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Is soil degradation unrelated to deforestation? Examining soil parameters of land use systems in upland Central Sulawesi, Indonesia

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Abstract

It is generally assumed that declining soil fertility during cultivation forces farmers to clear forest. We wanted to test this for a rainforest margin area in Central Sulawesi, Indonesia. We compared soil characteristics in different land-use systems and after different length of cultivation. 66 sites with four major land-use systems (maize, agroforestry, forest fallow and natural forest) were sampled. Soils were generally fertile, with high base cation saturation, high cation exchange capacity, moderate pH-values and moderate to high stocks of total nitrogen. Organic matter stocks were highest in natural forest, intermediate in forest fallow and lowest in maize and agroforestry sites. In maize fields soil organic matter decreased during continuous cultivation, whereas in agroforestry it was stable or had the tendency to increase in time. The effective cation exchange capacity (ECEC) was highest in natural forest and lowest in maize fields. Base cations saturation of ECEC did not change significantly during cultivation both maize and agroforestry, whereas the contribution of K cations decreased in maize and showed no changes in agroforestry sites. Our results indicate that maize cultivation tends to reduce soil fertility but agroforestry systems are able to stop this decline of soil fertility or even improve it. As most areas in this rain forest margin are converted into agroforestry systems it is unlikely that soil degradation causes deforestation in this case. On the contrary, the relatively high soil fertility may actually attract new immigrants who contribute to deforestation and start agriculture as smallholders.

Introduction

Indonesia is one of the major tropical rainforest areas worldwide, with 10% of the world's area or nearly 50% of Asia's remaining tropical rainforest. But Indonesia also has one of the highest deforestation rates worldwide: 1.17% annually in the last decade (FAO, 2001). Although large rainforest areas are still intact in the province Central Sulawesi, the area of annually cleared land increased significantly in the last 5 years (van Rheenen, 2003). The most important cause of deforestation is forest clearing for agriculture (FAO, 2001). Like many rainforest areas in Indonesia, Central Sulawesi's uplands are confronted with profound changes in land use and cultivation practices. Traditional methods like shifting cultivation and slash-and burn agriculture are replaced by permanent cultivation systems and introduction of income-generating cash crops. The land use type established after forest clearing has a major influence on the changes in soil fertility. Forest clearing for annual crops (like e.g. upland rice, *Oryza sativa* L. or maize, *Zea mays* L.) removes the major source of litter and therefore reduces the supply of organic material to the soil. In addition, the soil organic matter stock continues to decompose, possibly at higher rate, as removal of the forest cover leads to higher soil temperatures. Therefore we expect that clear cutting and conversion to annual crops lead to a decline in soil organic matter. This has been shown in previous studies under differ-

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ent climatic conditions (e.g. Guo and Gifford, 2002; Schlesinger, 1986; Davidson and Ackerman, 1993). Declining soil organic C may lead to a reduced effective cation exchange ca4pacity (ECEC) and reduced N stocks. A reduced ECEC may make cations more vulnerable to leaching which after some time of cultivation may result in a reduced cation stock or reduced base saturation. In contrast to annual cropping systems, agroforestry systems with their perennial crops and shade trees have a continuous vegetation cover which provides litter and shading to the soil. If legume shade trees are used, additional N is added to the system by biological N fixation. Soil parameters may improve in these systems compared to annual crops (Beer et al., 1998). The decrease in soil fertility during cultivation is often hypothesized to be a major cause of continuing clearing of forest for agricultural land (e.g. Nye and Greenland, 1965; Andriesse, 1977). This so-called 'nutrient mining' is the result of (ecologically unsustainable) land use systems that do not conserve nutrients. The hypothesis is mainly based on studies done in areas with strongly weathered and acidic soils (Andriesse and Schelhaas, 1987; Hölscher et al., 1997; Klinge, 1998; Sommer, 2000). However, large areas in the tropics do not have this kind of soils (e.g. Richter and Babbar, 1991; Sanchez and Logan, 1992) and the hypothesis may be wrong in areas with better soil conditions. Our goal was to test the hypothesis that the decrease in soil fertility is a major cause for forest clearing for the case of Central Sulawesi and the forest margin areas of the Lore Lindu National Park. This area is characterized by relatively young and fertile soils. To test the hypothesis we address the following questions:

(a) Which soil characteristics change in these soils after the conversion of forest to agricultural land?
(b) What is the influence of length of continuous cultivation of maize (annual crop) and cacao/coffee (perennial crop) on soil parameters?
(c) Does declining soil fertility force farmers in this area to clear new areas for agriculture?

To answer these questions, we sampled 66 sites divided over 5 villages covering 4 major land-use systems found in the research area (Maize, agroforestry with cacao (*Theobroma cacao* L.) and coffee (*Coffea arabica* and *C. canephora*), and tree-dominated fallow) analysed them for parameters that indicate the soil fertility and compared these with natural forest sites.

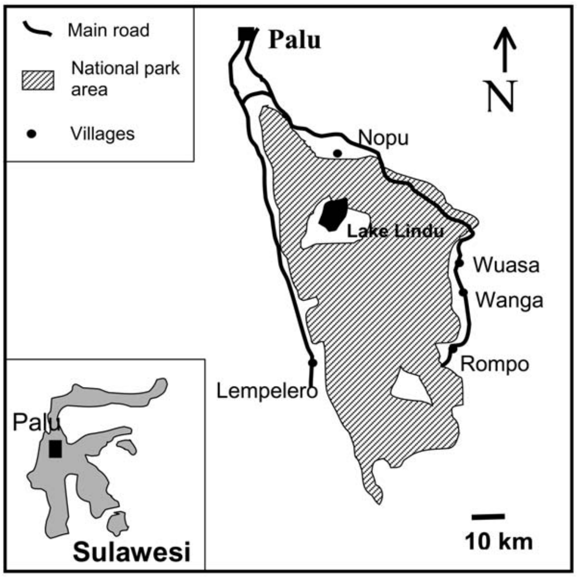

Figure 1. Map of the research region, with national park boundaries and villages where soil samples were taken.

Material and methods

Study area

The study was conducted in the area around the Lore Lindu National Park in Central Sulawesi, Indonesia (Latitude 01°05′–01°54′ South, Longitude 119°54′–120°19′ East, Figure 1). The area is mountainous with elevations up to 2300 m a.s.l. and is situated about 150 km south of the equator. This study area is characterized by large, intact submontane and montane rainforests in the National Park area and adjacent mountains, and mostly deforested valleys and lowlands with a strong encroachment pressure both within and outside the boundary of the National Park. According to the geological map (Sulawesi 2114, 1:250.000) and preliminary surveys mainly crystalline and metamorphic parent material (granite, granodiorite, quarzite, crystalline slate and phyllite) is found in the research area. Lower parts of the slopes are mostly covered with colluvial material, and the valleys have young colluvial, alluvial and lacustrine sediments. Depending on parent material and position fluvic Cambisols, Fluvisols and Gleysols (classification following FAO, 1998) occur in the valleys, and eutric or dystric Cambisols and Leptosols are found on the slopes and uplands (unpublished soil survey, 2000).

Due to the diverse geomorphological setting of Sulawesi the climate is characterized by large spatial variation. Whereas the main valley of the Palu river receives only 600 mm precipitation (making this area one of the driest in Indonesia), mountain slopes east and west of the valley may have up to 2500–3000 mm of annual precipitation. The sites selected for this study were 700–1100 m.a.s.l. and received 1400–1800 mm precipitation (unpublished data from 2002, climatic stations of the project). Mean daily temperature was in the range of 20–24 °C, depending on elevation.

Main land-use system in the valleys and alluvial plains is paddy rice; the most common upland cropping systems in the research area are maize and agroforestry with cacao or coffee. Our study concentrated on non-irrigated land use systems because conversion of natural forest rarely leads to the establishment of paddy rice, which is mostly found on land which has been cleared from forest decades ago and is located far away from forest margins.

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 66 sites were sampled (Figure 1). Sites of four major land use systems were selected and sampled: maize ($n = 28$), agroforestry ($n = 15$), forest fallow (tree- or shrub dominated fallows, $n = 11$), and natural forest ($n = 12$). Natural forest was sampled on each soil type and landscape position where also other land use systems were sampled. This allowed comparison of land use systems with natural forest as undisturbed situation, excluding soil type effects. Forest fallow is mainly found on newly cleared forest sites which are not immediately cultivated, or on agricultural fields which have been abandoned. Farmers mostly plant annual crops on freshly opened forest sites, and change to agroforestry after several years of continuous cultivation. Both maize and agroforestry are cultivated continuously, without regular fallow periods. 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 clearcutting, management practice and previous crops. Sites which had received fertilizer input in the last 5 years were excluded from the survey. Only very few sites were fertilised, but use of fertiliser is increasing, especially in the cacao-agroforestry system. Also sites with unclear site management history were excluded from the study.

Sampling and sample processing

From each site fifteen soil samples were taken with an auger at randomly chosen points from fixed depths (0–10 cm and 30–40 cm). Subsamples of five sampling points were mixed to form three composite samples per site to reduce small scale variation within the sites. Site size was between 400 and 3000 m^2, soils on most sites were relatively homogenous except sites on steep slopes, where soils could differ between the to or he bottom part of the slope. Within-site variation was mostly due to uneven distribution of ash piles from fresh burning, decomposing treetrunks or harvest residuals. Per composite sample we transported about 300 g of field-moist soil to the laboratory. 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 (0–0.1 m 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. In forest and forest fallow sites, where substantial amounts of litter were present, litter height was measured and three samples from a 30 cm × 30 cm square were taken.

Soil chemical and physical analysis

All soil samples were analyzed for total carbon and nitrogen. The air-dried and sieved soil samples were ground to powder using a ball mill. We determined the total organic C using an automated C & N analyzer (Heraeus vario EL). Exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+, Al^{3+} and H^+) were determined by percolation with 1M NH_4Cl following the method described in Meiwes et al. (1984). Total phosphorus and Ca, Mg, K, Na, Al, and Fe were determined after digestion under pressure with HNO_3 following the method described in Heinrichs (1989). Effective cation exchange capacity (ECEC) was calculated from exchangeable cations at field pH. Litter samples were analyzed for C and N only. Soil texture was determined using the pipette method.

Data processing

From the laboratory soil analysis we calculated nutrient concentrations (mg kg^{-1}) and nutrient stocks (kg ha^{-1}), using bulk density data and nutrient concentrations. Nutrient stocks are amounts of the element in a given soil volume (kg ha^{-1} in 0–10 cm and 30–40 cm depth, respectively) and are influenced by

Table 1. Mean topsoil parameters (0-10 cm depth) across land use systems of each soil type, mean (standard deviation).

Parameter	Slopes, weathered schist	Valleys, alluvial sediments	Slopes, weathered phyllite
Clay [%]	14.2 (5.0)	20.1 (6.9)	41.3 (18.6)
Sand [%]	52.0 (9.1)	40.4 (16.7)	21.9 (11.7)
Silt [%]	33.9 (7.0)	39.5 (13.0)	36.8 (7.5)
C [Mg ha^{-1}]	28.0 (1.2)	33.5 (1.4)	45.5 (4.9)
N [Mg ha^{-1}]	2.4 (0.1)	3.1 (0.1)	3.5 (0.3)
BD [g cm^{-3}]	1.14 (0.03)	1.08 (0.02)	0.95 (0.02)
ECEC [mmpl kg^{-1}]	131.4 (11.7)	178.4 (11.3)	160.8 (31.4)
BS [%]	94.9 (1.0)	97.2 (0.9)	70.6 (9.7)
pH [KCI]	5.0 (0.6)	5.2 (0.6)	5.2 (0.6)

bulk density. Because of the large variation in geomorphology across the study area, differences of soil parameters between sites can also be caused by different soil types of the sites. To avoid this we did not only analyse absolute nutrient concentrations and stocks, but additionally used natural forest sites, which were close to the sites of other land use systems on the same soil type, as reference and calculated relative differences of land use type compared to forest (as percentage). Soil type did not change within sites, and mostly sites around a village were all of the same soil type. Some villages (Wanga, Nopu) had sites on two soil types (slopes and alluvial plain).

For each variable normal distribution was tested ($P < 0.1$, Shapiro-Wilks W-test). We used analysis of variance (one-way ANOVA and Tukey's means separation) 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 length of cultivation with soil characteristics in maize and agroforestry systems. Data were analyzed using STATISTICA 6.0.

Results

Effects of soil type on soil parameters

Generally soils in the research region were young and fertile, not acidic or deeply weathered (Table 1). 53% had $pH_{(KCl)}$-values above 5.0. Al-saturation of the ECEC increased with depth, but in the topsoil never exceeded 15%, only few sites had an Al-saturation which was higher than 10%. Base saturation was mostly above 80%, with Ca contributing about 70%, Mg contributing about 20% and K contributing about 5%. We grouped the sampled soils into three groups depending on landscape position and parent material. This classification into three soil types corresponded well with the texture analysis (Table 1). Silt percentage was similar in all soil types (33–38%), but sand was highest in soils on weathered schist and lowest in soils on weathered phyllite, whereas clay was high in soils on weathered phyllite and low in sites on weathered schist. Soil on weathered schist showed a tendency to higher bulk density and largest differences of soil parameters between natural forest and cultivated sites, and carbon-, nitrogen stocks and ECEC were generally higher in soils on weathered phyllite than on alluvial sediments or weathered schist (Table 1).

Clay content of soils was positively correlated with C-, Al-, and Fe- stocks, and negatively correlated with bulk density and sand content. Silt content of soils was positively correlated with Mg- stocks. Carbon and Nitrogen concentrations were closely correlated; ECEC was positively correlated with pH (Pearson's correlation, $P \leq 0.05$). ECEC was correlated (but not significantly) with C concentration (Table 2).

Effects of land use system on soil parameters

When data were standardized with forest sites on the same soil type as reference, topsoil Carbon- and Nitrogen stocks declined after conversion (Table 3, ANOVA, $P \leq 0.05$). The losses of C-stocks after 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

Table 2. Pearson's correlations coefficients (r) and significance (P) between different soil parameters in the topsoil (0–10 cm)

x	y	r	P
C %	N %	0.9	<0.001
Clay %	C [Mg ha^{-1}]	0.8	0.001
Clay %	Al [% of ECEC]	0.8	0.001
Clay %	Sand %	−0.8	0.001
Clay %	Bulk density	−0.6	0.002
Silt %	Mg [Mg ha^{-1}]	0.6	0.001
ECEC	C %	0.5	0.500
ECEC	pH	0.7	0.001

depth, respectively. Decrease of soil C concentration after conversion to maize and agroforestry was as high as 29% and 26% in 0–10 cm and 7% and 8% in 30–40 cm depth. Soil N concentration 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 (data not shown).

Topsoil bulk density in all land-use systems was higher than natural forest; highest values were found in agroforestry followed by maize (Table 3, ANOVA, $P \leq 0.05$). Topsoil ECEC was similar in forest and forest fallow, and lower in agroforesty and maize, whereas in 30–40 cm depth ECEC increased in converted sites compared to natural forest (Table 3, ANOVA, $P \leq 0.05$). Base saturation showed no changes in the topsoil, but in 30–40 cm depth a tendency to increase was observed in converted sites (Table 3). Total P did not show significant changes in different land use systems (data not shown).

Litter was found in substantial amounts only in natural forest and forest fallows, whereas agroforestry systems had only very thin layers of litter. Forests had higher litter biomass stocks than forest fallows (33.0 ± 6.3 and 19.1 ± 6.3 Mg ha^{-1}, respectively), in both systems C and N stocks were around 20% of soil stocks in 0–10 cm depth.

Effects of length of cultivation on soil parameters

We found statistical significant decrease of topsoil (0–10 cm) carbon stocks in maize during cultivation ($P = 0.02$). In contrast, changes to agroforestry C stocks were not significantly different from zero (Figure 1a). Changes of N stocks during cultivation were not significant in either system. Bulk density increased significantly with age in maize ($P = 0.03$), but did not change in agroforestry ($P = 0.57$). ECEC increased in time in agroforestry, but showed no clear trend in maize ($P = 0.04$ and 0.07, respectively, Figure 1b). In maize fields potassium saturation of ECEC decreased strongly in time from high values in one year old sites ($P = 0.004$), in agroforestry no changes were observed in time (Figure 1c). Changes of total P stocks in time were not significant in either land use systems. Results from subsoil (30–40 cm) showed smaller and non-significant changes of soil parameters in time, except for Ca-saturation of ECEC, which in both agroforestry and maize increased in time in 30–40 cm depth ($r = 0.61$, $P = 0.02$ and $r = 0.55$, $P = 0.003$, respectively).

Discussion

Effects of land use on soil organic C, N and P

The C and N losses we measured following forest clearing for agriculture are lower than the losses reported by Guo and Gifford (2002) who did a meta-analysis covering 74 publications studying the conversion of forest to crop-land. They found an average decline of soil carbon of 40–50% (0–60 cm depth). Similar results were reported by Schlesinger (1986), Davidson and Ackerman (1993), and in a review of studies from Amazonia by McGrath et al. (2001). A possible explanation for the relatively low decrease in soil C and N in agricultural sites may be that most sites in our study sites were relatively young (maize: maximally 10 years old, median 3 years; and agroforestry: maximally 10 years old, median 4 years). This is because after some years of maize cultivation, farmers tend to switch to cultivation of perennial crops, and also due to recent immigration to the area and heavy forest clearing activity in the past 5–6 years. Soils may still have high nutrient and especially carbon stocks for several years following clearing, but carbon and nutrient stocks will decline further with time. Especially maize fields were almost all younger than 10 years and therefore the parameters measured in these soils may not represent findings from soils which have been under cultivation for a longer time. Together with the organic matter losses, bulk density increased in managed systems. The decrease in soil C and N concentrations was therefore stronger than the decrease in C and N stocks, a phenomena which must be considered when estimating changes in soil parameter caused by land use change (Veldkamp, 1994).

Table 3. C and N stocks, bulk density, ECEC and pH in different land use systems given as percentage relative to natural forest (= 100%), mean (standard deviation), different letters indicate statistically significant differences (ANOVA, Tukey's Means Comparison, $P < 0.05$, BD = bulk density, BS = base saturation)

	C Mg ha^{-1}	N Mg ha^{-1}	BD g cm^{-3}	ECEC mmol kg^{-1}	BS (%)	pH KCl
			0–10 cm			
Natural forest	100 (20) a	100 (18) a	100 (7) a	100 (33)	100 (9)	100 (10)
Forest fallow	88 (17) ab	90 (12) ab	106 (17) ab	100 (32)	102 (8)	104 (10)
Agroforest	81 (23) b	80 (22) b	120 (23) b	78 (37)	101 (8)	97 (11)
Maize field	81 (16) b	79 (17) b	112 (23) ab	77 (38)	101 (7)	99 (11)
			30–40 cm			
Natural forest	100 (19)	100 (18)	100 (5)	100 (11)	100 (22)	100 (10)
Forest fallow	113 (39)	108 (40)	101 (13)	132 (55)	124 (46)	105 (12)
Agroforest	94 (28)	90 (28)	102 (11)	137 (77)	125 (44)	106 (10)
Maize field	90 (29)	81 (35)	101 (12)	130 (63)	114 (43)	102 (10)

After conversion of forest into agricultural land cultivation does not always lead to decline of C and N as was found in this study during maize cultivation. Contrary to our findings, several other studies showed that conversion into pastures may lead to both decreases and increases in soil organic matter (e.g. Hughes et al., 2000; Kauffman et al., 1998 and Veldkamp, in press). Increase of soil C is possibly due to the permanent soil cover and high below-ground root biomass formed by the pasture grasses. Decrease or increase of soil organic C and N under pastures has been linked to the productivity and management of pastures (e.g. Post et al., 2000; Fisher et al., 1994). But also conversion into annual crop systems are not always reported to result in soil C decline. Klinge (1998) studied clearing of a secondary fallow forest in a rotation system, which had probably reached a new steady state of C-stocks on a lower level than the original natural forest. Finally, Schroth et al. (2002) measured changes of C following forest conversion in the top 0.3 m of the soil profile, but found no significant changes in the soil profile if a greater depth was studied (0–2 m).

Although in agroforestry systems soil C and N were significantly lower than in natural forests, these levels did not decrease during cultivation but were stable or had the tendency to increase. In our study area, agroforestry systems are often established on fields previously used for maize cultivation, which are depleted in soil C after some years of maize cultivation. Our results indicate that the agroforestry systems can stop the decrease in soil organic matter and they may even be able to reverse the trend. The ability of perennial crop vegetation to reverse the negative impact of forest conversion was also reported by Post and Kwon (2000). Other studies have found both decreases and increases of soil C in perennial land use systems with cacao or oil palm (review by Schroth et al., 2001).

We did not find significant differences of total P between land use systems or in the chronosequence of maize or agroforestry. Managed sites tended to have higher P stocks than natural forests, but these differences disappeared when bulk density was taken into account. In a detailed study in Borneo, Lawrence et al. (2001) did not find a decrease of total P in 200 years of shifting cultivation during time, but changes were found in some more labile P fractions, which we did not measure.

Effects of land use on base cations

Although K saturation of the ECEC was not significantly different in converted sites compared to natural forests, the chronosequence study revealed a fast decline from high exchangeable K saturation in young maize fields, to much lower levels in older fields (> 4 years continuous cultivation). This pattern was probably caused by the high input of wood-ash on freshly opened and burned sites, followed by leaching and harvest export of K during maize cultivation. In agroforestry, K-saturation did not change with time and was stable on a slightly higher level than under

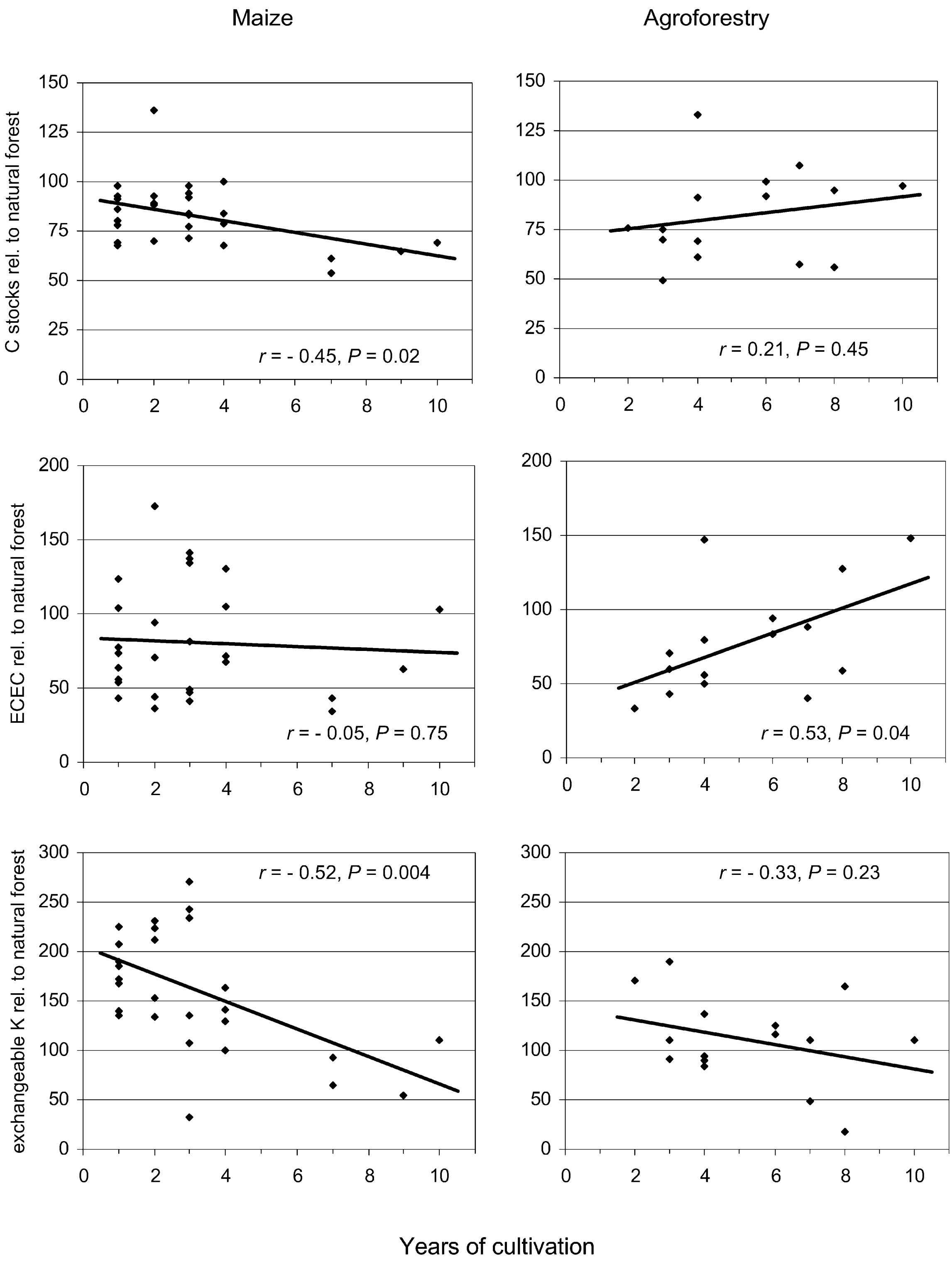

Figure 2. Relation between duration of cultivation and topsoil (0–10 cm) C stocks (a), ECEC (b), and exchangeable K (c), in agroforestry and maize. All values were standardized in relation to natural forest on the same soil type (natural forest = 100).

natural forest. Total K stocks did not show differences between land use or cultivation period.

Although Ca-saturation of ECEC did not change in the topsoil, we detected an increase of Ca saturation and base saturation with time at 30–40 cm depth in both land-use systems. Furthermore, Ca and Mg stocks were higher in converted systems compared to forest. The higher Ca and Mg stocks are probably the result of burning of above ground biomass-stocks, resulting in high input of bases through ashes. In time the Ca cations are leached to lower parts of the soil profile, explaining the increase in Ca saturation. Similar results were found by Klinge (1998) who reported increases in pH after clearing in Amazonia. Reiners et al. (1994) and Kauffman et al. (1998) reported increase of Ca-stocks and base saturation in pasture-soils compared to forests. In their review of 100 studies in Amazonia McGrath et al. (2001) concluded that conversion of forest to slash and burn agriculture lead to increased pH, bulk density and Ca saturation of ECEC. The effect of increasing Ca saturation with time in agroforestry systems cannot be explained by ash-input through burning alone. Burning of biomass will raise pH and base cation concentration of the soil, and burning of harvest residuals and weeds may be responsible for this accumulative effect in maize, where burning of harvest residuals and weeds is part of the mangement. However, burning is not part of the management in agroforestry (weeds are only cut frequently). The increased values compared to natural forest are the result of initial burning, but the continuing increase with time seems to be the effect of an ongoing process. One hypothesis that may explain this increase is the 'nutrient pumping' effect of deep rooting crop- and shade trees in agroforestry systems: leaf litter and frequent cutting of crop- shade trees and weeds bring nutrients to the soil which were taken from deeper soil layers by the tree-roots. However, the scale of this effect remains largely unknown (Sommer, 2000). In our study on soils with moderate pH and high reserves of base cations we did not find significant changes of pH with time and land use systems did not show differences in pH.

Effect of soil fertility on the stability of forest margins

Our study demonstrates that relatively fertile soils dominate the region. Farmers reported during interviews that systematical use of fallow periods to maintain soil fertility had been practiced in earlier times in some villages, but presently most plots were under permanent cultivation. Newly cleared land is normally converted to perennial plantations (cacao and coffee) after a few years of maize culture. Soil fertility was still relatively high after several years of continuous cultivation: Maize was reportedly grown up to 8 times without fertilizer input or fallow period with still reasonable harvests (about 1 ton ha^{-1}). Strongly degraded soils which only support a short cropping period were rare.

Although we measured declining soil C and N-stocks following conversion, we did not find decreases in cation-stocks with the exception of Potassium. Base saturation actually increased after forest clearing. The change after some years of annual maize-culture to agroforestry may be an adaptation of the farmers to reduced C- and N-stocks and ECEC in maize as agroforestry seems to stabilize the soil parameters and may even accumulate C and N in time.). However, several other reasons are possible which make farmers change to the perennial system. Apart from soil degradation during maize cultivation, also weed problems in the annual system, lower labour input and higher profitability of the agroforestry system may cause farmers to switch to agroforestry. Our study did not test these hypothesis.

Nutrient losses following conversion do not always indicate unsustainable soil use, but may indicate that the system equilibrates on a lower level, which is stable again (Schroth et al., 2001). This may be the case for the agroforestry systems in this research area with legume shade trees. From soil-conservation perspective our data suggest that agroforestry are a sustainable land-use system in the study area. C, N and ECEC are significantly lower than the natural forest situation, but they seem to stay stable in time. Continuous maize culture without addition of nutrients is not sustainable in long-term perspective. To increase sustainability of maize production management should focus on maintaining and preserving soil organic matter. This could be achieved by reducing the burning of biomass after harvest and by increasing the input of organic material (e.g. manure, etc). However, if burning would be reduced, the positive effect of burning on weed reduction must be supplemented by other methods, which may turn out to be too expensive. Another measure to improve the sustainability of maize cultivation could be the inclusion of legumes in the rotation cycle, which we actually observed on about 5 farms. These farmers rotated or intercropped maize and beans (*Phaseolus* or *Vigna* spp.). The effects of this cultivation practice would have to be studied in detail.

Conclusions

In this specific setting of the study on relatively fertile soils our results do not support the hypothesis that forest conversion is caused by soil degradation during agricultural land use. Heavily degraded soils are rare in the study area. Agroforestry systems are relatively stable from soil fertility perspective, at least in the age-classes that we investigated in this study, and maize, which would lead to soil degradation, was mostly grown continuously only for several years before perennials were planted. However, the study does not provide evidence that the change towards agroforestry is driven by soil fertility objectives or other (e.g. economic) reasons.

We conclude that ongoing forest clearing in the rainforest margin of Lore Lindu National Park was not driven by soil degradation, and must be attributed to other factors, which we did not test (immigration, population growth, expansion of agricultural area per farmer etc.). The high soil quality found in the research region compared to other areas in Indonesia may actually attract migrants, who clear land and start agriculture as smallholders.

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Appendix 1. Soil parameters from topsoil (0–10 cm), means ($n = 3$) and SE

Village	LUS	Age	Soil-	BD	Clay	Sand	Silt	pH KCl		C mg g^{-1}		N mg g^{-1}		P mg g^{-1}		ECEC mm kg^{-1}		BS	K % of ECEC		Ca % of ECEC	
		years	type		%	%	%	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	%	mean	SE	mean	SE
1	NF		1	1.15	16.4	46.7	36.9	4.8	0.3	27.7	3.5	2.5	0.2	0.4	0.0	132.9	66.3	98.40	2.0	0.7	64.8	0.2
1	NF		1	1.01	n.m.	n.m.	n.m.	5.0	0.5	41.8	5.6	3.5	0.4	0.3	0.0	154.6	64.7	98.70	2.7	0.7	78.0	4.9
1	SF		1	0.93	7.2	71.5	21.3	4.4	0.3	27.1	4.6	2.3	0.3	0.2	0.0	59.7	9.3	99.37	4.1	1.0	65.4	14.4
1	SF	5	1	1.03	22.8	39.9	37.3	4.4	0.3	32.1	5.2	2.9	0.8	0.4	0.1	106.0	15.0	97.10	4.0	1.3	62.7	5.9
1	AF	10	2	1.01	n.m.	n.m.	n.m.	5.1	0.2	30.5	2.8	2.7	0.2	0.8	0.0	197.1	14.5	99.61	2.2	0.4	76.0	1.8
1	MF	2	1	1.21	6.8	71	22.2	5.5	0.2	24.4	0.6	1.9	0.1	0.2	0.0	94.2	16.4	84.77	4.4	1.1	78.4	1.3
1	MF	2	1	1.21	10	43.1	46.9	4.4	0.1	23.3	1.9	2.0	0.1	0.4	0.0	48.0	5.3	97.48	4.2	0.8	66.1	3.9
1	MF	10	2	1.21	n.m.	n.m.	n.m.	4.8	0.1	18.2	1.7	1.7	0.1	0.7	0.0	136.8	11.4	85.94	2.2	0.2	73.6	1.4
1	MF	1	2	1.15	15.2	25.4	59.4	4.7	0.1	21.6	1.5	2.1	0.2	0.7	0.1	138.8	28.0	98.56	2.7	0.4	69.5	2.2
1	MF	2	1	0.94	15.2	53.4	31.4	4.5	0.3	23.5	12.5	1.6	0.8	0.4	0.1	58.3	23.4	95.51	4.5	1.5	70.2	11.4
2	NF		1	0.72	21.6	51.3	27.1	5.8	0.3	62.8	12.9	5.8	1.2	0.8	0.1	319.1	55.9	33.54	2.1	0.2	71.1	5.3
2	NF		1	0.94	18	51.5	30.5	5.2	0.3	31.9	1.7	3.2	0.1	1.1	0.1	167.3	30.8	99.04	5.2	0.6	68.1	5.2
2	SF	2	1	1.20	9.2	47	43.8	5.7	0.1	23.7	1.9	2.5	0.2	0.5	0.1	157.7	14.4	98.85	3.3	1.8	83.6	3.3
2	AF	7	1	1.41	13.2	57	29.8	4.7	0.3	15.3	2.3	1.2	0.2	0.7	0.0	96.6	12.7	98.14	4.0	0.9	81.1	1.7
2	AF	4	2	1.29	10	37.7	52.3	4.7	0.1	17.9	1.1	2.1	0.1	0.9	0.1	122.6	25.9	88.42	3.4	0.1	71.7	12.3
2	MF	4	1	1.17	12	46.7	41.3	6.5	0.4	25.4	1.3	2.5	0.2	1.1	0.5	316.2	115.5	97.76	3.7	0.5	83.5	2.9
2	MF	7	1	1.42	12.8	50.5	36.7	4.9	0.2	16.2	1.8	1.4	0.2	0.6	0.1	105.8	18.3	91.87	3.4	0.3	78.7	2.4
2	MF	1	1	1.18	8.8	45.3	45.9	5.6	0.5	21.5	3.1	2.3	0.4	0.8	0.2	131.5	13.1	87.39	6.9	3.4	76.3	5.9
2	MF	7	1	1.44	12.8	52.7	34.5	4.7	0.2	14.0	3.1	1.6	0.3	0.6	0.1	81.7	18.8	99.03	2.3	0.7	76.7	2.4
3	NF		1	1.01	12.8	54.6	32.6	5.0	0.5	25.9	6.0	2.6	0.6	0.7	0.2	181.8	44.4	99.10	2.6	0.3	74.4	5.2
3	NF		1	1.03	29.6	34.2	36.2	5.2	0.4	30.3	7.5	2.8	0.6	0.5	0.1	186.8	69.8	96.28	2.6	0.6	59.6	2.1
3	NF		1	0.68	n.m.	n.m.	n.m.	4.2	0.2	59.6	11.7	4.4	0.8	0.5	0.1	116.7	18.3	98.45	5.2	0.9	48.6	24.1
3	SF	2	1	1.10	18.4	45.5	36.1	4.5	0.3	24.0	2.2	2.2	0.2	0.5	0.1	176.4	25.0	99.47	3.1	0.8	49.9	9.3
3	SF	3	1	1.20	12.4	54.4	33.2	5.0	0.5	18.4	9.0	1.7	0.8	0.7	0.1	124.7	25.8	96.94	4.6	1.3	65.1	9.2
3	AF	7	1	1.37	n.m.	n.m.	n.m.	5.0	0.6	22.4	4.7	1.9	0.3	1.0	0.2	161.8	34.0	97.71	1.3	0.4	76.8	4.8
3	AF	2	1	1.34	n.m.	n.m.	n.m.	4.2	0.1	16.3	0.6	1.2	0.1	0.5	0.0	60.0	10.8	98.84	4.5	1.3	64.9	5.4
3	AF	3	1	1.32	12.0	60.4	27.6	4.3	0.2	15.2	1.5	1.3	0.1	0.6	0.1	79.9	4.6	99.35	2.9	0.1	71.6	2.2
3	AF	4	1	1.24	12.0	56.4	31.6	5.5	0.2	21.0	1.8	1.6	0.1	0.5	0.1	103.7	15.5	43.31	2.4	0.6	80.8	4.4

Appendix 1. Continued

Village	LUS	Age	Soil-	BD	Clay	Sand	Silt	pH KCl		C mg g^{-1}		N mg g^{-1}		P mg g^{-1}		ECEC mm kg^{-1}		BS	K % of ECEC		Ca % of ECEC	
		years	type		%	%	%	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	%	mean	SE	mean	SE
3	AF	8	1	1.28	12.4	54.5	33.1	5.0	0.2	21.3	1.4	1.7	0.1	0.6	0.1	108.1	11.4	97.04	4.3	1.5	66.4	0.9
3	MF	3	1	1.27	n.m.	n.m.	n.m.	4.7	0.2	17.4	1.4	1.5	0.1	0.7	0.0	90.3	11.1	94.93	6.4	3.3	55.5	1.4
3	MF	3	1	1.27	12.0	59.5	28.5	4.6	0.2	18.7	0.7	1.4	0.1	0.5	0.0	74.7	9.2	99.29	6.2	1.0	70.9	4.3
3	MF	3	1	1.20	11.2	57.6	31.2	4.9	0.7	20.1	2.8	1.5	0.1	0.4	0.0	86.8	30.3	99.74	7.1	0.8	66.3	5.4
3	MF	1	1	1.01	17.2	47.1	35.7	4.6	1.0	25.9	2.2	1.9	0.0	0.4	0.1	118.2	43.8	98.59	5.9	1.2	46.5	12.1
3	MF	1	1	1.14	12.4	59	28.6	5.2	1.5	20.0	0.2	1.7	0.2	0.4	0.1	141.1	54.9	98.49	3.7	0.1	77.0	4.0
4	NF		2	1.10	14.4	69.6	16	5.7	0.5	41.0	6.0	3.4	0.4	0.7	0.1	247.8	85.3	97.46	2.5	0.7	86.0	3.7
4	NF		2	1.07	20.8	49.4	29.8	4.5	0.4	29.1	2.5	2.9	0.3	0.7	0.0	134.8	26.8	98.48	1.9	0.5	73.9	8.3
4	NF		2	1.12	n.m.	n.m.	n.m.	5.8	1.0	38.1	7.9	3.7	0.5	0.7	0.0	219.6	52.1	87.60	1.7	0.5	89.0	4.3
4	SF	4	2	0.98	16	61.9	22.1	5.9	0.2	43.0	4.5	3.8	0.2	0.7	0.0	271.2	15.0	93.26	3.8	1.8	82.8	4.2
4	SF		2	1.10	22.8	51.3	25.9	5.6	0.3	32.0	5.0	3.1	0.4	0.6	0.1	207.6	24.4	95.35	2.5	0.5	82.0	0.7
4	SF		3	0.99	28	26.6	45.4	4.9	0.4	38.2	8.0	3.8	0.8	1.2	0.3	218.4	17.7	95.06	3.1	1.3	74.3	6.9
4	SF	2	1	1.10	15.6	59.2	26.2	6.0	0.2	38.0	2.4	3.2	0.0	0.8	0.1	254.6	75.8	95.22	2.2	0.2	86.1	3.8
4	SF	10	2	1.05	25.6	18.2	56.2	5.1	0.2	34.1	4.2	2.9	0.2	0.8	0.1	228.7	36.1	94.66	1.4	0.3	77.0	2.5
4	AF	3	2	1.22	n.m.	n.m.	n.m.	5.0	0.1	23.4	1.4	2.3	0.1	0.8	0.1	115.2	7.1	93.78	4.2	1.3	78.5	2.9
4	AF	6	3	1.06	28.4	33.4	38.2	4.7	0.3	35.5	2.8	3.4	0.2	1.0	0.3	159.6	23.3	96.75	2.7	0.5	68.9	3.4
4	AF	4	2	1.06	31.2	13.2	55.6	5.5	0.1	47.7	6.0	4.4	0.4	1.7	0.1	282.1	9.6	98.97	1.8	0.4	81.3	1.7
4	AF	4	2	1.11	6.8	53.8	39.4	5.3	0.1	23.6	1.1	2.4	0.1	0.7	0.0	150.8	11.1	97.58	3.0	0.8	78.8	0.9
4	AF	3	2	1.21	n.m.	n.m.	n.m.	4.3	0.2	15.2	3.6	1.6	0.5	0.9	0.1	136.2	11.1	99.06	2.0	0.5	70.9	2.8
4	AF	6	2	1.14	n.m.	n.m.	n.m.	5.7	0.3	32.2	7.9	3.1	0.6	0.6	0.0	180.7	51.8	99.85	2.5	0.9	86.9	0.5
4	MF	4	2	1.21	15.2	45.2	39.6	5.7	0.1	31.4	2.9	2.9	0.3	0.8	0.1	201.0	13.0	99.35	3.6	0.5	76.8	1.2
4	MF	1	3	1.06	28.8	28.6	42.6	4.1	0.0	33.4	1.1	3.1	0.2	0.4	0.0	82.5	6.9	99.81	3.7	0.2	46.7	4.2
4	MF	3	3	0.94	20.8	39.2	40	4.7	0.4	37.3	3.7	2.8	0.3	0.5	0.1	154.6	31.6	98.97	6.0	2.1	68.4	13.4
4	MF	2	3	0.99	24	28.6	47.4	4.9	0.1	34.3	3.6	3.4	0.3	1.5	0.0	180.1	20.9	99.22	3.4	1.0	74.0	1.7
4	MF	4	2	1.19	17.6	51.6	30.8	4.9	0.0	27.0	2.3	2.5	0.2	0.6	0.1	129.4	6.4	98.56	3.1	0.5	78.9	0.6
4	MF	1	2	0.87	29.2	25.9	44.9	4.5	0.2	37.7	5.1	3.4	0.4	1.2	0.2	141.8	4.6	98.06	4.6	0.2	65.6	5.7
4	MF	1	2	1.11	11.6	61.6	26.8	5.2	0.2	23.6	0.5	2.2	0.0	0.7	0.0	107.2	9.5	97.04	3.8	0.0	81.4	1.4
4	MF	4	2	1.23	14.4	53.8	31.1	4.8	1.0	21.2	15.2	1.7	1.2	0.4	0.2	138.4	60.7	99.29	2.9	0.4	73.4	13.7
4	MF	3	2	1.09	22.4	16.9	60.7	5.7	0.1	34.5	3.1	3.3	0.4	0.9	0.1	256.9	32.1	94.80	3.0	0.9	78.9	1.8

Appendix 1. Continued

Village	LUS	Age	Soil-	BD	Clay	Sand	Silt	pH KCl		C mg g^{-1}		N mg g^{-1}		P mg g^{-1}		ECEC mm kg^{-1}		BS	K % of ECEC		Ca % of ECEC	
		years	type		%	%	%	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	%	mean	SE	mean	SE
4	MF	1	2	1.14	18	58	24	6.2	0.3	32.8	1.9	3.4	0.1	0.7	0.0	237.8	25.2	95.44	4.1	0.9	84.6	2.6
4	MF	4	2	1	n.m.	n.m.	n.m.	6.5	0.5	47.4	11.2	4.0	0.6	0.7	0.1	331.8	90.0	88.93	3.0	2.4	87.6	3.3
5	NF		3	0.83	59.6	13.6	26.8	4.4	0.5	59.1	0.9	3.8	0.7	0.7	0.1	96.7	51.0	86.66	4.5	2.0	42.5	20.4
5	NF		3	0.90	54.1	10.6	35.3	5.1	1.4	96.8	10.0	6.7	0.6	0.8	0.1	287.7	222.3	96.75	2.1	1.7	65.9	18.5
5	SF	2	3	0.97	34.4	27.5	38.1	5.9	0.6	52.1	0.4	4.2	0.3	0.7	0.1	259.6	54.2	97.67	1.4	0.4	72.4	0.9
5	AF	8	3	0.90	38	25	37	5.8	0.3	42.2	4.3	3.6	0.2	0.6	0.2	244.6	24.7	99.35	0.5	0.1	61.5	7.4
5	MF	3	3	0.96	n.m.	n.m.	n.m.	5.7	0.1	50.6	7.1	4.2	0.5	1.1	0.1	263.0	69.7	98.86	1.0	0.3	70.6	3.8
5	MF	9	3	0.91	n.m.	n.m.	n.m.	4.6	0.4	48.8	3.4	3.9	0.3	1.3	0.1	121.9	53.0	99.62	1.8	1.0	58.4	20.0
5	MF	3	3	0.96	n.m.	n.m.	n.m.	5.4	0.7	37.2	7.0	3.3	0.7	1.1	0.1	269.7	7.2	71.88	3.6	1.3	71.6	2.1
Means				1.09	19.87	43.74	36.40	4.98		31.64		2.72		0.71		153.98		92.28	3.57		68.23	

Abbreviations:
LUS = land use system
n. m. = not measured
ECEC = effective cation exchange capacity
BD = bulk density
BS = base cation saturation
SE = standard error

Land use systems:
NF = natural forest
SF = secondary forest
AF = Agroforestry
MF = maize field
GF = grass fallow

Villages:
1 = Rompo
2 = Nopu
3 = Lempelero
4 = Wuasa
5 = Wanga