sulawesi uplands were selected as research region for a multidisciplinary research project, "Stability of rainforest margins in Indonesia" (STORMA) (see www.storma.de). This project was founded by the Universities of Göttingen and Kassel-Witzenhausen, in co-operation with the Institut Pertanian Bogor (IPB), and Universitas Tadulako, Palu, Sulawesi. The project was funded by the DFG (Deutsche Forschungsgemeinschaft). Both sociological, economical, agricultural and ethnological driving factors of rainforest conversion as well as biological and hydrological consequences of rainforest clearing were studied. The present study was subproject D4 within the frame of STORMA aimed at investigating the effects of rainforest conversion and agriculture on soil fertility.

The overall goal of this study was to test the hypothesis that declining soil fertility causes further deforestation because of declining harvest yields, forcing farmers to clear new land for agriculture. Furthermore this study was aimed at evaluating which major agricultural land use systems in forest margins is more suitable in terms of nutrient sustainability. Effects of deforestation on soil parameters and nutrient stocks were studied. Additionally, nutrient balances in two major land use systems were measured and compared with natural forest as reference.

Two approaches were used to study these objectives, therefore the study was devided in two parts. A survey on a regional scale was used to study long term effects of deforestation on soil parameters. Effects of continuous cultivation were studied with the chronosequence approach. Nutrient input-output balances on plot scale were used to evaluate nutrient sustainability of land use systems.

Part 1: Effects of deforestation were studied by sampling 74 sites during a soil survey of different land use systems and comparing the results with natural forest sites. The selected land use systems were agroforestry, maize, forest fallow, grass fallow, and natural forest as undisturbed reference. Samples were analysed for soil parameters (pH, bulk density, ECEC, and base saturation) and macronutrient stocks. For each agricultural site, data on the duration of cultivation was collected. This enabled to study effects of continuous agriculture on soil parameters in a chronosequence (false time series).

Part 2: In this part of the study nutrient input and output balances were measured on plot scale. Nutrient inputs by rain and outputs by harvest export and leaching were measured in a case study in agroforestry, maize and as a reference in undisturbed natural forest. The objective was to investigate which land use system has higher nutrient losses, and which input or output pathway is important for plant macronutrients.

Materials and methods

Part 1:

Sampling sites were identified and sampled in the period from April-September 2001. In five villages (Wuasa, Wanga, Nopu, Lempelero and Rompo) and their surrounding area a total of 74 sites were sampled. All these villages were situated around the Lore Lindu Nation Park in Central Sulawesi, Indonesia. Sites of five major land use systems were selected and sampled: maize, cocoa and/or coffee agroforestry, forest fallow, grass-fallow and natural forest as reference sites for the undisturbed situation. All sites were visited together with the owner of the plot, and the owner was interviewed on site about the age of the site since clear cutting, management practice, and previous crops. Sites which had received fertiliser input in the last 5 years were excluded from the survey.

From each site fifteen soil samples were taken with an auger at randomly chosen points from fixed depths (0-0.1 m and 0.3-0.4 m). Sub-samples of five sampling points were mixed to form three composite samples per site to reduce small scale variation within the sites. Soil was weighed and dried at 45 °C within 1-2 days and passed through a 2 mm sieve. In addition, bulk density was sampled on each site for both depths (0-0.1m and 0.3-0.4 m) using three 100 cm^3 steel cylinders per site. Bulk density samples were transported in plastic bags and dried in the laboratory at 105 °C in paper bags and weighed.

All soil samples were analysed for total carbon and nitrogen, total P, exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+, Al^{3+}) and total Ca, Mg, K, Na and Al. The air-dried and sieved soil samples were ground to powder using a ball mill. Effective cation exchange capacity (ECEC) was calculated from exchangeable cations at field pH.

Nutrient stocks were calculated using bulk density data and nutrient concentrations. Because of the large variation in soil characteristics, differences between soil parameters can also be caused by soil type, slope, elevation etc. To avoid this not only nutrient concentrations and stocks were analysed, but natural forest was also used as reference and relative differences of land use type compared to forest were calculated.

For each variable normal distribution was tested ($P < 0.1$, Shapiro-Wilks W-test). Analysis of variance (one-way ANOVA and Tukey’s means separation) was used to test for significant effects of soil type, land use system and length of cultivation on soil properties. Pearson’s product moment correlation coefficients were calculated to relate duration of cultivation with soil characteristics in maize and agroforestry systems. Data were analysed using STATISTICA 6.0.

Part 2:

Two locations were selected which had different land use systems close to each other on relatively homogenous soil. Location 1 with forest, agroforest and maize was on deep, alluvial sediments with sandy loam texture (fluvic cambisol, FAO, 1998a), location 2 with forest and maize was on deeply weathered phyllite as parent material and a clay texture, soil type was dystric cambisol. 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 x 75 m, the agroforestry plot was 50 m x 80 m, and the maize plot in location 2 was 50 m x 50 m. Planting density of maize was about 40,000-50,000 plants per hectare. The agroforestry site was a mixed stand of cocoa (40 %), coffee (60 %) and shade trees (*Erythrina fusca* and *Gliricidia sepium*). Cocoa and coffee was planted approximately at 2 x 2 m spacing (about 2000-3000 plants per hectare), and shade trees at about 5 x 5 m. 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 fertiliser or manure on the research sites. Forest sites were studied as reference representing the undisturbed situation.

On all sites of location 1 and the maize site of location 2 a total of 16 lysimeters (plastic pipes 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 8 lysimeters were installed. It was assumed that soil water samples from this depth were taken below the main rooting zone. Four lysimeters were placed at the corners of a square of approximately 1m^2; two lysimeters each were connected to one brown 0.5L glass bottle to collect the soil water, so that 8 bottles per site were collecting soil water samples. At both locations a set of 5 rain water samplers were installed on open areas 2 m above ground level. Soil and rain water samples were taken weekly and brought to the laboratory and were stored frozen within 24 hours after collection. Analysis of the soil water and rain water samples was conducted at the laboratory unit at Tadulako University, Palu. Samples were analysed for pH, total N, K, Mg, Na and Ca, using ICP-OEC. Values for Al and P were below detection limit.

A simple water balance was calculated with climatic data obtained from climatic stations closest to the experimental site to estimate leaching from the soil profile. Potential evapotranspiration was calculated with the Penman-Monteith formula on a daily basis following procedures given by FAO (1998b). FAO's standard calibration values were used for a reference crop (watered grass, 12 cm height) which is recommended by FAO (1998b) as it has shown to be representative of a wide range of climatic and vegetational situations and enables comparisons with other studies.

From daily means weekly sums were calculated of both precipitation and evapotranspiration. Weekly evapotranspiration was subtracted from the weekly rainfall and excess rainfall was assumed to percolate the soil and leave the system. Leaching of nutrients per area was calculated from data of nutrient concentration in soil water and the amount of water leaching per week. For months without concentration data mean concentration data were used from the period which was sampled. Nutrient fluxes were calculated as kg ha^{-1} a^{-1}.

Calculated leaching losses must be regarded cautiously in absence of reliable data for actual ET for each land use system separately. It also must be noted that nutrient balances in agroforestry sites may vary depending on proportions of coffee and cocoa, and planting densities. These parameters varied across the research region.

On the maize and agroforestry sites nutrient export through harvest was measured. Maize harvest were estimated by harvesting 5 replicates of 4 m^2 subplots, drying of the maize-cobs for 24 hours at 105°C and calculating the total harvest of maize cobs dry matter per site. The harvest was analysed for concentrations of macronutrients N, C, Mg, Ca, K and Na. 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 conservatively. 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 continuing process with harvests of coffee or cocoa weekly or bi-weekly. Samples of the coffee- or cocoa fruits were taken regularily and analysed for nutrient concentrations. Total export was estimated by interviewing the farmer every week about the harvest (in kg) of the week before.

Results

Part 1:
If non-standardised data were compared to natural forest in topsoil only bulk density, base saturation and Ca-saturation of ECEC was higher in converted sites, all other parameters were lower in managed or fallow systems compared to natural forest (Table 1). Statistically significant differences were found in topsoil C and N stocks, which were statistically significantly lower in agroforestry and maize compared to natural forest (one way ANOVA, $P \leq 0.05$), grass fallow was similar to maize and forest fallow intermediate between natural forest and cultivated sites. ECEC decreased from natural forest > forest fallow > agroforestry and maize > grass fallow. Grass fallow had lower pH, topsoil ECEC, C and N stocks compared to all other land-use systems. Increase of topsoil P stocks in converted systems was not significant. In the subsoil ECEC was higher in converted sites than in natural forest (Table 1).

If data were standardised with forest as reference, Carbon- and Nitrogen concentrations and stocks in topsoil were lower in converted sites. The losses of C -stocks after rain forest conversion to agroforestry and maize were 19 % for both land uses in 0-10 cm and 6 % and 10 % in 30-40 cm, respectively. Losses of N-stocks after conversion to agroforestry and maize were 20 % and 21 % in 0-10 cm depth and 10 % and 19 % in 30-40 cm depth, respectively. Decreases in concentrations of C after conversion to maize and agroforestry were as high as 29 % and 26 % in 0-10 cm and 7 % and 8 % in 30-40 cm depth. Soil N concentrations decreased after conversion to agroforestry and maize by 30 % and 28 % in 0-10 cm depth and by 12 % and 16 % in 30-40 cm depth, respectively. In 30-40 cm depth C and N decreased less in the cultivated systems and were similar to natural forest in forest fallow and grass fallow. Topsoil bulk density in all land-use systems was higher than natural forest; highest values were found in agroforestry followed by maize

If soil parameters of agroforestry- or maize-sites were correlated with duration of cultivation, in topsoil (0-10 cm) carbon- and nitrogen-stocks decreased in maize during time ($P = 0.02$ and 0.04, respectively) and showed no significant change with age in agroforestry ($P = 0.45$ and 0.53, respectively, Table 9). Bulk density increased significantly with age in maize ($P = 0.03$), but did not change in agroforestry ($P = 0.57$). ECEC increased during cultivation in agroforestry, but showed no clear trend in maize ($P = 0.04$ and 0.07, respectively, Table 9). Potassium saturation of ECEC decreased strongly in maize fields during cultivation from high values ($P = 0.004$). In agroforestry no changes were observed in the false time series. Changes of total P stocks in time were not significant in both land use systems. Results from subsoil (30-40 cm) showed generally smaller and non-significant changes of soil parameters after conversion of forest than in topsoil, except for Ca-saturation of ECEC, which in both agroforestry and maize increased after conversion in 30-40 cm depth ($P = 0.003$ and 0.02, respectively, Table 9).

Table 1. Nutrient stocks, pH, bulk density and ECEC in different land use systems, all sites (mean and standard error, different letters indicate statistically significant differences between land use systems, ANOVA, Tukey's Means Comparison, $P < 0.05$)

	C	N	Bulk density	ECEC	pH
	-------- Mg ha^{-1}	---------	g cm^{-3}	mmol kg^{-1}	KCl
			0-10 cm		
Natural forest	41.9 (4.6) a	3.5 (0.3) a	1.0 (0.04) a	187.2 (20.0) a	5.1 (0.2)
Forest fallow	34.4 (2.6) a	3.1 (0.2) a	1.1 (0.03) a	187.7 (20.8) a	5.2 (0.2)
Agroforest	29.2 (2.2) b	2.7 (0.2) a	1.2 (0.04) b	146.6 (15.7) ab	5.0 (0.1)
Maize field	30.5 (1.5) b	2.7 (0.1) b	1.1 (0.03) b	151.4 (14.6) ab	5.1 (0.1)
Grass fallow	32.6 (3.0) a	2.5 (0.2) a	1.0 (0.04) a	80.9 (16.1) b	4.2 (0.1)
			30-40 cm		
Natural forest	13.8 (1.7)	1.3 (0.1)	1.3 (0.04)	75.8 (8.2)	4.1 (0.1)
Forest fallow	12.7 (1.4)	1.3 (0.2)	1.3 (0.05)	91.9 (9.7)	4.2 (0.2)
Agroforest	11.0 (0.7)	1.1 (0.1)	1.3 (0.03)	90.8 (9.6)	4.3 (0.1)
Maize field	10.6 (0.7)	1.0 (0.1)	1.3 (0.02)	78.9 (6.6)	4.2 (0.1)
Grass fallow	15.4 (2.6)	1.3 (0.2)	1.3 (0.04)	66.3 (15.7)	4.1 (0.1)

Table 2. Pearson's correlations coefficients between soil nutrient stocks, nutrient concentrations, Ca, K and Mg saturation of ECEC, pH, BD, BS and ECEC (standardised values) with duration of cultivation in maize and agroforestry sites (r = correlation coefficient and P = significance level)

	0-10 cm depth				30-40 cm depth			
	Agroforestry		Maize		Agroforestry		Maize	
	r	P	r	P	r	P	r	P
C stocks	0.21	0.45	**-0.44**	**0.02**	-0.11	0.71	-0.22	0.26
C %	0.27	0.33	**-0.47**	**0.01**	-0.06	0.85	-0.24	0.23
N stocks	0.17	0.53	-0.28	0.15	-0.03	0.92	0.01	0.96
N %	0.25	0.36	**-0.38**	**0.04**	0.03	0.91	-0.01	0.96
P stocks	0.12	0.68	0.36	0.06	0.18	0.55	0.33	0.08
pH KCl	-0.43	0.11	-0.11	0.56	0.46	0.10	0.31	0.12
ECEC	0.52	0.04	-0.05	0.76	0.03	0.93	-0.05	0.81
Ca	0.08	0.77	0.05	0.78	**0.61**	**0.02**	**0.55**	**0.003**
K	-0.33	0.22	**-0.52**	**0.004**	-0.11	0.71	-0.12	0.54
Mg	0.08	0.77	0.05	0.79	0.16	0.59	-0.10	0.60
BS	0.28	0.31	0.00	0.99	0.39	0.17	0.35	0.07
BD	-0.16	0.57	**0.42**	**0.03**	-0.13	0.67	0.18	0.37

Part 2:

The wet season was between May and June, and the dry season from July until October (Table 6). In three months (March-May) 46 % of annual precipitation was measured. Evapotranspiration was 65 % of annual precipitation. Water balance calculations (P-ET) showed highest perkolation of water from March until end of May. During this time about 85 % of the annual amount of leaching was calculated. During July and August calculations of weekly water balance resulted often in evapotranspiration exceeding precipitation.

Input of nutrients by rain differed between both locations, mainly due to different concentrations in rain water. N and K inputs were about 50 % lower in location 2 compared to location 1. In both agricultural systems N, Ca and Mg inputs by rain were insignificant compared to leaching and harvest exports. However, precipitation replaced 54% of K in maize of location 1 and 32 % of K in maize of location 2, and 19 % of K losses in agroforestry. In natural forest, rain replaced 32 and 70 % of N leaching losses, respectively.

In general, leaching losses on less fertile soils on weathered phyllite (location 2) were considerably lower than on more fertile alluvial soils (location 1). Leaching losses of N in forest were four times higher in location 1 than in location 2, leaching losses of Ca and K were even six times higher in location 1 compared to location 2. This was mainly due to lower nutrient concentrations in soil water. It seems that differences in leaching losses depended more on soil type than on land use type. Nitrogen was the only notable exception. Concentrations of Al and P in soil and rain water were below detection limit; therefore P balances in natural forest without harvest export were calculated as zero. In agroforestry, leaching losses were highest for N, Ca and Mg compared to forest and maize (Table 4).

Harvest export of nutrients was higher in the agroforestry system for all elements compared to maize. Especially exports of N, K, Mg and Ca were substantially higher in the agroforestry system. K-export was cause by the high potassium content of coffee beans, Ca-export was mainly caused by the shells of the Candle nuts and with 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 (Table 4).

Nutrient losses under forest were lower than maize and agroforestry except for Ca and Na. In location 1 forest had highest Na losses of all three land use systems. In both agroforestry and maize, leaching was the major output pathway for Ca, Na and Mg (> 50 % of total losses). The main output pathway for N, P and K was harvest.

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 and Mg losses were 14.3 % and 4.5 % of exchangeable stocks, respectively. K losses in maize of location 2 were 7.8 % of exchangeable stocks (Table 7).

Table 3. Soil texture (0-10 cm depth), C, N and P stocks (0-40 cm depth) and soil chemical parameters (0-10 cm depth) of the research sites (NF = natural forest, AF = agroforestry, MF = maize field)

Site	Clay	Sand	Silt	C	N	P	BS	ECEC	pH
		%		Mg ha^{-1}, 0-40 cm			%	mmol kg^{-1}	KCl
Location 1, fluvic cambisol									
NF	22.8	51.3	25.9	109.0	10.6	2.9	98.9	220	5.8
AF	18.0	58.1	24.0	97.4	9.9	2.6	99.4	181	5.7
MF	15.2	45.2	39.6	134.6	11.8	2.7	99.6	332	6.5
Location 2, dystric cambisol									
NF	59.6	13.6	26.8	134.8	9.3	2.1	76.7	96	4.4
MF	63.0	8.5	28.3	134.4	11.0	4.6	85.9	122	4.6

Table 4. Annual input-output balance of nutrients (kg ha^{-1})

	N	P	Ca	K	Mg	Na
Forest, loc. 1						
In: Rain	2.7	n. d.	7.6	20.6	0.2	7.2
Out: Leaching	8.5	n. d.	62.7	36.3	12.6	27.9
Balance	**-5.8**	**0**	**-55.1**	**-15.7**	**-12.4**	**-20.7**
Forest, loc. 2						
In: Rain	1.4	n. d.	4.4	10.1	0.7	6.2
Out: Leaching	2	n. d.	10.6	5.1	5.5	8.2
Balance	**-0.6**	**0**	**-6.2**	**5.0**	**-4.8**	**-2**
Agroforest, loc. 1						
In: Rain	2.7	0	7.6	20.6	0.2	7.2
Out: Leaching	19.6	0	133.6	34.8	23.5	13.1
Out: Harvest	57.0	9.1	12.2	41.8	6.4	0
Balance	**-73.9**	**-9.1**	**-138.2**	**-56.0**	**-29.7**	**-5.9**
Maize, loc. 1						
In: Rain	2.7	n. d.	7.6	20.6	0.2	7.2
Out: Leaching	19.3	n. d.	51	19.3	12.2	17.6
Out: Harvest	38.0	5.9	0.4	13.8	2.2	0
Balance	**-54.6**	**-5.9**	**-43.8**	**-12.5**	**-14.2**	**-10.4**
Maize, loc. 2						
In: Rain	1.4	n. d.	4.4	10.1	0.7	6.2
Out: Leaching	4.8	n. d.	7.9	4.6	2.4	8.9
Out: Harvest	44.0	12.7	0.5	19.7	4.1	0
Balance	**-47.4**	**-12.7**	**-4.0**	**-14.2**	**-5.8**	**-2.7**

Table 5. Removal of biomass by harvest, fresh weight (FW) and dry weight (DW), kg ha^{-1} (^{1} = measured, ^{2} = information provided by farmer)

Location		per harvest (kg ha^{-1}) DW	per year (kg ha^{-1}) DW
1	Maize^1	2010	4020
2	Maize^1	2130	4260
1	Agroforestry, total:		2680
1	Coffee ^{2}		1140
1	Cocoa ^{2}		540
1	Candle Nut ^{2}		900

Table 6. Climatic data and water balance, December 01-December 02, (T= temperature, P= precipitation, ET= Evapotranspiration, R = global radiation), annual sums (P, ET, P-ET) and annual means of daily means (P, ET, rel. hum., windspeed, R, cloudiness).

	T °C	rel. hum %	P mm d^{-1}	P mm a^{-1}	ET mm d^{-1}	ET mm a^{-1}	wind m s^{-1}	R Mj m^2 d^{-1}	P-ET mm a^{-1}	cloud. %
Loc. 1	21.1	81.4	4.2	1525	2.7	985	1.0	18.3	540	62
Loc. 2	21.4	80.2	3.9	1427	2.7	1002	1.0	18.2	425	62

Table 7. Annual losses (-) or gains (+) of nutrients (percentage of soil stocks of total N, total P, total Ca, K and Mg, and exchangeable Ca, K and Mg, 0-40 cm depth)

Site	% of total stocks					% of exchangeable stocks		
	N	P	Ca	K	Mg	Ca	K	Mg
NF 1	- 0.1	- 0.0	- 0.4	- 0.04	- 0.1	0.5	- 2.9	1.6
AF 1	- 1.0	- 0.5	- 1.1	- 0.2	- 0.1	0.3	- 14.3	4.5
MF 1	- 0.5	- 0.2	- 0.2	- 0.04	- 0.1	1.4	- 1.3	1.3
NF 2	- 0.01	- 0.0	- 0.1	+ 0.9	- 0.1	0.2	+ 2.0	0.6
MF 2	- 0.4	- 0.3	- 0.1	- 4.3	- 0.1	0.1	- 7.8	0.7

Discussion

Part 1:

Results from the first part of the study showed that soils in the research area are generally fertile, with medium to high pH, high base cation saturation, and large stocks of total C and N. As expected from previous studies (Schlesinger 1986, Davidson et al. 1993, Guo and Gifford 2002), conversion of rainforest resulted in significantly lower total C and N stocks in maize and agroforestry. However, significant differences were found between maize and agroforestry during continuous cultivation in a chronosequence (false time series). During maize cultivation C and N stocks declined significantly, whereas in agroforestry C and N stocks stayed stable, with a tendency to increase. Farmers usually switched from maize cultivation to agroforestry a few years after conversion of a forest site. This may be an adaptation to reduced N-supply of maize sites after some years of continuous cultivation.

Only few sites with low native soil fertility were found. These sites were regularly burnt grasslands (some, but not all dominated by *Imperata cyclindrica*), mostly on dystric cambisols. These soils had low pH values, low base cation saturation, and higher Al-saturation of ECEC. These grasslands were generally not used for agriculture, but it is unclear if these sites were the result of past cultivation periods or if they had developed naturally.

No evidence was found that forest conversion has negative effects on base cation stocks or base cation saturation. Ca-saturation of ECEC even increased in 30-40 cm depth in converted sites. The case study of nutrient input and output balances showed that in agroforestry and maize annual losses of Mg and Ca were only small percentages of available soil stocks in the 0-40 cm soil profile. The only exception was K, where annual net losses were about 15 % in agroforestry and 1 % to 8 % in maize of exchangeable K stocks in 0-40 cm depth. Consequently, declines of exchangeable K during cultivation were found in the chronosequence in both agroforestry and maize, but only the latter was statistically significant. However, non-exchangeable stocks of base cations are high, and weathering of minerals on these geologically young soils is hypothesised to replaces base cation losses.

These results indicate that forest conversion in uplands of Central Sulawesi is not driven by declining soil fertility. Sites under cultivation do not show signs of serious degradation. Soil parameters stay stable in agroforestry, and farmers switch from (unsustainable) maize cultivation to agroforestry after some years of harvesting maize. Degraded areas are very rare, there are still relatively large uncultivated areas outside of the forest which could be used.

Furthermore, this study shows that stability of rainforest margins does not nescessarily increase when soils are fertile and land use is sustainable. Farmers may be encouraged to invest into new cropland if rentability is high, and additional farmers may be attracted into apparently fertile areas from other parts of the country. Both factors lead to intensified deforestation. Therefore the hypothesis of declining soil fertility driving forest conversion in Central Sulawesi is rejected.

Part 2:

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 nutrient sustainability. Results of the second part of this study show that other nutrient pathways may be critical to evaluate nutrient sustainability. Future research must focus on studying nutrient pathways which have not yet been sufficiently quantified, e.g. biological N fixing and mineral weathering, to increase significance of nutrient balance studies (Figure 1).

Partial nutrient balances used in this study resulted in higher N losses in the agroforestry system compared to maize. However, the chronosequence study did not show decline of soil N during cultivation in the agroforestry system. This shows that these agroforestry systems combine high outputs and productivity with high N inputs. Our results suggest that N_2- fixing legume shade trees in the agroforestry system contribute N to the system by prunings and litterfall, balancing the annual net losses of N, whereas unfertilised maize cultivation is mining on soil N stocks, which developed under natural forest conditions. To stabilize soil N stocks in the agroforestry system in this case study, biological N fixation must contribute at least about 74 kg N ha^{-1} annually (e. g. N input by legumes: Beer et al. 1998, Fassbender 1998). In maize sites results of the chronosequence study showed an annual decline of topsoil N stocks of 2 %, which is about 80 kg ha^{-1} a^{-1} in the case of the maize field of location 1. However, results of the partial nutrient balance showed only a annual loss of about 55 ha^{-1}. This suggests that there are possibly also additional N output pathways (volatilisation losses, denitrification), which were not measured in the partial nutrient balance (Figure 1). Also N-losses during the first year following clear cutting have probably been higher than in following years.

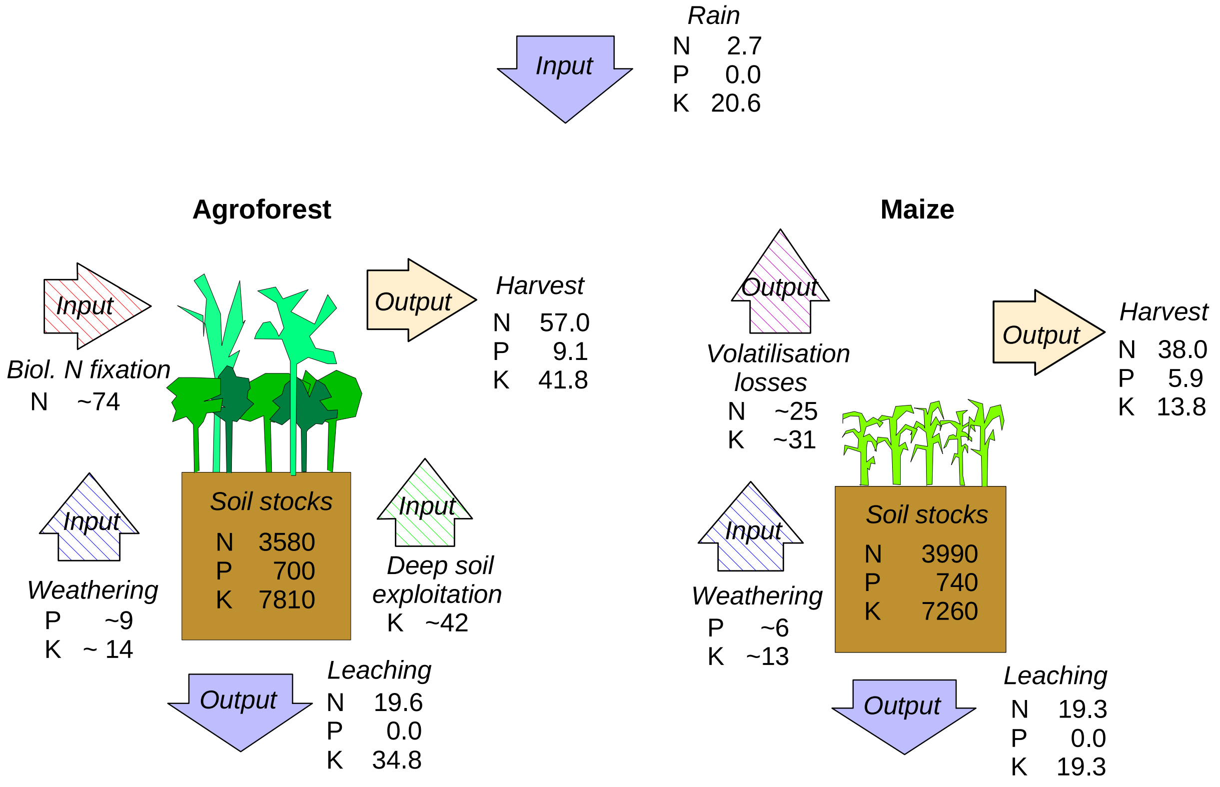

Figure 1. Nutrient balance of agroforestry and maize, location 1. Solid arrows indicate measured fluxes, hatched arrows indicate nutrient fluxes that were not measured, but estimated based on indirect evidence (see text). Soil stocks are in kg ha^{-1}, all fluxes in kg ha^{-1} a^{-1}.

Results from the chronosequence study show annual decline of exchangeable K in the topsoil by 14 % in maize and 6.4 % in agroforestry, this equals losses of about 45 kg ha^{-1} a^{-1} in maize and 14 kg ha^{-1} a^{-1} in agroforestry of location 1. However, partial nutrient balances in this location result in lower K losses in maize (13 kg ha^{-1} a^{-1}) and higher losses in agroforestry (56 kg ha^{-1} a^{-1}). This also may be caused by missing nutrient pathways in the partial balance. In maize, volatilisation of K by burning harvest residues may be an additional K-export pathway, whereas in agroforestry crop plants can take up nutrients from deeper soil layers, and topsoil changes of nutrient stocks my not be representative (Figure 1).

Contrary to other studies (Schroth et al. 2001), results showed larger losses through leaching in agroforestry than in maize. But overall the effect of native soil fertility on leaching was stronger than land use. Lower leaching losses were found on more acidic, infertile soils compared to more fertile soils with higher pH.

This study shows that soils in the research region are fertile and suitable for permanent agriculture. If land use systems are not fertilized, agroforestry is a better option in terms of nutrient sustainability compared to maize monoculture. Although maize cultivation is productive at first, production will degrade in time without N input and management of soil organic matter. This study also highlights the problems with commonly used partial nutrient balance studies. These studies are unsuitable to evaluate nutrient sustainability in land use systems if important nutrient pathways are not measured.

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