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Impact of stand age on soil C, N and P dynamics in a 40-year chronosequence of alder-cardamom agroforestry stands of the Sikkim Himalaya

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Nutrient concentrations;
Nutrient pool sizes

Summary

The impact of age (5, 10, 15, 20, 30, 40 years) on chemical characteristics of mineral soil under an age sequence of alder-cardamom agroforestry stands was studied in the Eastern Himalayas. The seasonal variation in soil organic carbon (OC), soil organic matter (SOM), total nitrogen (TN), forms of phosphorus (total P, organic P, inorganic P, available P, fractionated forms of P), mineral nitrogen, potential N mineralization and nitrification was measured in the chronosequence across three replicate sites each having six representative stand ages. We hypothesized that nutrient stocks would be lower in younger agroforestry stands, would eventually increase with stand age due to the influence of alder but then decline as the stands mature further. The expected pattern of increasing soil nutrient stocks with stand age did occur with a peak at 15–20 years; nutrient stocks then substantially declined in 30- to 40-year-old stands. A significant seasonality, which coincided with cardamom flowering and fruiting, was observed in soil nutrient contents and N transformation rates. The 15–20-year-old stands had the highest nutrient pools and potential N transformation rates, whereas the youngest and oldest stands had the lowest nutrient pools. Soil acidity increased with stand age. Soil pH was negatively related to stand age and SOM in the linear regression. Nutrient dynamics varied with age depending on the successional stage, which limited soil nutrient availability for plant uptake after the 20-year point. The performance of both alder and cardamom was reduced after this age likely due to limited soil nutrient availability and nutrient dynamics as a result of recurrent biomass removal – part of the traditional management practice. This study concludes that the ecological and economic sustainability of this particular

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agroforestry system is possible by adopting a 20-year re-plantation cycle for alder and cardamom, and a phase-wise agroforestry rotation.

Introduction

Recent challenges confronting sustainable development are linked to large-scale land use transition, which have resulted in the increased vulnerability of people dependent on forests and traditional agroforests. Agroforestry practices offer multiple opportunities to farmers for improving soil fertility, increasing farm productivity and income, and can also provide a number of productive and protective functions (Sharma et al. 2008a). One example of this type of practice is large cardamom (*Amomum subulatum*)-based agroforestry. Large cardamom is one of the profitable crops of the Eastern Himalayan region. It is cultivated as a perennial crop under Himalayan alder (*Alnus nepalensis*) at elevations ranging from 500 to 2100 m asl. Details of this crop are also presented in Sharma et al. (2002a, b, 2008a, b), and Sharma and Singh (2004). It is grown over about 30,000 ha on the mountain hill slopes of Sikkim and Darjeeling, with the former being the largest production area in the world with a 53% market share; the remainder is produced in eastern Nepal and Bhutan. Annual crop production in Sikkim is 3833 Mt (Srinivasa 2006), which represents approximately US$ 15–17 million per year.

Sharma et al. (1994) reported that the incorporation of N_2-fixing alder in non-N_2-fixing cardamom-based agroforestry systems resulted in increased productivity and accelerated nutrient cycling. Reports of such inclusion of N_2-fixing species have revealed a wide range of effects on ecosystem production and nutrient cycling, and a wide variation in these effects across species, locations and stand designs (Binkley et al. 1994; Gardiana et al. 1995; Binkley 1997; Binkley and Ryan 1998; Pearson and Vitousek 2001). The presence of N_2-fixing trees increases the rates of nutrient cycling in all situations, but the effects on ecosystem productivity and on the growth of the associated species have been variable. Mixtures of N_2-fixing and non-N_2-fixing trees have typically shown increased rates of nutrient cycling, particularly for N and P (Binkley 1983; Cote and Camire 1987; DeBell et al. 1989; Binkley et al. 1992a, b). Other studies indicate that N_2-fixing trees may increase the supply of available N in the soil, thus benefiting both the N_2-fixing and non-N_2-fixing associated tree species (Binkley 1997). N_2-fixing tree species can have variable feedback effects on the soil P supply with an increase in the latter possibly enhancing long-term growth of the N_2-fixer (Binkley et al. 1999). Similar reports are available on the potential impacts of exotic N_2-fixers on the supply of N to the system and its availability for uptake by other plants. *Myrica faya* in Hawaii (Vitousek et al. 1987) and *Elaeagnus umbellata* in the Western USA (Baer et al. 2006) are examples; such invasive species also accelerate nutrient cycling and the supply of nutrients (Allison and Vitousek 2004).

Therefore, in mixtures of N_2-fixing with non-N_2-fixing species, such as the alder-understory cardamom agroforestry system, we hypothesized that nutrient cycling would be highest in the younger stands. We also proposed that this accelerated nutrient cycling, caused by N_2-fixing alders, would diminish after a certain age, which would affect stand nutrient dynamics by reducing nutrient use efficiency. The present study was a follow-up on our previous research on productivity, energetics, nutrient cycling, biological N_2-fixation by alder nodules and N_2-fixation efficiency, and on our litter decomposition studies in an age series of alder-cardamom agroforestry stands (Sharma et al. 2002a, b, 2008a, b). Sharma et al. (2002a, b, 2007) concluded that the net primary productivity (NPP), agronomic yield, net energy fixation rates, production efficiency, energy conversion efficiency and energy efficiency in N_2-fixation were comparatively higher in younger stands and suggested an optimal rotation for such agroforestry systems of 20 years. The magnitude of nutrient and energy release in those younger plantations was large, indicating accelerated nutrient cycling through litter production, decomposition and associated heat sinks compared to stands older than 20 years (Sharma et al. 2008a, b). However, evidence of the impact of stand age on soil nutrient dynamics under the influence of alder in cardamom-based agroforestry systems has been lacking to support conclusions that would guide system management and practice. Thus, an understanding of soil nutrient dynamics as a function of stand age would not only support our earlier findings but be critical for management recommendations.

The main objectives of this study were to examine the seasonal variation of (a) the change in soil pH, moisture, soil organic carbon (OC) and soil organic matter (SOM), (b) N transformation through mineralization and net nitrification and (c) different forms of soil P and pools of fractionated forms of P in an age series of alder-cardamom agroforestry stands. We expected the soil OC, SOM, total nitrogen (TN), nitrogen availability (NA), total phosphorus (TP), inorganic phosphorus (IP) and available phosphorus (AP) contents to be lower in the early stages of agroforestry development, but then to increase with age as stand succession proceeds. Finally, we expected a subsequent decline of soil nutrient pools in the older stands after the system peaks at certain age.

Materials and methods

Study areas

Three experimental sites, located at Kabi (North District), Thekabong (East District) and Sumik (East District), in the Sikkim Himalaya were selected in this study. These sites lie within 27° 08′ 56.37″–27° 23′ 56.40″ N latitude and 88° 41′ 27.40″–88° 21′ 55.38″ E longitude at an elevation of between 1350 and 1600 m asl. These study sites are part of the Indian monsoon region characterized by a temperate climate. Mean monthly maximum temperature ranged from 14.3 to 23.3 °C, mean monthly minimum temperature from 5.4 to 15.8 °C and rainfall amounts from 2500 to 3500 mm during the 3-year study period. Relative humidity varied between 80% and 95% during the rainy season and decreased to about 45% in spring (Sharma et al. 2002a, b, 2008a, b).

All three experimental sites in Sikkim have several pure agroforestry stands of cardamom grown under Himalayan alder shade trees. Cardamom is a shade-loving plant and is generally cultivated under shade trees for which alder is a common choice. The altitudinal range of alder is sympatric with the agroclimatic range of large cardamom (Sharma et al. 2000). There is no traditional rotation length for cardamom agroforestry, although old plantations are less productive (Sharma et al. 2002a). The alder-cardamom stands of all three experimental sites were represented by an age series that included 5-, 10-, 15-, 20-, 30- and 40-year-old agroforestry stands for a total of 18 plots. Thus, each stand age was replicated three times and each site had plantations of all the six stand ages. Stand age refers to the same age for both cardamom and alder as they were planted simultaneously. The age of the alder-cardamom stands was confirmed by interviewing the farmers of the plantations at the different sites. In addition to alder and cardamom planting time, farmers were asked about changes in management as stands mature under the traditional agroforestry practice.

The study sites at the three locations were closely comparable; the structural and functional differences were attributed to the age of the agroforestry systems. The mean stand tree density per hectare was 347, 553, 417, 321, 204 and 180 in the 5-, 10-, 15-, 20-, 30- and 40-year-old stands, respectively. The density of trees and cardamom bush numbers were almost similar in stands of the same stand age in all three sites. Site variation was comparatively low among stands of different ages and structure. Light interception by canopy interference was high until 15 years of age and comparatively lower in older stands. Sampled stands at the sites were all south-west facing (Sharma et al. 2002a; Sharma and Singh 2004). Similarly, tree heights ranged between 15 and 27 m in stands up to 20 years of age and increased to 35 m in 40-year-old stands. Tree canopy cover increased with advancing age and was optimal for the understory cardamom crop in the younger stands until they reached 20 years of age. Coppicing or loping of alder branches is not practiced in alder-cardamom agroforestry. Density of cardamom tillers increased from the youngest age group ($130–160 \times 10^3$ tillers ha^{-1}) to a maximum for the 15-year-old stand ($560–630 \times 10^3$ tillers ha^{-1}) after which tiller numbers decreased along the age series (40-year-old stand; $20–40 \times 10^3$ tillers ha^{-1}). Net primary productivity of the stands increased from 16.33 to 22.38 t ha^{-1} year^{-1} for the 5- and 15-year-old stands but declined thereafter to 7.33 t ha^{-1} year^{-1} for the 40-year-old stand (Sharma et al. 2002a). The light interception by alder canopy was highest (80–96%) in the 5- and 15-year-old stands where tree density was high. The average height of the understory crop was between 2 and 3 m (Sharma and Singh 2004). The soils under cardamom plantations, predominantly Typic Hapludolls and Dystric Eutrochrepts, were generally acidic due to heavy rainfall and the subsequent leaching of bases from surface soil. Red and yellowish podzolic soils are found in the agroforestry stands of Sikkim (Mukhopadhyaya 1998). Soil was acidic (pH 3.7–5.6) and while pH varied widely with depth, the variation in surface soil pH was small between stands (17%). The soil was a sandy loam ranging in composition from 11% to 30% clay, 15% to 40% silt and 34% to 65% sand, with a soil porosity between 57% and 70%.

Soil sampling and analysis

Seasonal soil sampling (winter, spring and rainy season) was carried out in the sample plots (30 × 40 m) for each of the six age series (5-, 10-, 15-, 20-, 30- and 40-year-old stands) in all three true replicate sites between 1998 and 2000. Five subsamples (pseudo-replicates) from two different soil depths (0–15 cm, 15–30 cm) were collected by sampling each stand randomly at approximately 3–5 m from the alder trees. Fresh soil samples were immediately taken to the laboratory. Subsamples were later mixed together and analyzed in replicates of three (3 replicates × 2 soil depths × 3 seasons × 3 sites × 6 stand age = 324). Soil samples, used for nutrient analysis, were air dried, ground and passed through a 2-mm sieve. Fresh soil samples were used to analyze pH. Percent soil moisture was determined by drying the soil samples at 80 °C until constant weight was achieved. Soil OC was analyzed following the Walkley–Black method and TN was estimated by a modified Kjeldahl method (Anderson and Ingram 1993). SOM was calculated following Anderson and Ingram (1993). TP was estimated using a hydrogen peroxide oxidized acidified ammonium fluoride extract with the chlorostannous-reduced molybdophosphoric blue colour method (Jackson 1967); IP was estimated using dilute HCl ammonium fluoride extract with the chlorostannous-reduced molybdophosphoric blue colour method (Jackson 1967). AP was determined using sodium bicarbonate extract with the colorimetric method (Anderson and Ingram 1993) while Al-, Fe-, Ca- and occluded Fe-phosphate were measured with the P-fractionation method of Jackson (1967).

To estimate N mineralization and nitrification, *in situ* field aerobic incubation (14 days) of soil samples was performed seasonally in all six stand ages of three site replicates. Fresh soil samples (0–20 cm) were used to estimate inorganic N concentrations, namely NH_4^+ and NO_3^-, following methods given by Anderson and Ingram (1993). Net mineralization rates were determined as the difference in mineral nitrogen (NH_4^++NO_3^-) between the pre- and post-incubated soil samples. Net nitrification rates were calculated as the difference in nitrate-N between pre- and post-incubated soil samples.

Soil bulk density (mass per unit volume in g cm^{-3}) in all experimental plots was determined from random cores taken at 0–15 and 15–30 cm depths. Samples were oven dried at 80 °C to constant weight. Soil nutrient contents in different seasons in each soil horizon (0–15 and 15–30 cm) were estimated from bulk density, soil volume and nutrient concentration values (Sharma et al. 1985). Nutrient contents estimated in both horizons were summed to obtain total content down to a 30-cm depth.

Statistical analysis

We used Systat 6, SPSS Inc., 1996 to perform the analyses of variance (ANOVA) to determine differences among the three sites, six stand ages, three seasons, two depths, and to determine any interactions. Simple regression analyses were employed to compare the strength of relationships between pH, moisture, SOM and other soil variables as a function of stand age. Data were pooled across sampling dates, sites and depths to simplify the analyses.

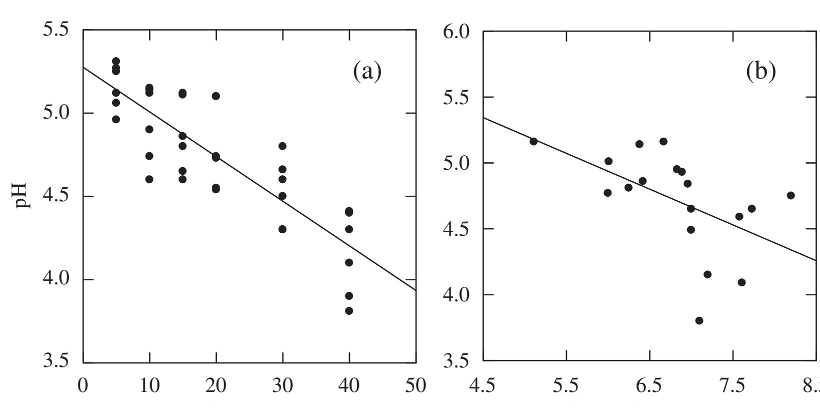

Figure 1. Relationship between (a) soil pH and stand age ($y = 5.37-0.027\,x$, $r^2 = 0.52$, $P<0.0001$) and (b) soil pH and SOM ($y = 6.57-0.272\,x$, $r^2 = 0.53$, $P<0.001$) in an age series of alder-cardamom agroforestry stands. Values are pooled from all the sites and stand ages.

Table 1. Seasonal variation in soil pH, organic carbon (OC), soil organic matter (SOM) and total nitrogen (TN) in an age series of alder-cardamom agroforestry stands.

Stand age (year)	Soil depth (cm)	pH			OC (%)			SOM (%)			TN (%)		
		Winter	Spring	Rainy	Winter	Spring	Rainy	Winter	Spring	Rainy	Winter	Spring	Rainy
5	0–15	5.06±0.10	5.01±0.08	4.96±0.10	3.78±0.38	4.59±0.14	5.10±0.52	6.52±0.65	7.91±0.28	8.79±0.89	0.30±0.05	0.34±0.01	0.48±0.28
	15–30	5.35±0.11	5.31±0.07	5.32±0.07	2.14±0.39	2.81±0.09	2.64±0.31	3.70±0.68	4.84±0.16	4.55±0.53	0.23±0.23	0.20±0.02	0.24±0.03
10	0–15	4.86±0.18	4.58±0.14	4.74±0.21	4.41±0.37	4.57±0.13	5.06±0.66	7.60±0.64	7.87±0.23	8.71±1.13	0.41±0.05	0.40±0.03	0.47±0.03
	15–30	5.15±0.21	5.14±0.22	5.12±0.14	2.56±0.29	2.88±0.10	2.95±0.31	4.42±0.51	4.96±0.18	5.08±0.54	0.21±0.02	0.25±0.02	0.29±0.02
15	0–15	4.80±0.17	4.56±0.31	4.64±0.19	5.62±0.55	5.03±0.29	5.03±0.72	8.96±0.95	8.68±0.49	8.67±1.24	0.49±0.08	0.43±0.03	0.55±0.03
	15–30	5.10±0.14	5.11±0.25	4.86±0.16	3.30±0.58	3.04±0.14	4.29±0.33	5.69±1.00	5.24±0.24	7.74±0.58	0.28±0.03	0.29±0.03	0.39±0.04
20	0–15	4.73±0.18	4.54±0.23	4.55±0.27	5.82±0.60	4.11±0.41	5.50±0.55	8.59±1.03	9.08±0.71	9.48±0.95	0.51±0.05	0.56±0.04	0.79±0.32
	15–30	5.07±0.17	4.80±0.19	4.74±0.21	2.69±0.35	3.56±0.23	2.62±0.37	5.63±0.61	5.42±0.40	6.51±0.63	0.38±0.03	0.39±0.02	0.31±0.02
30	0–15	4.30±0.15	4.53±0.27	4.51±0.28	4.90±0.44	4.83±0.15	5.19±0.60	7.73±0.75	7.32±0.26	8.77±1.03	0.49±0.05	0.48±0.03	0.47±0.05
	15–30	4.68±0.16	4.77±0.27	4.66±0.23	3.46±0.28	4.15±0.22	3.70±0.35	6.24±0.49	7.15±0.39	6.39±0.61	0.29±0.04	0.27±0.04	0.32±0.04
40	0–15	3.81±0.16	3.72±0.14	4.01±0.18	3.16±0.31	4.19±0.27	4.84±0.29	6.89±0.54	6.23±0.47	6.35±049	0.54±0.05	0.41±0.06	0.50±0.06
	15–30	4.48±0.26	4.57±0.10	4.42±0.11	2.51±0.19	3.11±0.17	2.84±0.31	5.33±0.33	4.37±0.24	5.81±0.13	0.21±0.02	0.22±0.02	0.24±0.05
ANOVA													
Stand age		$F_{5,288}=17.90$, $P<0.0001$			$F_{5,288}=3.33$, $P<0.006$			$F_{5,288}=3.32$, $P<0.0001$			$F_{5,288}=3.74$, $P<0.003$		
Season		$F_{2,288}=7.32$, $P<0.001$			$F_{2,288}=10.00$, $P<0.0001$			$F_{2,288}=10.00$, $P<0.0001$			$F_{2,288}=14.82$, $P<0.001$		
Depth		$F_{1,288}=9.57$, $P<0.002$			$F_{1,288}=172.72$, $P<0.0001$			$F_{1,288}=172.72$, $P<0.0001$			$F_{1,288}=238.15$, $P<0.0001$		
Stand age × Depth		NS			NS			NS			$F_{5,288}=2.8$, $P<0.01$		
Stand age × Season		NS			NS			NS			NS		
Stand age × Season × Depth		NS			NS			NS			NS		

Values are means of three replicates of each stand age ($n=9$).

Table 2. Seasonal variation in total P (TP), inorganic P (IP), IP/TP ratio and available P (AP) at two-soil depths in an age series of alder-cardamom agroforestry stands.

Stand age (year)	Soil depth (cm)	TP (mg 100 g^{-1} soil)			IP (mg 100 g^{-1} soil)			IP/TP ratio			AP (mg 100 g^{-1} soil)		
		Winter	Spring	Rainy	Winter	Spring	Rainy	Winter	Spring	Rainy	Winter	Spring	Rainy
5	0–15	101.79±7.13	105.33±6.91	90.04±4.91	5.40±1.29	5.57±0.86	6.23±0.56	0.06±0.02	0.06±0.01	0.07±0.01	7.78±1.95	9.21±2.16	7.87±1.21
	15–30	87.07±6.58	97.46±7.34	86.39±5.00	4.02±1.16	1.90±0.11	5.70±0.90	0.05±0.02	0.02±0.00	0.07±0.02	4.78±1.08	6.05±1.35	5.82±1.70
10	0–15	110.98±4.57	113.26±8.05	95.94±5.99	5.54±1.85	2.75±0.33	7.96±2.10	0.05±0.02	0.03±0.01	0.10±0.03	6.75±1.22	8.22±1.41	9.09±0.65
	15–30	91.04±4.63	93.30±7.30	83.81±6.31	4.09±1.09	2.87±0.51	4.53±1.25	0.04±0.01	0.03±0.00	0.07±0.02	5.30±1.49	5.60±1.44	5.25±1.54
15	0–15	101.52±8.57	101.91±9.78	90.17±6.66	5.99±1.86	4.05±0.85	9.02±2.10	0.05±0.01	0.04±0.01	0.11±0.03	6.87±1.10	8.08±2.19	7.15±1.78
	15–30	92.62±8.55	98.63±11.20	80.86±6.37	4.58±1.23	2.20±0.27	6.40±1.44	0.05±0.01	0.03±0.01	0.09±0.03	4.03±1.23	4.80±1.45	5.20±1.60
20	0–15	94.64±8.04	98.32±15.10	95.84±8.74	4.85±1.0	3.58±0.46	8.39±1.18	0.05±0.01	0.03±0.01	0.10±0.02	5.55±1.71	6.65±1.06	6.49±1.26
	15–30	89.94±6.16	95.57±12.42	86.41±8.82	3.62±0.88	1.60±0.31	5.20±1.07	0.04±0.01	0.02±0.00	0.07±0.02	3.76±1.06	5.71±1.24	4.27±0.75
30	0–15	96.48±6.54	108.28±7.30	86.26±3.87	4.72±0.88	6.63±1.75	7.26±1.29	0.05±0.02	0.06±0.01	0.09±0.02	5.52±0.30	6.41±2.23	6.47±0.96
	15–30	86.40±7.23	96.18±8.60	75.46±1.97	5.52±1.80	4.29±0.94	6.24±1.26	0.06±0.02	0.04±0.01	0.08±0.02	3.66±0.43	4.78±1.83	4.60±0.81
40	0–15	84.58±8.35	113.26±7.35	86.66±5.44	5.49±1.34	4.19±0.95	7.93±0.87	0.07±0.02	0.04±0.01	0.10±0.02	3.76±0.76	5.71±1.41	5.37±1.93
	15–30	77.77±7.10	101.08±8.90	78.27±3.92	3.37±0.74	2.83±0.57	5.30±0.63	0.05±0.01	0.03±0.01	0.07±0.01	2.59±0.64	4.78±1.17	4.27±0.29
ANOVA													
Stands		NS			NS			$F_{5,288} = 3.36$, $P < 0.0001$			NS		
Season		$F_{2,288} = 8.29$, $P < 0.0001$			$F_{2,288} = 23.42$, $P < 0.0001$			$F_{2,288} = 34.29$, $P < 0.0001$			$F_{2,288} = 4.59$, $P < 0.01$		
Depth		$F_{1,288} = 13.30$, $P < 0.0001$			$F_{1,288} = 19.56$, $P < 0.0001$			$F_{1,288} = 19.14$, $P < 0.0001$			$F_{1,288} = 13.18$, $P < 0.0001$		
Stand × Depth		NS			NS			NS			NS		
Stands × Season		NS			NS			$F_{10,288} = 1.94$, $P < 0.01$			NS		
Stands × Season × Depth		NS			NS			NS			NS		

Values are means of three replicates of each stand age ($n = 9$).

Results

Soil pH and nutrient concentrations

Soil pH showed significant variation among the agroforestry stands, seasons and depths (d.f. = 5, $F_{5,288} = 17.90$, $P<0.0001$). Mean soil pH of the upper soil horizon was less (3.78–5.01) than the lower horizon (4.42–5.35) (d.f. = 1, $F_{1,288} = 9.57$, $P<0.0001$); among seasons the highest pH values were recorded during winter and the lowest during the rainy season. Pooled soil pH data showed a significant decline with increasing agroforestry stand age and showed a significant negative correlation with stand age in the regression analysis (Figure 1a). Soil pH also had a negative correlation with SOM (Figure 1b). Average soil moisture levels ranged from 24% in the winter to 45% in the rainy season.

Soil depths and seasonal variations of concentrations of OC, TN, SOM, TP, IP and AP are presented in Tables 1 and 2. Details of the ANOVA for each nutrient are presented under each column in the table. Total nitrogen ranged from 0.21% to 0.79%, TP from 75.46 to 113.26 mg 100 g^{-1} soil and OC from 2.56% to 5.50% in the 0–30 cm soil horizon. Concentrations were significantly higher in the upper soil horizon (0–15 cm) than in the lower one (15–30 cm). TN concentrations were highest in the rainy season and lowest in the spring while the reverse was observed for TP concentrations, which were highest in the spring and lowest in the rainy season.

OC, SOM and TN showed significant variation among stand ages, seasons and depths in the analysis of variance (Table 1). TP and IP showed no significant difference along the chronosequence, although they differed with season and soil depth. Concentrations of OC, TN, TP and AP showed a gradual increase with stand age up to 20 years after establishment but decreased in 30- and 40-year-old stands (Tables 1 and 2). Inorganic P

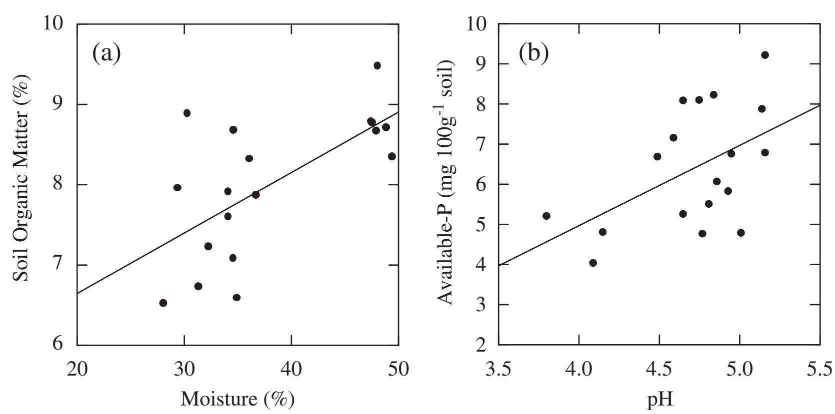

Figure 2. Linear regression between (a) SOM and with soil moisture ($y = 5.14+0.08x$, $r^2 = 0.70$, $P<0.005$), and (b) available P and with soil pH ($y = 1.289+1.148$, $r^2 = 0.73$, $P<0.001$) in an age series of alder-cardamom agroforestry stands.

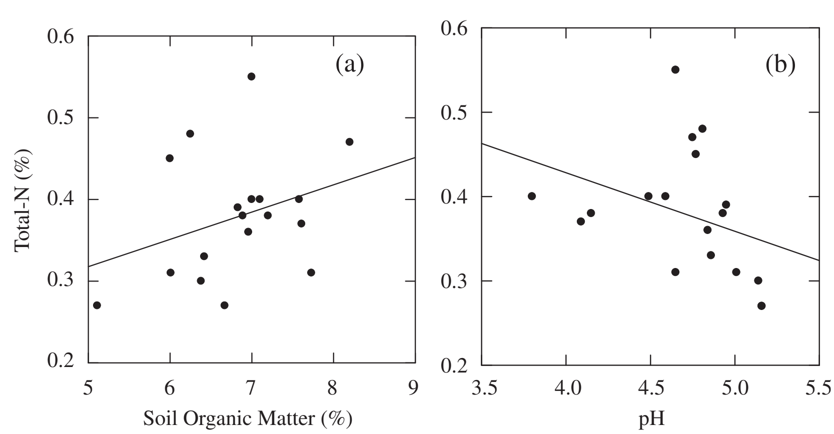

Figure 3. Relationship between (a) total N and SOM ($y = 5.63+3.181x$, $r^2 = 0.34$, $P<0.001$), and (b) total N and soil pH ($y = 5.374-1.751x$, $r^2 = 0.0.35$, $P<0.001$) in an age series of alder-cardamom agorofrestry stands. Values are pooled from all the sites and stand ages.

did not show any significant trends. Alder-cardamom tree density, floorlitter accumulation and cardamom bush number were highest at 15 years after establishment after which time farmers started thinning out alder trees as part of the traditional management practice (described in Sharma et al. 2002a). SOM increased with age up to 20 years of age; thereafter it declined to 22% in the 40-year-old stands. SOM was dependent on soil moisture with both variables positively correlated in the regression analysis ($P<0.005$) (Figure 2a). Concentrations of AP were positively related to soil pH confirming that the younger agroforestry stands had more AP than the older ones (Figure 2b). In the age series, molar C:N ratio ranged from 9.30 to 14.83 with higher values found at 15–30 cm compared to the 0–15 cm depth. The ratio was comparatively higher in spring and lower in the rainy season. Mean C:N ratio was lowest in the 15-year-old stands and highest in the 40-year-old stands. TN had a negative relationship with soil pH in the aging agroforestry stands while it showed a positive correlation with SOM in the regression analysis (Figure 3a and b).

Soil mineral N and potential N transformation pools

Nitrate-N and ammonium-N

Soil nitrate-N concentrations were lowest (13.7–17.3 $\mu g\,g^{-1}$ soil) in the 5-year-old stand, then increased significantly with advancing stand age to the maximum value (14.7–25.9 $\mu g\,g^{-1}$ soil) in the 40-year stand. Concentrations were low (13.17–15.20 $\mu g\,g^{-1}$ soil) during the rainy season and higher (17.26–27.90 $\mu g\,g^{-1}$ soil) in the spring. The effects of stand age and season were highly significant ($P<0.001$) (Figure 4). The concentrations of ammonium-N (0–20 cm) showed dramatic variation that increased from the youngest stand to a maximum range found under the 10-year-old alder-cardamom stand (11.13–69.2 $\mu g\,g^{-1}$ soil) and a minimum value for the 40-year-old stand (9.63–19.68 $\mu g\,g^{-1}$ soil) (Figure 4). Soil ammonium-N concentrations were lowest in the rainy season and highest in the winter. Stand age and season had significant effects ($P<0.001$). Both nitrate-N and ammonium-N were dependent on soil moisture with an inverse relationship evident from the regression (Figure 5). Concentration levels

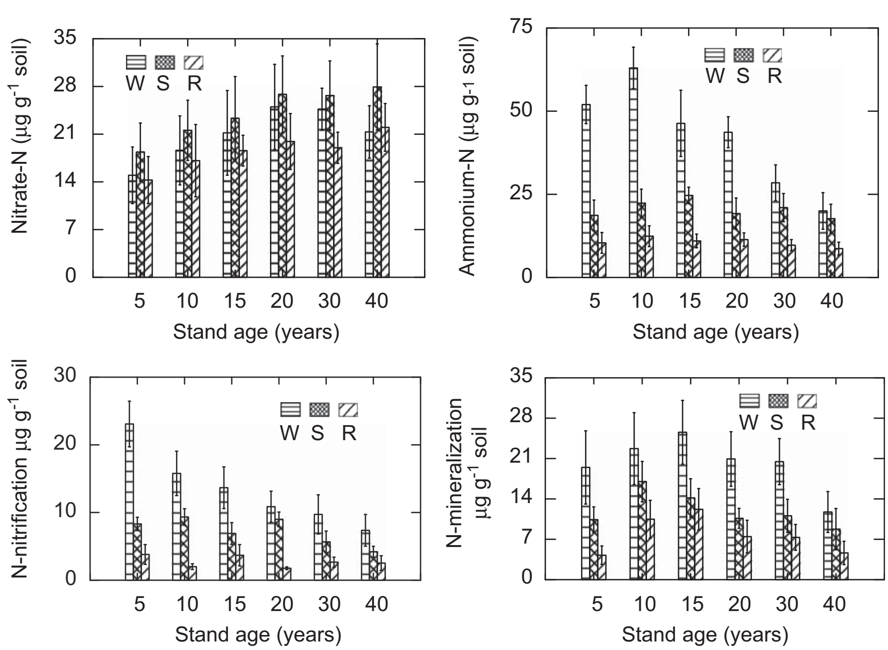

Figure 4. Seasonal variation of nitrate-N, ammonium-N, N-nitrification and N-mineralization at a soil depth of 0–20 cm in an age series of alder-cardamom agroforestry stands. Error bars indicate ±SE. ANOVA: Nitrification—Stand age $F_{5,162}=3.04$, $P<0.022$, Season $F_{2,162}=27$, $P<0.0001$, Stand age × Season = NS; N Mineralization—Stand age $F_{5,162}=9.14$, $P<0.001$; Season $F_{2,162}=12$, $P<0.0001$; Stand age × Season NS; Nitrate—Stand age $F_{5,90}=5.9$, $P<0.001$, Season $F_{2,162}=35$, $P<0.001$, Stand age × Season $F_{10,162}=1.29$, $P<0.02$, LSD (0.05) = 1.56; Ammonium—Stand age $F_{5,162}=12$, $P<0.0001$, Season $F_{2,162}=140$, $P<0.0001$, Stand × Season $F_{10,162}=11$, $P<0.0001$, LSD (0.05) = 3.7.

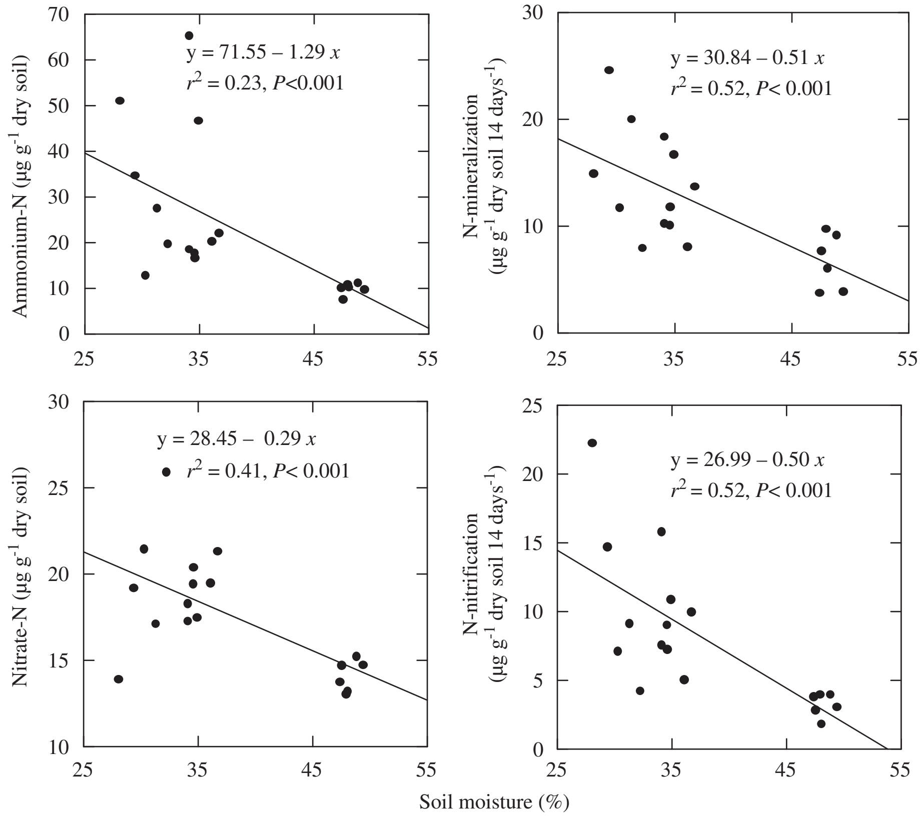

Figure 5. Relationship between ammonium-N and nitrate-N, and soil moisture, and N mineralization and net nitrification, and soil moisture in an age series of alder-cardamom agroforestry stands. Values are means of three site replicates.

were very low at >50% moisture level, but were high within the range of 30–50% soil moisture.

N nitrification and mineralization

Net N nitrification and mineralization varied with season and stand age but did not vary across the sites (Figure 5). N nitrification was highest in winter (7.10–28.23 $\mu g\,g^{-1}$ soil), decreased in spring (3.60–15.40 $\mu g\,g^{-1}$ soil) and further decreased in the rainy season (1.80–4.81 $\mu g\,g^{-1}$ soil). Similarly, N mineralization rates were highest (11.72–27.85 $\mu g\,g^{-1}$ soil) during the winter followed by spring rates (7.91–13.79 $\mu g\,g^{-1}$ soil) with the lowest rates recorded in the rainy season (3.73–9.72 $\mu g\,g^{-1}$ soil) (Figure 5). N nitrification pool sizes were highest in the youngest stands and significantly declined along the age sequence. Pool sizes of N mineralization increased consistently to a maximum in the 15-year-old stands and subsequently decreased in the 20-, 30- and 40-year-old stands. Both N nitrification and N mineralization were dependent on soil moisture and showed inverse relationships (Figure 5). N mineralization and nitrification were positively related to the decreasing soil pH along the stand ages in the linear regression ($r^2 = 0.32$, $P<0.01$).

Fractionated forms of phosphorus

Among the fractionated forms of phosphorus, iron phosphate (Fe-P) and occluded iron phosphate (Occlu. Fe-P) showed significant differences among the stand ages whereas all P forms showed significant variation with season (Table 3). Ca-P and occluded Fe-P were highest in the winter and lowest in the rainy season. In contrast, Al-P and Fe-P were higher in the spring compared to the winter. Occluded Fe-P concentrations were 9–35 times higher than other forms. The range in differences in the fractionated forms of phosphorus followed the order: occluded Fe-P > Ca-P > Fe-P > Al-P in the alder-cardamom agroforestry stand chronosequence.

Total soil nutrient pools

Consistent with our hypothesis that nutrients would increase to a maximum at certain age in an agroforestry succession with a subsequent decline in the older stands, our results showed that stand age had a dramatic effect on nutrient pool sizes with significant increases up to 15–20 years after

Table 3. Seasonal variation in fractionated forms of phosphorus in soil samples (0–30 cm depth) in an age series of alder-cardamom agroforestry stands.

Stand age (year)	Season	Fractionated forms of phosphorus			
		Al-P (μg g^{-1})	Fe-P (μg g^{-1})	Ca-P (μg g^{-1})	Occl. Fe-P (mg 100 g^{-1})
5	Winter	29±09	105±17	100±13	1007±72
	Spring	86±20	126±28	98±07	784±26
	Rainy	40±09	77±07	86±05	285±39
10	Winter	47±09	101±06	108±24	1077±59
	Spring	91±22	111±18	83±22	978±23
	Rainy	37±06	74±15	84±05	374±59
15	Winter	32±03	264±29	110±08	1099±23
	Spring	174±04	150±25	99±13	1056±75
	Rainy	37±05	153±10	80±10	412±46
20	Winter	40±06	126±11	148±14	1145±37
	Spring	78±05	87±05	97±05	803±52
	Rainy	48±10	42±04	70±01	394±12
30	Winter	36±05	124±05	140±27	922±127
	Spring	100±11	115±15	115±11	953±38
	Rainy	36±03	54±02	49±10	389±22
40	Winter	52±05	164±26	106±11	919±52
	Spring	83±41	85±15	91±06	571±41
	Rainy	59±02	57±02	65±07	375±53
ANOVA: *P* values					
Stand age		NS	0.0001	NS	0.003
Season		0.0001	0.0001	0.0001	0.0001
Stand age × Season		NS	NS	NS	NS

Values are means of three replicates of each stand age ($n = 9$).

Table 4. Soil nutrient contents (to a 30-cm soil depth) and nitrogen availability index (NAI) in an age series of alder-cardamom agroforestry stands.

Nutrients	Stand age (year)					
	5	10	15	20	30	40
Organic C (Mg ha^{-1})	85±6	89±5	116±15	106±10	96±8	90±5
SOM[a] (Mg ha^{-1})	145±9	152±5	200±11	158±9	169±15	143±10
Total N (Mg ha^{-1})	8.4±2.1	8.7±1.8	9.9±1.7	11.7±2.9	9.8±1.9	8.9±2.1
Inorganic N (kg ha^{-1})	90±8	93±15	95±17	101±11	82±6	78±5
NAI[b] (kg ha^{-1})	21.9±4.2	30.8±5.0	38.0±9.4	28.9±8.0	26.6±7.4	17.5±4.1
Total P (kg ha^{-1})	2285±105	2312±110	2554±121	2457±139	2255±129	2192±136
Inorganic P (kg ha^{-1})	110±19	117±14	162±20	126±21	120±19	107±25
Available P (kg ha^{-1})	135±17	137±19	182±26	147±16	143±16	130±13

Pooled values are presented from the means of three replicates of each stand age.
[a]Soil organic matter.
[b]Nitrogen availability index.

establishment and declining thereafter. Soil nutrient contents (OC, SOM, TN, IN, TP, IP, AP) showed increased nutrient pools in the younger stands after which time nutrient pools declined in the aging stands (Table 4). Organic carbon, SOM, TN and IP had the largest pools in the rainy season, and the lowest pools were recorded in winter. In contrast, pools of IN and NA were largest in winter and lowest in the rainy season. TP and AP had the largest pool sizes in the spring season and the smallest in the dry winters. Thus, nutrient contents declined with stand age after 20 years. This sharp decline resulted in the loss of a considerable amount of nutrients by 40 years after stand establishment (Table 4). Nutrient pools did not vary across the sites with differences consistently related to successional agroforestry stand age, season and soil depth.

Discussion

The influence of Himalayan alder on soil acidification resulted in the consistent decline of soil pH with increasing alder-cardamom agroforestry stand age. Similar findings have been reported for red alder in the Pacific Northwest (Van Cleve and Viereck 1972; Bormann and DeBell 1981; Binkley 1983; DeBell et al. 1983). Authors of those studies also suggested that the lower base saturation resulted from the production of H^+ in nitrification, with H^+ displacing base cations, which then leached from the soil with NO_3^- (Binkley and Sollins 1990). In our study, the increase in acidity with stand age may be related to the accumulation of acidic SOM, and increased water percolation due to high rainfall, which in turn leads to accelerated leaching losses of large quantities of base cations and nitrates from the soil profile. The similarities between alder-cardamom and alder-conifer ecosystems from two extreme ends of the world may not, however, explain all of the results obtained in the current study.

Soil OC, TN, NA, TP, IP and AP levels were highly seasonal and concentrations were higher in the upper soil horizons where they are readily available for uptake by the understory cardamom crop. Site variations were very small and, therefore, not included in the interpretations of the results. SOM was negatively related to pH but was positively related to moisture retention in soil. A similar relationship between SOM and pH was reported by Bormann and DeBell (1981), and suggests that soil pH is strongly related to organic matter and moderately related to nitrogen weight. The increased SOM should improve soil tilth and stabilize soil N. A decreasing trend of SOM after 20 years was recorded in the present study. Such a trend was also reported by Pengfei et al. (2008) from a chronosequence of mixed plantations of alder (*Alnus cremastogyne*) and cypress (*Cupressus funebris*) in Sichuan China. The inclusion of N_2-fixing trees in an ecosystem often stimulates production and may lead to an increase in SOM; this increase can lower soil pH. The higher value of soil pH promoted both N nitrification and N mineralization leading to increased N availability in the younger agroforestry stands but considerably diminished N availability in 30–40-year-old stands.

Total N was invariably higher at a pH range of 4.3–5.3. This is indicative of low nitrogen content in the older, low-pH agroforestry stands. Simple regression between TN and pH showed a negative relationship in alder-cardamom stands which has also been reported in an age series of red alder stands (Bormann and DeBell 1981; Debell et al. 1983). N availability and supply over short time scales is regulated by the current pool sizes of inorganic, ammonium-N and nitrate-N, and the mobility of these ions. Concentrations of NO_3^- increased with advancing age and decreased soil pH. This was also observed in red alder chronosequences on the Pacific Coast of the US (Martin et al. 2004). For larger time scales, pools are small relative to the fluxes. Inorganic pool fluxes result from the difference in N mineralization and N nitrification of labile pools or from the difference in the rate of immobilization of released organic N. In the present study, N nitrification rates were markedly higher in the 5-year-old stands and decreased with age with significant variation, while N mineralization slightly increased with age (up to 10 years post-establishment) and decreased sharply thereafter. Further, N nitrification was lower in the rainy season than in the winter when uptake by plants was lowest and chances of leaching losses were less. High rates of both N mineralization and nitrification would be due to rapid immobilization and heterotrophic activity during winter season (Ramakrishnan and Saxena 1984; Sharma et al. 2008a, b). Low rates in the older stands are attributed to reduced amounts of SOM and its mineralization, which in turn causes a decrease in N and P supply (Tiessen et al. 1994). The potential net rate of N transformation through N mineralization and nitrification was more than two-fold higher in the younger agroforestry stands compared to the oldest and consequently, more nitrogen was available for plant uptake in the younger plantations. The presence of alder increased the total N pools and its supply benefiting the understory crop. Similar results were reported in mixed stands of *Eucalyptus saligna* and *Albizia falacataria* in Hawaii (Garcia-Montiel and Binkley 1998).

Soil C:N ratio ranged from 9 to 12 (mean 10.17), while C:P ranged from 37 to 45 (mean 41.31). Values reported in the present study are within the range of what has been reported elsewhere (Saratchandra 1984; Srivastava and Singh 1989; Sharma and Rai 2004). Soils with very high C:N ratios had low net rates of mineralization. Larcher (1975) had described that the ratio most favourable for mineralization lies between 10:1 and 20:1 which is comparable to the present investigation. N mineralization rates were highest in the 15-year-old stand and lowest in both the 5- and 40-year-old stands. Fifteen-year-old stands had the lowest C:N ratio with a correspondingly high one in both the 5- and 40-year-old stands. These results are very comparable to results from studies conducted by Sharma et al. (1985) in pure *A. nepalensis* plantations. A C:N ratio between 10 and 12 appeared most favourable for high N mineralization in the alder-cardamom agroforestry stands.

Among the different forms of phosphorus measured, most was found to be in organic forms. The IP:TP ratio was higher in the upper soil horizon than the lower one, indicating relatively greater IP availability for plant uptake in the upper horizon. The ratio was comparatively lower during spring and higher in the rainy season indicating relatively greater IP availability during the latter season. This time coincided with cardamom crop flowering and fruiting, which occurs from April to September. Phosphorus availability was highly dependent on pH and showed a positive relationship with pH in the agroforestry chronosequence. Less available P with increasing stand age would have resulted the correspondingly lower pH observed (Sharma 1993). The increasing acidity in these stands would cause transition of phosphate into less soluble compounds with Fe and Al (Brozek 1990; Sharma et al. 1997). A considerable amount of phosphate is not available to plants as it is fixed either as occluded Fe-P or by Ca, Al or Fe, which regulate available P uptake in plants. The lower concentrations of Ca-P, Al-P and Fe-P and occluded Fe-P with increasing acidity in the older plantations resulted in lower available P compared to the younger stands. The amount of organic P exceeded inorganic P, and the turnover of organic P pools provided a large portion of P taken up by the plants. Thus, P budget and availability was considerably controlled by N_2-fixing alder, which proved to be a beneficial associate.

The correlation between input of N and P through litter decomposition, and N fixation and indices of N and P availability in soil suggest that the greater nutrient supply in younger stands is the result of greater inputs through litter and N fixation by alder root nodules. This is in agreement with the earlier studies by Sharma et al. (2008a, b) who showed that the magnitude of nutrient release and energy in younger plantations was rapid, indicating accelerated nutrient cycling through litter production, decomposition and associated heat sinks, compared to the older stands (>20 years of age). The nutrient budget showed substantial N loss from the system at 40 years after stand establishment compared with the younger stands. The 40-year-old stand had less soil N (approx. 800 kg N ha^{-1} less), and slightly more N in vegetation (approx. 100 N ha^{-1} more), with a net loss of 700 kg N ha^{-1} (or 30 kg N ha^{-1} $year^{-1}$). At the same time N fixation is supposed to be in the order of 100 kg N ha^{-1} $year^{-1}$ for a total input of approximately 2500 kg N ha^{-1} over 25 years. This decline in soil N can be largely attributed to removal of tree biomass, which is part of the traditional thinning practice (373 fewer trees in 40-year-old stands compared to 10-year-old stands). Nutrient leaching losses from soil and biomass removal from the system with cardamom harvest are other important causes of nutrient imbalance (Sharma et al. 2002a, b).

Conclusion

The age of agroforestry stands had a considerable effect on soil nutrient pools, which increased significantly from the early successional stage at 5 years to the 15- to 20-year, mid-successional alder-cardamom agroforestry stage. After 20 years of establishment, however, a considerable amounts of soil nutrients were lost. The rise in soil nutrient pools in younger stands was attributed to the increase in tree density, high canopy cover, litter accumulation, N_2-fixation by alder and faster litter decomposition rates (Sharma et al. 2002a, b, 2008a, b). As hypothesized, the expected trend of increasing nutrients with successional change peaking at a certain agroforestry age had consistent effects on nutrient pools that occurred around 15 to 20 years of age. High rates of annual litter production and large forest floorlitter build-up with increased tree numbers, litter productivity, faster litter decomposition and gap filling of cardamom bushes/tillers in maturing agroforestry stands could be the indications of higher nutrient turnover until 20 year stands. Interestingly, nutrient contents dramatically decreased in older agroforestry stands. Such depletion of nutrients can be attributed to changes in biological and physical process in the soil (Sharma and Rai 2004) followed by biomass removal due to thinning of alder trees (about 40–60% by 30–40-year stand age), thus opening canopy cover, low litter production and floor accumulation rates, and decrease of number of cardamom bushes. It can be concluded that the increase of soil acidity with agroforestry age, the decrease in N transformation rates, the sharp decline in soil nutrient pool sizes and the limited availability of OC, SOM, TN, NA, TP and AV in old stands clearly show that the younger stands until 20 years are sustainable while older stands tend to show a nutrient-depleted system.

Our earlier studies on the same system and sites on biomass and productivity, stand nutrient dynamics, N_2-fixation and energetic and litter decomposition studies have recommended that adoption of 20-year re-plantation cycle for both alder and cardamom is appropriate for sustainable management (Sharma et al. 2002a, b, 2008a, b). The present research also supports the recommendations of earlier studies for a rotational agroforestry that provides high economic return and reclaims soil nutrient levels with the new succession.

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