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Soil fertility and nutrient status of traditional Gayo coffee agroforestry systems in the Takengon region, Aceh Province, Indonesia

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Abstract

Little is known about the traditional coffee cultivation systems in Central Aceh, Indonesia, where coffee production is a major source of income for local Gayo people. Based on field observations and farmer interviews, 14 representative agroforestry coffee plantations of different age classes (60–70 years, 30–40 years, and 20 years) as well as seven adjacent grassland and native forest sites were selected for this study, and soil and coffee leaf samples collected for nutrient analysis. Significant differences in soil and coffee leaf parameters were found between former native forest and Sumatran pine (*Pinus merkusii*) forest as previous land cover indicating the importance of the land use history for today's coffee cultivation. Soil pH as well as exchangeable Na and Ca concentrations were significantly lower on coffee plantations compared to grassland and forest sites. Soil C, N, plant available P, exchangeable K, and Mg concentrations showed no consistent differences between land use groups. Nitrogen (N), phosphorus (P), and potassium (K) concentrations of coffee leaves were in the sufficiency range, whereas zinc (Zn) contents were found to be consistently below the sufficiency threshold and significantly lower in coffee plantations of previous pine forest cover compared to those of previous native forest cover. While the results of this study provided insights into the nutrient status of coffee plantations in Central Aceh, the heterogeneity of site conditions, limited sampling size, and scarcity of reliable data about the land use history and initial soil conditions of sampled sites preclude more definitive conclusions about the sustainability of the studied systems.

Keywords: *Coffea arabica*, agroforestry, Indonesia, Gayo, sustainability

1 Introduction

Indonesia is the fourth largest coffee exporting country after Brazil, Colombia and Vietnam (ICO, 2009), and the province of Aceh in Northern Sumatra is the biggest producer of *Arabica* coffee in the country (Karim, 1999; Nur & Melala, 2001). Most of the low external input agroforestry plantations with an average size of 1.4 ha are owned by the ethnic minority of Gayo people living in the highlands of Aceh Tengah, Bener Meriah and Gayo Lues (Dinas Perkebunan, 2008). Given that the surrounding natural vegetation consists of highly diverse native rain forests, the sustainability of coffee production in Aceh is a key to their conservation.

In Aceh, Dutch development programs in the 1980's focused on the coffee production and improvement of cultivation practices and coffee quality (Leyder, 1980; Vermeulen, 1980; Schuiling, 1982; ITC, 1984; Renes, 1989). General consent was the necessity to improve production systems and coffee processing. Furthermore, the then ongoing extension of coffee cultivation areas to marginal land with steep slopes and non-volcanic soils with low fertility was widely criticized.

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Further studies focusing on organic coffee production in Aceh Tengah and Bener Meriah were published in the 1990's (Wibarya *et al.*, 1995; Karim, 1996, 1999; Karim *et al.*, 1999; Karim & Ali, 2001) However, until the Tsunami event in 2004 a long-lasting civil war severely restricted research and coffee marketing while leading to the deterioration of many plantations.

To identify research gaps for coffee production in the Central Aceh highlands, in May and June 2009 we analyzed the nutrient status of coffee (*Coffea arabica* L.) production systems and compared soil parameters of coffee land units of different age to those of adjacent native forest and grassland areas as an indicator of the ecological sustainability of local coffee production. We hypothesized that the land use history significantly affected soil and coffee plant properties.

2 Materials and Methods

2.1 Study site

The study was conducted north of Lake Laut Tawar in the district of Aceh Tengah, Aceh Province. The area comprised the villages of Sintep, Kelitu, and Gegarang in the subdistricts (*kecamatan*) Kebayakan and Bintang, at about 4°38'N and 96°56'E. The major local town of Takengon is at a distance of 12 km. Coffee plantations (agroforestry systems) extend from altitudes of 1300 m – 1800 m asl. The first plantations were established in the 1930's with the assistance of Dutch developers (Renes, 1989) on the slopes at 1400 m – 1600 m asl replacing native rain forest, whereas at lower altitudes Sumatran Pine (*Pinus merkusii* Jungh & de Vriese) was planted for resin collection (ITC, 1984). After the abandonment of resin collection in the 1980's and 1990's pine forest land was given to locals for further establishment of coffee plantations. During the time of political conflict from 1995–2004, many plantations had been abandoned for up to 10 years and only rehabilitated a few years ago. The land surrounding the coffee plantations of different ages is typically covered by sparse pine vegetation and grassland, which is occasionally burnt. Metamorphic limestone is the dominant soil parent material in the area (ITC, 1984; Billing, 1991) locally dissected by layers of phyllite (YLI, 2009a). According to the US Soil Taxonomy soils were classified as Podsols and Litosols (Bakosurtanal, 2003) or Inceptisols, Alfisols, and Entisols (YLI, 2009b). The humid tropical climate is characterized by an annual rainfall of about 2000 mm, average temperatures of 20 °C and monthly average temperature fluctuations of 1–2 °C (KNMI, 2009; ITC, 1984). Local rainfall is strongly influenced by topography (Whitten *et al.*, 1997; Laumonier, 1997).

While climatic conditions and altitude are optimal for coffee production (Descroix & Snoeck, 2009), slope steepness and low soil fertility hamper long-term productivity as compared to other areas in Aceh Tengah where soils are of volcanic origin.

2.2 Sampling design

Following interviews with plantation owners and local authorities, Gayo coffee plantations were selected to represent land use and plantation age classes, topographical position and management practices. The information on general patterns of land use history as obtained in interviews were confirmed in the course of this study by the interpretation of historical landsat images (not addressed here). Given the structure of the land use history, it was not always possible to use the same number of replicates for land use groups, which are defined by the current and previous land cover (Table 1). Native forest cover and grassland after previous pine forest cover were chosen as control plots since they are the dominant alternative land cover types. However, one site of grassland after native forest cover was also sampled to obtain some indication of the effects of previous compared to current land cover on soil properties.

Basic site and management characteristics of sampled plantations and plots were obtained during first inspection and farmer interviews (Table 2). The dominant shade tree in all plantations is *Leucaena leucocephala*, while other shade and fruit trees and vegetable species are also grown sporadically in most plantations.

2.3 Soil and leaf sampling

In each sampled coffee plantation, five soil samples were taken along a transect parallel to the slope (further referred to as sampling points) in-between coffee rows, whereby the distance between sampling points ranged from 20 to 50 m, depending on the length of the plantations. In grassland and forest plots the lengths of transects and distances between sampling points were mainly determined by topography and accessibility. At each sampling point three samples of 0–20 cm depth were taken within a radius of 1 m using an Edelmann auger after removal of the litter layer, mixed thoroughly, and a sub-sample of about 200 g was air-dried for further analysis. In coffee gardens coffee leaves of the 3–4 trees surrounding the soil sampling point were sampled by collecting and air drying five leaves per tree

Table 1: *Sampling design and total number of sampling points for soil (SS) and leaf (LS) analysis used for the survey of Gayo coffee plantations in Aceh Tengah, Aceh Province, Indonesia.*

Current land cover		*Previous land cover*	
		Pine	*Native forest*
Coffee plantations	Young (20 years)	3 × (CP_{young}), SS = 15, LS = 15	
	Medium (30–40 years)	4 × (CP_{medium}), SS = 20, LS = 20	2 × (CF_{medium}), SS = 10, LS = 10
	Old (60–70 years)	1 × (CP_{old}), SS = 5, LS = 5	5 × (CF_{old}), SS = 25, LS = 25
Alternative land cover	Grassland	3 × (F_{grass}), SS = 15	1 × (F_{grass}), SS = 3
	Native forest		3 × (Forest), SS = 15

CP_{young} = young coffee plantations (20 years) on former pine forest sites, CP_{medium} / CF_{medium} = medium aged coffee plantations (30–40 years) on former pine forest / native forest sites, CP_{old} / CF_{old} = old coffee plantations (60–70 years) on former pine forest / native forest sites, P_{grass} = grassland on former pine forest sites, F_{grass} = grassland on former native forest sites, Forest = native forest.

of the 3rd leaf pair from the tip of a growing branch. Each sampling point was mapped with a hand-held GPS (Trimble® GeoExplorer 3) and the slope measured with a height meter (SUUNTO PM-5/1520, Suunto Oy, Vantaa, Finland).

2.4 Soil and leaf analysis

The air-dried soil samples were crushed and passed through a 2 mm sieve; stones and plant material not passing the sieve were removed. Soil pH was determined in a mixture of 10 g soil suspended in 25 ml $CaCl_2$. For C and N measurements, the samples were ground with a ball mill and C and N were determined with a Vario Max CHN Analyser (Elementar Analysensysteme GmbH, Hanau, Germany). Carbonate C content was determined on 5 samples of highest pH with a calcimeter (Prolabo, Paris, France). Plant available phosphorus (P) was determined according to the P-Bray I method in 5 g of air dried soil and P concentrations of the extract determined colorimetrically (Gericke & Kurmies, 1952; Hitachi U-2000 spectrophotometer, Tokyo, Japan). Exchangeable cations (sodium, Na; potassium, K; calcium, Ca; and magnesium, Mg) were determined after extraction with 1 N NH_4-acetate and analysis of the extract by atomic absorption or flame emission spectrophotometry. Soil texture was analyzed by a combined sieving and pipette method (Gee & Bauder, 1986) on two samples of each plot (the lowest and highest sampling point of the transect). Prior to sieving, organic matter (OM) in 15 g of sample material was destroyed by addition of 30 % H_2O_2 and placing the sample in a hot water bath at 50 °C for a maximum of 24 h. Soil aggregates were dispersed by mixing with 25 ml of a 0.4 N $(NaPO_3)_6$ solution left overnight and shaken for two hours. Sand fractions were determined by passing samples through 630 μm, 200 μm, and 63 μm sieves. Silt and clay fractions were determined according to the pipette method (DIN, 2000).

Air-dried leaves were milled and stored until further analysis. Nitrogen concentration was measured with a FP-328 N-Analyzer (Leco, St. Joseph, MI, USA). Phosphorus and K concentrations were determined after incineration as above and Zn by atomic absorption (AAS Model 906 AA, GBC, Hampshire, MA, USA). For the evaluation of mean leaf nutrient concentrations the threshold levels defined by Willson (1985) were taken as a reference.

2.5 Statistical analysis

The software SPSS (ver. 12.0, SPSS Inc, Chicago, IL, USA) was used for statistical analyses. It was hypothesized that the land use history (native forest – pine forest) and the current land cover (coffee plantations of different age classes – native forest – grassland) have significantly affected soil properties, which is reflected in the sampling design (Table 1). Additionally, slope, altitude, and soil texture were presumably affecting soil properties. To test these hypotheses, soil chemical and coffee leaf properties of all sampling points were subjected to an analysis of covariance (ANCOVA), with previous land cover and current land cover as fixed factors and slope, altitude, clay, and sand fractions as covariates (full-factorial model).

Table 2: *Basic characteristics of sampling sites.*

Sampling site	*Size (ha)*	*Age (a)*	*Altitude (m asl)*	*Slope (%)*	*fertilization* *($kg\,ha^{-1}y^{-1}$)*	*other crops and tree species grown* *
previous pine forest						
$CP_{young}1$	2.3	19	1397 – 1491	51 – 60	46 kg N, 52 kg S	*L.l., P.a. , M.p., D.z.*
$CP_{young}2$	1.1	19	1335 – 1398	25 – 45	cow manure	*L.l., Citrus spp.,P.a., S.b., A.h., M.e., C.a.*
$CP_{young}3$	1	20	1294 – 1344	34 – 53	26 kg N, 30 kg S	*L.l., Citrus spp.,P.a., M.p., D.z.*
$CP_{medium}1$	0.4	39	1405 – 1427	21 – 40	130 kg N, 150 kg S	*L.l., Citrus spp.,P.a., M.p., D.z., Cin. spp., A.c., C.a.*
$CP_{medium}2$	0.8	30	1270 – 1295	42 – 60	60 kg N, 66 kg S	*L.l., Citrus spp.,P.a., Syz. spp., D.z., M.e., Z.m., C.a.*
$CP_{medium}3$	1	32	1526 – 1565	25 – 73	20 kg N, 24 kg S	*L.l., Citrus spp., M.p., Syz. spp., Cin. spp.*
CP_{old} †		60	1515 – 1529	0 – 34	none	
$P_{grass}1$	n.a.	n.a.	1409 – 1461	25 – 70		
$P_{grass}2$	n.a.	n.a.	1285 – 1312	55 – 65		
$P_{grass}3$	n.a.	n.a.	1318 – 1371	40 – 65		
previous native rainforest						
$CF_{medium}1$	0.5	30	1514 – 1594	45 – 75	none	*L.l., Citrus spp.,P.a., M.p., S.b., A.h.*
$CF_{medium}2$	0.4	35	1506 – 1534	29 – 34	none	*L.l., Citrus spp.,P.a., M.p., D.z., Pass. spp.*
$CF_{old}1$	0.6	60	1528 – 1581	16 – 34	none	*L.l., Citrus spp.,P.a., M.p., S.b., N.t., Syz. spp., M.i., C.a., Pass. spp.*
$CF_{old}2$ †	1.5	60	1540 – 1580	5 – 55	none	*L.l., Citrus spp.,P.a., M.p., M.i., A.h., S.b., C.a.*
$CF_{old}3$	0.4	70	1477 – 1527	19 – 55	none	*L.l., Citrus spp.,P.a.*
$CF_{old}4$	0.4	60	1505 – 1550	45 – 65	none	*L.l., P.a., S.b.*
$CF_{old}5$	0.4	70	1655 – 1713	65 – 90	none	*L.l., Citrus spp.,P.a., A.h.*
Forest1 ‡	n.a.	n.a.	ca. 1800			
Forest2	n.a.	n.a.	ca. 1800			
Forest3	n.a.	n.a.	ca. 1800			
F_{grass}	n.a.	n.a.	1524 – 1582	55 – 81		

CP_{young} = young coffee plantations (20 years) on former pine forest sites, CP_{medium} / CF_{medium} = medium aged coffee plantations (30–40 years) on former pine forest/ native forest sites, CP_{old} / CF_{old} = old coffee plantations (60–70 years) on former pine forest/ native forest sites, Pgrass = grassland on former pine forest sites, F_{grass} = grassland on former native forest sites, Forest = native forest.

* L.l. = *Leucaena leucocephala*, P.a. = *Persea americana* Mill., M.p. = *Musa paradisiaca* L., D.z. = *Durio zibethinus* Murr., S.b. = *Solanum betaceum* Cav., A.h. = *Artocarpus heterophyllus* Lam., M.e. = *Manihot esculenta* Crantz, C.a. = *Capsicum annuum* L., Cinn. spp. = *Cinnamomum* spp., A.c. = *Ananas comosus* L., Syz. Spp. = *Syzygium* spp., Z.m. = *Zea mays* L., Pass. spp. = *Passiflora* spp., N.t. = *Nicotiana tabacum* L., M.i. = *Mangifera indica* L.

† CP_{old} and $CF_{old}2$ are part of the same plantation, therefore no separate size is indicated

‡ Altitude and slope of forest sampling sites could not be obtained due to dense vegetation

Next to the P value as an indicator of significance, η^2 was calculated as a measure of effect size (Levine & Hullett, 2002), and the observed power of the test was determined (Janssen & Laatz, 2005). For an interpretation of group differences, means of land use groups were compared with the non-parametric Kruskal-Wallis-test, the t-test (in case of two treatment groups), or an analysis of variance (ANOVA; in case of three or more treatment groups). The low intensity of Gayo coffee production is reflected by the fact that only in a few plantations mineral fertilizers were applied and only one farmer used organic fertilizers (Table 2). To detect effects of fertilization and exclude effects of other known factors, we tested for significant differences in soil and leaf parameters among the three CP_{young} plantations using an ANOVA, whereby sampling points within a plantation were treated as replicates (N = 5). To test for normal distribution and equality of variance for all groups, the Kolmogorov-Smirnov-test and the Levene test based on the median were conducted beforehand. Where data was not normally distributed or variances were not homogenous, ANOVA was followed by the Games-Howell post-hoc test (Janssen & Laatz, 2005). Otherwise, the Scheffé post-hoc test was conducted which is also applicable when group sizes are not uniform (Janssen & Laatz, 2005). The significance level for all analyses was set at $\alpha = 0.05$. The F_{grass} sites were not included in the statistical analysis due to the small number of samples in this land cover group and the low power of tests.

3 Results

3.1 *Factor effects*

Previous land cover significantly affected soil pH, C, C/N ratio, P, and Ca concentrations as well as coffee leaf N, P, and Zn concentrations (Table 3). The effect sizes of previous land cover were highest for C/N ratio, leaf N, and Zn concentrations. Nutrient concentrations and pH tended to be lower and C/N ratio higher at sites of previous pine cover compared to sites of previous native forest cover (Figures 1–3).

Current land cover significantly affected C, C/N ratio, Na, and coffee leaf P concentrations, whereas altitude significantly affected soil C/N ratio as well as coffee leaf N, P, and Zn concentrations. Also slope determined soil pH and Ca and coffee leaf N and Zn concentrations (Table 3).

3.2 *Soil analysis*

Soil pH ranged from 4.4 to 7.2 and was significantly lower in older plantations compared to alternative land cover both on sites previously covered by pine and native forest (Figure 1).

Carbonate C contents were below 0.1 % for soils with pH > 6.7, therefore the contribution of carbonate C to total soil C was neglected and measured C values were considered to represent organic C. Soil C concentrations of all land use groups ranged from 2.4 % to 12.2 % and N concentrations from 0.2 to 0.9 %. Coffee plantations established after native forest had lower C concentrations than the native forest, whereas in land cover groups following pine vegetation soil C increased with age (Figure 1). Soil N concentrations behaved similarly. Regardless of their age class, coffee plantation soils tended to have lower C/N ratios than alternative land cover plots, though these differences were not always statistically significant (Figure 1).

Plant available P concentrations ranged from 0.5 to 80 mg kg^{-1} with a strong decline with plantation age. Bray-P values in plantations established after native forest were significantly higher than those in native forest (Figure 1).

Calcium contributed 70–96 % to soil exchangeable cations, followed by K (0.9–20.8 %), Mg (1–13.1 %), and Na (0.2–1.1 %). Grassland soils contained significantly higher Na levels than soils under coffee plantation after pine while differences between coffee plots and sites of native forest cover were inconsistent (Figure 2). Potassium ranged from 29.6 to 422.4 mg kg^{-1} and was not different between current land cover groups (Figure 2). Calcium concentrations tended to be lower under coffee compared to forest or grassland. Concentrations of Mg were between 52.4 and 360 mg kg^{-1} and means did not differ between land cover groups (Figure 2).

Soils of F_{grass} sites tended to resemble forest sites rather than P_{grass} sites, particularly with respect to pH (6.2), C/N ratio (12.2), and Ca levels (19.9 mg kg^{-1}) (data not shown in graphs).

The recovery rate of texture analysis was between 94 and 103 %. Sand fractions ranged from 9–48 %, silt fractions from 21–64 %, and clay fractions from 6–71 %, with no significant differences between land cover groups (Table 4).

3.3 *Coffee leaf analysis*

In plantations following pine, coffee trees in older plantations had significantly lower leaf P concentrations than those in younger ones. Coffee plantations following native forest, in contrast, had similar leaf N, P, K, and Zn concentrations. Compared to published threshold levels (Willson, 1985) average leaf concentrations of

Table 3: *ANCOVA of all sampling sites, η^2 and observerd power for the factors 'previous land cover' and 'current land cover' (main effects and interactions), and the covariates 'altitude', 'slope', 'sand', and 'clay fraction' (α = 0.05)*

	previous land cover			*current land cover*			*previous × current*			*altitude*			*slope*			*sand*			*clay*		
	P	η^2	power	P	η^2	power	P	η^2	power	P	η^2	power	P	η^2	power	P	η^2	power	P	η^2	power
pH	.001	.233	.929	.858	.014	.092	.401	.035	.196	.118	.048	.344	.018	.118	.684	.870	.000	.053	.189	.033	.255
C	<.001	.197	.984	.038	.105	.676	.668	.009	.109	.252	.015	.204	.577	.003	.085	.011	.081	.752	.485	.005	.105
N	.121	.027	.339	.197	.053	.386	.437	.018	.181	.700	.002	.066	.817	.001	.056	.002	.131	.919	.369	.009	.143
C/N	<.001	.449	1.000	<.001	.187	1.000	.486	.006	.162	.016	.026	.698	.322	.004	.163	.589	.001	.082	.856	<.001	.054
P	.020	.186	.664	.942	.008	.070	.228	.065	.301	.386	.016	.136	.338	.020	.156	.999	<.001	.050	.302	.023	.173
Na^+	.766	.001	.060	<.001	.410	.999	.006	.138	.858	.508	.005	.099	.775	.001	.059	.505	.005	.100	.637	.003	.075
K^+	.066	.070	.455	.461	.050	.216	.513	.026	.153	.983	.000	.050	.099	.055	.377	.835	.001	.055	.409	.013	.127
Ca^{2+}	.006	.147	.816	.504	.040	.199	.131	.073	.408	.303	.018	.173	.037	.080	.562	.965	.000	.050	.495	.008	.102
Mg^{2+}	.753	.003	.061	.344	.085	.275	.767	.013	.088	.439	.015	.118	.621	.006	.077	.425	.016	.122	.140	.057	.311
N_{leaf}	.001	.306	.948	.199	.075	.322	.100	.064	.375	<.001	.508	.996	.027	.122	.622	.169	.044	.274	.645	.005	.073
P_{leaf}	.016	.147	.706	.037	.166	.634	.413	.015	.125	.009	.185	.794	.211	.036	.234	.837	.001	.054	.040	.105	.554
K_{leaf}	.067	.070	.455	.200	.065	.321	.346	.017	.151	.793	.001	.057	.487	.009	.103	.611	.005	.078	.134	.045	.318
Zn_{leaf}	<.001	.645	1.000	.901	.003	.064	.157	.027	.288	.001	.184	.951	.019	.083	.684	.569	.004	.085	.174	.025	.269

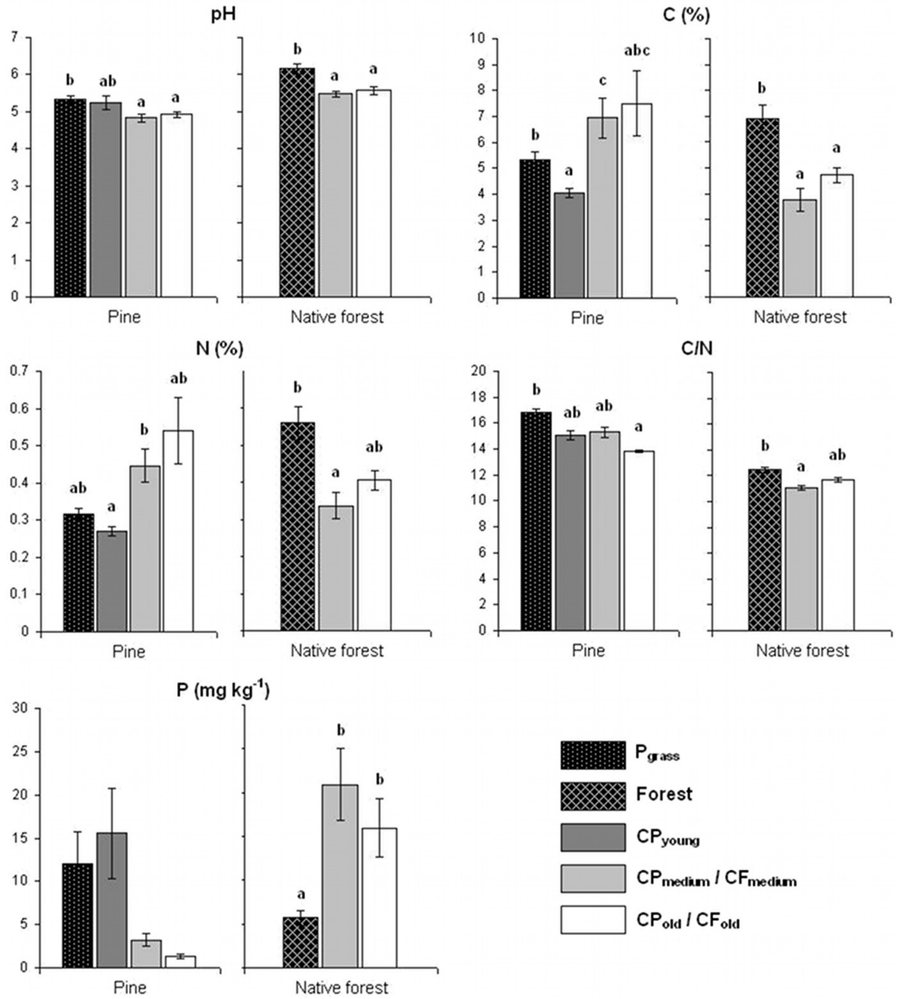

Fig. 1: *Soil pH, carbon (C), nitrogen (N), C/N ratio and available P (Bray I) in soils (0–20 cm) of coffee plantations of different age classes and forest/ grassland on sites of former pine and native forest vegetation in Aceh Tengah, Aceh Province, Indonesia (data show means ± standard error). Different letters above columns indicate significant differences between land use groups within one previous land cover group according to the Games-Howell-test (pH, C and N of pine sites, available P) or Scheffé-test (α= 0.05).* P_{grass} *= grassland on former pine forest sites, Forest = native forest,* CP_{young} *= young coffee plantations (20 years) on former pine forest sites,* CP_{medium}/CF_{medium} *= medium aged coffee plantations (30–40 years) on former pine forest/ native forest sites,* CP_{old}/CF_{old} *= old coffee plantations (60–70 years) on former pine forest/native forest sites.*

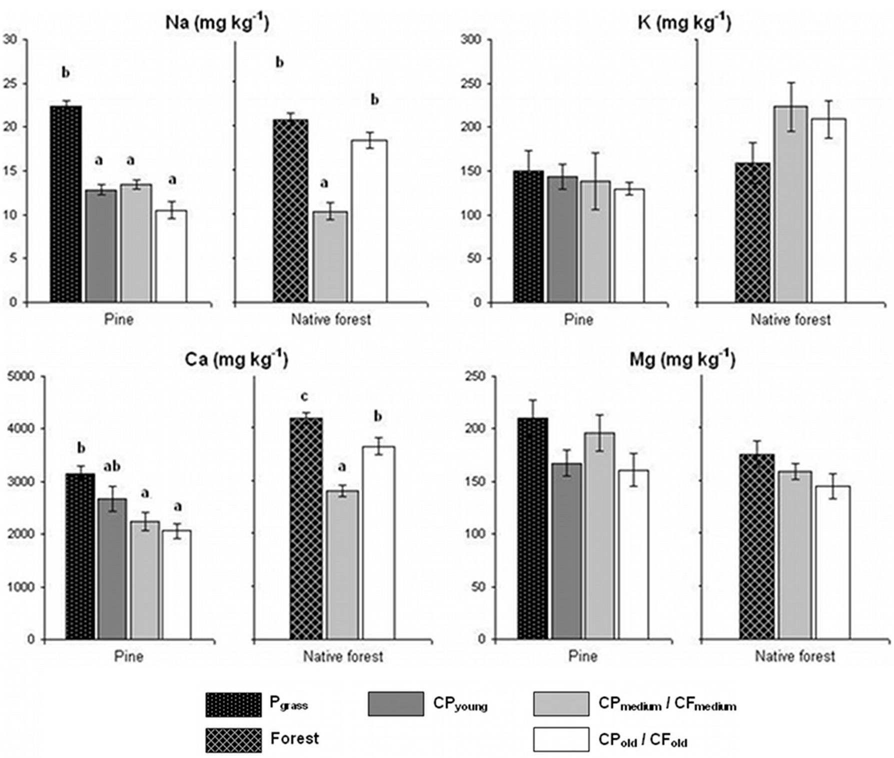

Fig. 2: *Soil exchangeable cations of coffee plantations of different age classes and forest/ grassland on sites of former pine and native forest vegetation in Aceh Tengah, Aceh Province, Indonesia (data show means ± standard error). Different letters above columns indicate significant differences between land use groups within one previous land cover group according to the Games-Howell-test (K of pine sites; Ca and Mg of native forest sites) or Scheffé-test (α= 0.05).* P_{grass} *= grassland on former pine forest sites, Forest = native forest,* CP_{young} *= young coffee plantations (20 years) on former pine forest sites,* CP_{medium}/CF_{medium} *= medium aged coffee plantations (30–40 years) on former pine forest/ native forest sites,* CP_{old}/CF_{old} *= old coffee plantations (60–70 years) on former pine forest/native forest sites.*

Table 4: *Means and standard errors (s.e.) of the sand, silt and clay fractions per land cover group.*

	Sand (%)		*Silt (%)*		*Clay (%)*	
	mean	*s.e.*	*mean*	*s.e.*	*mean*	*s.e.*
CP_{young}	19.95	2.86	41.58	4.35	38.07	6.91
CP_{medium}	27.75	5.83	41.72	4.03	28.73	9.49
CP_{old}	23.00	6.00	55.81	2.06	20.70	5.23
CF_{medium}	25.86	1.57	50.78	3.05	21.88	3.79
CF_{old}	23.32	2.20	53.97	2.12	21.73	3.80
Forest	23.48	3.59	48.25	1.25	26.63	3.31
P_{grass}	18.73	2.67	45.57	2.76	35.64	5.56

N, P, and K were within the sufficiency range, whereas Zn levels were consistently below thresholds (Figure 3).

3.4 *Effects of fertilization practice*

Among CP_{young} plantations, plantations with application of cow manure had significantly higher soil pH, soil Ca, and leaf P concentrations than plantations in which reportedly different levels of mineral fertilizer had been applied (Table 5). The level of mineral N application was not reflected in soil N levels since the plantation with highest amounts of applied N had significantly lower concentrations of soil N and C than the other plantations.

4 Discussion

4.1 *Statistical power and factor effects*

The rather small number of replications compared to the large number of factors affecting the soil and plant parameters analysed limited the statistical power of this study, particularily regarding the effect of current land use, i.e. coffee cultivation. Likely measurement errors

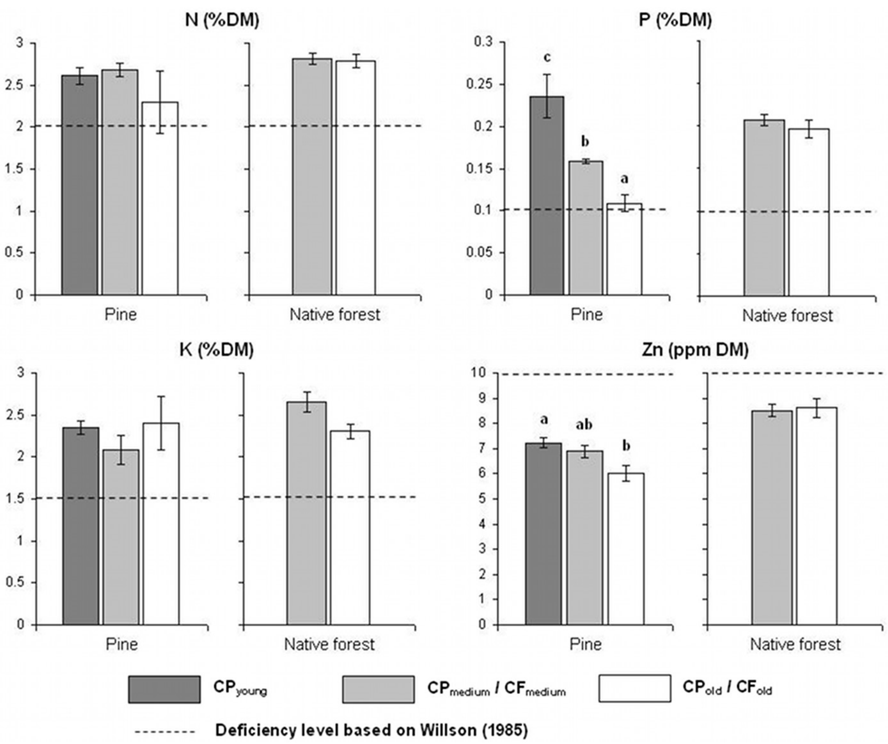

Fig. 3: *Coffee leaf nutrient concentrations of coffee age classes on sites of former pine forest and native forest (data show means ± standard error). Different letters above columns indicate significant differences between land use groups within one previous land cover group according to the Games-Howell-test (P and K of pine sites; P and N of native forest sites) or Scheffé-test (α= 0.05).* CP_{young} *= young coffee plantations (20 years) on former pine forest sites,* CP_{medium}/CF_{medium} *= medium aged coffee plantations (30–40 years) on former pine forest/native forest sites,* CP_{old}/CF_{old} *= old coffee plantations (60–70 years) on former pine forest/native forest sites.*

Table 5: *Soil and leaf parameters of young coffee plantations established after pine with different fertilization practices. Different letters behind numbers indicate significant differences between land use groups according to the Games-Howell-test (C/N ratio, available P, Na, leaf N) or Scheffé-test (α= 0.05, N = 5).*

	organic		*mineral* (26 $kg\ N\ ha^{-1}y^{-1}$)		*mineral* (46 $kg\ N\ ha^{-1}y^{-1}$)	
	mean	*s.e.*	*mean*	*s.e.*	*mean*	*s.e.*
Soil parameters						
pH ($CaCl_2$)	6.11 *b*	0.23	4.75 *a*	0.14	4.85 *a*	0.10
C (%)	4.41 *b*	0.26	4.49 *b*	0.11	3.25 *a*	0.16
N (%)	0.28 *b*	0.02	0.31 *b*	0.01	0.22 *a*	0.01
C/N	15.8	0.95	14.39	0.21	15.08	0.13
P (mg kg^{-1})	34	12	3	< 0.01	10	4.00
Na (mg kg^{-1})	13.8	2.3	11.5	< 0.01	11.5	< 0.01
K (mg kg^{-1})	109.5	19.6	132.9	19.6	187.7	23.5
Ca (mg kg^{-1})	3679.3 *b*	290.6	2164.3 *a*	174.3	2170.3 *a*	286.6
Mg (mg kg^{-1})	140.9	19.4	168.9	20.7	192.0	23.1
Leaf parameters						
N (% DM)	2.79	0.26	2.47	0.05	2.56	0.09
P (% DM)	0.35 *b*	0.04	0.16 *a*	0.01	0.19 *a*	0.01
K (% DM)	2.38	0.20	2.33	0.12	2.34	0.13
Zn (ppm DM)	7.80	0.40	6.94	0.20	6.92	0.26

in the covariates (altitude, slope, sand, and clay fractions) were another source of variation (Garson, 2009), to which the uncertainty regarding the reported age of coffee plantations is to be added. Nevertheless, across sites land cover history significantly affected soil and coffee leaf parameters (Table 3) and soil samples of the F_{grass} sites were similar to those of forest sites. This suggests that the differences in soil parameters observed between P_{grass} and forest sites are indeed due to differences in land cover history (pine forest and native forest) rather than due to differences in current vegetation types (grassland and forest). However, F_{grass} soil samples were only taken at one location and it cannot be excluded that other factors are responsible for this apparent similarity. Nonetheless, the opposing trends between the two groups of land cover history emphasize the importance of taking initial soil conditions into account when evaluating the ecological sustainability of agroforestry systems (Sanchez, 1987).

Factor expressions were partly autocorrelated due to natural conditions and socio-economic developments, particularly plantations on former rain forest land occurred generally at higher altitudes than plantations on former pine forest land. Likewise no fertilizers were applied on any of the plantations established after rain forest. The apparent effect of altitude may thus mainly be due to the fact that pine forests in the past were mostly situated at lower altitudes than native forests. On the other hand, factor effects may also be related to geological phenomena and hence to altitude-related changes in soil parent material. Also, altitude-related temperature differences may have contributed to differences in leaf nutrient levels. Effects of slope on soil cation concentrations (Table 3) may also indicate increased erosion processes on sites with steeper slopes.

4.2 *Soil nutrient status*

Previous studies showed that soils under several decades of pine forest may have lower pH, N, and Ca concentrations, and that their soil OM has a higher C/N ratio than soils under other tree species (Rhoades, 1997; Smolander & Kitunen, 2002; Hartemink, 2003). Results of this study suggest a similar trend since soils previously under pine had lower soil pH, N, and Ca levels and a higher C/N ratio than those previously under native forest.

A soil pH ($CaCl_2$) of 4.4–5.5 is considered most suitable for coffee growth (Snoeck & Lambot, 2009). The average soil pH of the coffee plantations sampled in this study was between 4.4 and 6.1 and therefore largely within this range. The significantly lower pH levels on coffee sites than on forest or grassland sites may indicate an acidification process induced by coffee cultivation. Concentrations of Na and Ca were also lower under coffee, suggesting increased leaching of basic cations which would hence reflect acidification. The plantation where organic fertilizers in the form of cow manure were applied had significantly higher pH and Ca levels than comparable plantations where mineral fertilizers were applied, suggesting that organic fertilization has the potential to improve or maintain soil characteristics compared to mineral fertilization.

Soil OM levels were often found to decrease after conversion of natural forest to cultivated land (Hairiah *et al.*, 2005; Lumbanraja *et al.*, 1998). In this study, C concentrations were high and comparable to results by ITC (1984) who found total C contents of coffee gardens on volcanic parent material in Aceh Tengah ranging from 3–8 %. The significant differences in soil C levels between the studied land use groups (Figure 1) may be hard to interpret in terms of system effects on soil OM levels since charcoal found in most soil samples considerably contributed to measured C. This most likely results from slash and burn land clearing practiced before the establishment of coffee gardens as well as from occasional spreading of household fire residues. High soil C levels have been previously found in tropical areas were land clearing by slash-and-burn is common (Ketterings *et al.*, 2000). The contribution of recalcitrant (black) C to total C was, however, not quantified in this study.

Harvest of coffee berries leads to a major extraction of N (Willson, 1985). Among plots of previous native forest cover, N levels were lower under coffee plantations than under forest, whereas on plots following pine, N levels tended to be higher in medium and older coffee plantations and under grassland. Younger coffee plantations had the same N level as grassland (Figure 1). Soils of coffee plantations had lower C/N ratios than those of the respective grassland or forest sites, although such numerical differences were not always significant, suggesting that the soil may have reached a new equilibrium of C/N ratio under coffee cultivation. Increase or at least a stability of N levels in agroforestry systems may be attributed to biological N_2 fixation by leguminous shade trees such as *Leucaena leucocephala* (Dommergues, 1987). Nitrogenous fertilizers were applied on some plantations, but this apparently did not affect soil N concentrations. However, it is not clear how these fertilizers were spread. If they were applied near the coffee tree, their effect on soil nutrients may not have been detectable in samples taken between trees.

While P is considered to be a limiting factor in many weathered tropical soils (Sanchez, 1987; Szott & Melendez, 2001) available P levels were increased in soils under coffee plantations established after native forest compared to forest (Figure 1). This may be attributed to the low productivity of coffee gardens, the P supply by litter of shade trees as well as the low uptake of P by the coffee plant (Willson, 1985). However, in coffee plantations after pine forest, we found a decreasing trend in P levels with duration of use. Karim *et al.* (1999) reported P losses in coffee soils investigated in Aceh Tengah at all yield levels and van der Vossen (2005) estimated a loss of 3 kg P $ha^{-1}y^{-1}$ at a yield level of 0.5 t $ha^{-1}y^{-1}$ in shaded coffee. Levels of available P were in the same range as those reported by ITC (1984) from soils of coffee gardens in Aceh Tengah (5–16 mg Bray II P kg^{-1}). Sampled coffee plants of the plantation where organic fertilizers were applied had higher leaf P concentrations and tended to have higher available P concentrations than plantations where mineral N fertilizers were applied (Table 5). This suggests that organic fertilization improved the status of plant available P by supplying P, chelators for ligand exchange (providing an organic P source), and / or maintaining higher pH levels (Szott & Melendez, 2001). The encountered heterogeneity of P levels within plots and treatment groups prevented detection of significant differences among plots, suggesting that a higher sampling density may be necessary to allow any conclusions about the P status of such systems (Hartemink, 2003).

Potassium is the most important nutrient exported with harvested coffee beans (Willson, 1985). However, no decline of soil K levels induced by coffee cultivation was observed in this study (Figure 2), which may be due to low productivity levels and comparatively large soil reserves. The study of Karim *et al.* (1999) revealed that soil K concentrations did not decline at yield levels of 1 t $ha^{-1}y^{-1}$. On the other hand, soil K concentrations were partly explained by slope (Table 3), suggesting that erosion processes affected K levels irrespective of land cover. The regular supply of plant material from shade and coffee trees and weeds may slow down the decline of soil K levels in coffee agroforestry systems (Snoeck & Lambot, 2009). Across sampling points K:Mg ratios ranged from 1:8.5 up to 1:0.24 while an optimum K:Mg ratio of 1:3 has been reported by Snoeck & Lambot (2009). Potassium and Mg are known to behave antagonistically in soils and an excess of K and deficiency of Mg can lead to accelerated leaf fall, lower yield, and production of poor quality beans (Snoeck & Lambot, 2009). In our study area higher K:Mg ratios seemed to mainly occur in the oldest coffee plantations following native forest. Continued coffee cultivation also led to a decrease in soil Na levels, possibly due to increased leaching or run-off processes in coffee plantations though no effect of slope was found.

In our study Ca levels were high compared to previous results from Sumatra (ITC, 1984; Lumbanraja *et al.*, 1998). This may be attributed to the metamorphic limestone predominating in the study area. Calcium levels decreased with pine vegetation as well as coffee cultivation (Figure 2). Since removal of Ca with the harvested beans is small (Willson, 1985), the decreases induced by coffee cultivation may be caused by erosion or leaching (Karim *et al.*, 1999). Similar to Mg, low levels of Ca affect bean quality (Snoeck & Lambot, 2009). In the plantation where organic fertilizers were applied, significantly higher soil Ca levels were found compared to plantations where mineral fertilizers were used. This was presumably due to the supply of Ca in manure. On the other hand plantations differed in weed management and the species richness of shade trees (Table 2) which may also contribute to differences in soil Ca.

Lumbanraja *et al.* (1998) studied soil fertility changes in Southern Sumatra after deforestation of primary forests and observed a significant decline of C_{org}, N, available P, total P, and exchangeable Ca, K, and Na after 20 years of conversion to coffee and other land use systems. While decreases of Ca and Na could be observed in this study, other soil nutrient levels seemed to be rather stable even after many decades of coffee cultivation.

4.3 Coffee plant nutrient status

Comparable leaf nutrient levels were reported from the survey of Leyder (1980) in coffee gardens of Aceh Tengah, where Zn was also consistently deficient. Snoeck & Lambot (2009) stated that Zn deficiency is frequent in acid or exhausted coffee garden soils. Previous land cover had considerable effects on leaf N, P, and Zn levels that tended to be lower in CP plantations than in CF plots (Table 3, Figure 3). This suggests that previous pine vegetation affected the availability of nutrients, particularly Zn, which may also be related to lower pH (Snoeck & Lambot, 2009) or nutrient imbalances which can restrict the uptake of Zn by the coffee plant (Willson, 1985). A decrease of P and Zn levels with coffee plantation age was noted on former pine sites where P levels were close to deficiency (Figure 3). Leaf nutrient levels seemed to be more stable in coffee plantations following natural forest.

4.4 Soil texture

While no significant differences of soil texture between land cover groups were found (Table 4), results of texture analysis in this study have to be evaluated critically, since analysis was complicated by the presence of OM, especially charcoal, in the samples. At reported efficiencies of <20 % to >93 % wet oxidation with H_2O_2 does not completely remove OM (Mikutta *et al.*, 2005). Hydrogen peroxide is ineffective in removing charcoal and there is a limited degradation of lignin under acid conditions. Furthermore, in soils with high clay contents OM removal by oxidation with H_2O_2 has been shown to be less effective (Mikutta *et al.*, 2005). High amounts of residual OM and charcoal were found after pretreatment with H_2O_2 in the samples studied here. These may have contributed to the particle size fractions determined by sieving and sedimentation. While the sedimentation and pipette method assumes a standard particle density of quartz (2.65 g cm^{-3}), OM and coal particles have lower densities and hence lower settling velocities, potentially leading to an underestimation of particle size compared to mineral particles (Schmidt *et al.*, 1999). Furthermore, Ketterings *et al.* (2000) showed that exposure of the topsoil to high temperatures due to slash-and-burn agriculture may lead to a pronounced increase of the apparent size of the sand fraction and a corresponding decrease of the silt and clay fractions. Results of texture analysis may therefore be ambiguous.

4.5 Implications for plantation management

The study area is only marginally suitable for coffee cultivation compared to the region with fertile volcanic soils in Aceh Tengah and it was thus suggested that sustainable coffee production in the Lake Laut Tawar area is only possible with continued application of fertilizers to avoid depletion of nutrients (Schuiling, 1982). However N, P, and K levels seemed to be sufficient on the sampled sites and it is questionable whether the application of mineral N fertilizer is indeed necessary and economic at the current levels of production and with the high shading intensity in the Gayo agroforestry systems. On the other hand, the decline of leaf P with plantation age suggests that P deficiency in coffee plants may become an issue in the future. Likewise, the low Zn levels in coffee leaves especially on sites with previous pine forest cover are alarming and should be addressed to avoid negative effects on plant growth in the future. However, under the local conditions the low Zn concentrations in coffee leaves may reflect an unclear combination of nutrient imbalances in the soil and adverse environmental conditions.

The apparently negligible soil fertility decline regarding the measured macronutrients after many decades of coffee production may be largely attributed to the low productivity of the systems. Karim *et al.* (1999) concluded that 8 t ha^{-1}y^{-1} of organic fertilizer are needed to supply sufficient amounts of nutrients (N, K , Ca, and Mg) in coffee gardens of central Aceh, whereas an enrichment with P is necessary. There is a potential to improve nutrient cycling in Gayo coffee plantations by composting harvest residues such as coffee pulp and parchment which at present are hardly ever composted and returned to the system. However, van der Vossen (2005) stated that 3–4 times the amount of compost from fruit waste produced in the field is necessary for a sustainable production at any yield level. Examples of plantations producing organic coffee rely to high levels of external nutrient inputs from such sources as cattle manure and rock phosphate (van der Vossen, 2005). The surrounding grassland areas in the studied area may provide a source of OM by using them as grazing grounds or by cutting the grass which is finally recycled onto coffee land. On the other hand, Metzler-Amieux & Dosso (1998) investigated soil fertility in a coffee production area in Burundi at a hill scale where OM was taken from hill sites as mulch for coffee fields, and found that production was not sustainable since soil OM was exhausted at the hill scale. Hence, while the apparently better soil status of the plantation using organic manure points towards the potential of improving sustainability of coffee production in the future, there is the danger of a further decline of soil fertility in the surrounding grassland if organic production was to be adopted on a larger scale.

On the other hand, it is questionable whether farmers have the means to produce and spread sufficient amounts of organic fertilizer since most are forced to engage in other activities besides coffee growing to secure their livelihoods. Also deficiencies of micronutrients such as Zn are difficult to compensate by organic fertilization.

The production of high quality coffee is largely determined by coffee bean drying and processing techniques (Wintgens, 2009; CRI, 2006). The Gayo coffee is appreciated in countries such as the US and Japan for its special character, but problems with quality have been reported due to inconsistent processing (Nur & Melala, 2001).

Erosion in coffee plantations has been shown to be more responsible for losses of N, Ca, and Mg than yield (Karim *et al.*, 1999). The problem of lacking anti-erosion measures in coffee plantations of central Aceh has been underlined by Schuiling (1982). He suggested that contour planting be introduced and considered the construction of terraces necessary for slopes exceeding 15 °. Furthermore, he criticized the deforestation of steep slopes and emphasized that slopes > 45 ° should not be cultivated and farmers of already existing plantations 'should be persuaded to move to suitable locations'. It seems that none of these recommendations were implemented in the years following the report. This issue is particularly important for the Lake Laut Tawar ecosystem which reportedly has been experiencing pollution, decrease of water level, eutrophication and endangerment of local fish species in recent years (YLI, 2008). The sampling depth of 0–20 cm chosen in this study did not always coincide with the A-horizon of the soil, but often extended into the B-horizon. This suggests that erosion took place on these particular sites, but it could not be quantified in this study. On the other hand, slope was found to have an effect on the level of some soil nutrients (Table 3) and the decline of nutrients such as Na and Ca induced by coffee cultivation can be attributed to increased erosion or leaching processes in coffee plantations.

5 Conclusions

Major nutrients exported by the coffee crop such as N and K were found to be rather unaffected by plantation age class, which may be due to the low productivity of coffee trees, the contribution of *Leucaena leucocephala* trees to N supply, and the supply of litter fall from coffee and shade trees. On the other hand, levels of soil exchangeable cations seemed to have decreased in coffee plantations compared to grassland and forest sites. While export of these nutrients with the crop is small, their decline may reflect the effects of increased soil erosion and leaching in coffee plantations. Measures against erosion will therefore likely be of increasing importance in the future in order to prevent further losses of nutrients and organic C. Concentrations of available P showed different trends depending on the previous land cover of coffee plantation sites. While N, P, and K concentrations of coffee leaves were high, Zn concentrations were deficient. At the current productivity level and applied management practices Gayo coffee cultivation in the Lake Laut Tawar area seems sustainable, but any increase in yield levels may challenge this sustainability. Increases of farmer income should therefore primarily be achieved by exploiting the potential of producing beans of high quality and encouraging the marketing of organic and fair trade specialty coffee.

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