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Performance of an Age Series of *Alnus*–Cardamom Plantations in the Sikkim Himalaya: Productivity, Energetics and Efficiencies

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Biomass, net primary productivity, energetics and energy efficiencies were estimated in an age series of *Alnus*–cardamom plantations in the eastern Himalaya. The impact of stand age (5, 10, 15, 20, 30 and 40 years) on the performance of mixtures of N_2-fixing (*Alnus nepalensis*) and non-N_2-fixing (large cardamom) plants was studied. Large cardamom (*Amomum subulatum*) is the most important perennial cash crop in the region and is cultivated predominantly under *Alnus* trees. Net primary productivity was lowest (7 t ha^{-1} per year) in the 40-year-old stand and was more than three times higher (22 t ha^{-1} per year) in the 15-year-old stand. Agronomic yield of large cardamom peaked between 15 and 20 years of age. Cardamom productivity doubled from the 5- to the 15-year-old stand, and then decreased with plantation age to reach a minimum in the 40-year-old stand. Performance of cardamom in association of N_2-fixing *Alnus* remained beneficial until 20 years of age. Annual net energy fixation was highest (444×10^6 kJ ha^{-1} per year) in the 15-year-old stand, being 1·4 times that of the 5-year-old stand and 2·9-times that of the 40-year-old stand. Inverse relationships of production efficiency, energy conversion efficiency and energy utilized in N_2-fixation against stand age, and a positive relationship between production efficiency and energy conversion efficiency suggest that the younger plantations are more productive. The *Alnus*–cardamom plantation system will be sustainable by adopting a rotational cycle of 15 to 20 years.

Key words: *Alnus nepalensis, Amomum subulatum* (large cardamom), biomass, energy efficiency, production efficiency, energy flow, net primary productivity, plantation age.

INTRODUCTION

Large cardamom (*Amomum subulatum* Roxb.) is the most important perennial cash crop of the Sikkim Himalayan region, with 26 000 ha cultivated in Sikkim and Darjeeling between elevations of 600 and 2000 m. Annual agronomic production of the crop from this region amounts to 4 million kg (worth approx. 8 million US $ in 1993), of which 85 % comes from Sikkim and the remainder from the hills of Darjeeling (Adhikary *et al.*, 1993). The capsule (fruit) is used as spice/condiment and contains approx. 3 % essential oil rich in cineole (Gupta *et al.*, 1984). It is cultivated as an understorey perennial crop in association with Himalayan alder (*Alnus nepalensis* D. Don) as the shade tree. Both *A. nepalensis* and large cardamom are native to the Himalayan region. The altitudinal range of *A. nepalensis* is sympatric with the agroclimatic range of cardamom (Sharma *et al.*, 1998, 2000). Roots of *A. nepalensis* are nodulated with *Frankia* as an endophyte, and rates of biological N_2-fixation are high (Sharma and Ambasht, 1984, 1988). New plantations and large patches of *Amomum subulatum*-based systems have recently incorporated *Alnus nepalensis* as a shade tree (Sharma *et al.*, 1994).

The potential increase in productivity of plants growing near N_2-fixing species has long been recognized. The effects of N_2-fixing trees on interplanted non-N_2-fixing trees have most often been characterized in terms of tree dimensions (Newton *et al.*, 1968; Cole and Newton, 1986; Heilman, 1990). Intensive research over the past few decades has provided a relatively solid foundation for understanding many of the major ecological interactions that occur in mixed stands of N_2-fixing and non-N_2-fixing trees (Binkley, 1992). Mixed stands present ecological opportunities for increasing both the total stand growth and growth of the non-N_2-fixing associates (Binkley, 1983; Cote and Camire, 1987; DeBell *et al.*, 1989; Binkley *et al.*, 1992). Studies have been carried out on biomass production and energetics in an age series of monocultures of *A. nepalensis* (Sharma and Ambasht, 1991). In an 8-year-old stand, productivity and yield of understorey large cardamom doubled when planted with N_2-fixing *A. nepalensis* as a shade tree compared with non-N_2-fixing tree associates (Sharma *et al.*, 1994). However, no information is available on mixtures of N_2-fixing and non-N_2-fixing stands with respect to stand age and maturity. *Alnus*–cardamom plantations in the Sikkim Himalaya can potentially provide valuable

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TABLE 1. *Tree dimensions, number of understorey cardamom tillers and bushes, basal area, litterfall and floor-litter in an age series of* Alnus*–cardamom plantation stands*

Parameters	Age of plantation stands (years)					
	5	10	15	20	30	40
Alnus trees						
Density (trees ha^{-1})	347 ± 20	553 ± 65	417 ± 17	321 ± 33	204 ± 29	180 ± 9
d.b.h. range (cm)	8–25	13–35	18–40	23–47	34–67	37–77
Height (m)	15·19 ± 1·02	15·40 ± 1·09	19·60 ± 1·51	26·57 ± 4·48	32·06 ± 4·43	34·99 ± 1·42
Basal area (m^2 ha^{-1})	8·3 ± 1·43	12·03 ± 2·00	19·51 ± 3·43	22·29 ± 3·55	23·12 ± 3·75	30·25 ± 7·45
Cardamom						
Bush (number ha^{-1})	6786 ± 655	13 484 ± 3100	25 316 ± 1706	8797 ± 1733	7962 ± 2467	1733 ± 186
Tiller density (×10^4 tillers ha^{-1})	15·61 ± 1·51	31·01 ± 7·13	58·23 ± 3·92	20·23 ± 3·99	18·31 ± 5·67	3·99 ± 0·43
Basal area (m^2 ha^{-1})	36·52 ± 3·51	72·57 ± 8·10	136·25 ± 20·31	47·35 ± 6·75	42·85 ± 7·89	9·33 ± 2·11
Stand basal area (m^2 ha^{-1})	44·82 ± 0·16	84·60 ± 4·60	155·76 ± 5·95	69·64 ± 3·73	65·97 ± 3·82	39·58 ± 7·55
Litter production (t ha^{-1} per year)	5·88 ± 0·58	8·24 ± 1·72	10·25 ± 0·46	7·11 ± 3·77	6·62 ± 1·46	4·08 ± 0·54
Floor-litter (t ha^{-1})	18·51 ± 0·25	23·16 ± 2·06	34·91 ± 1·24	28·05 ± 1·44	24·27 ± 0·58	14·67 ± 1·04

Values are means of three site replicates.

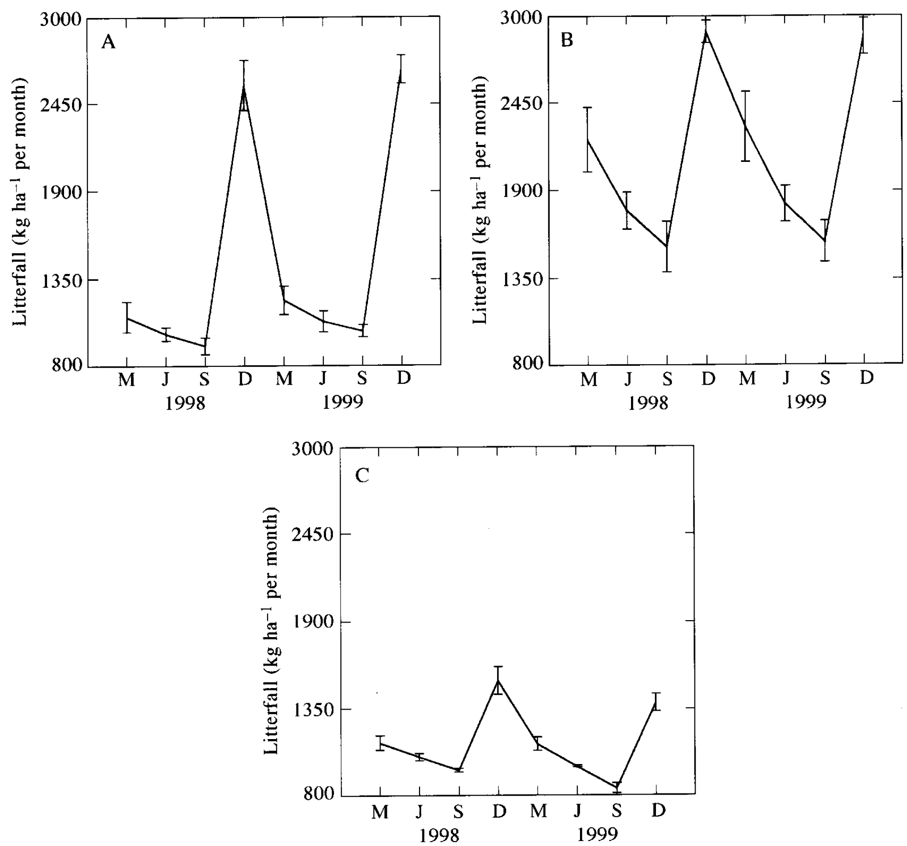

FIG. 1. Temporal distribution of litter production in a 5- (A), 15- (B) and 40- (C) year-old stand of *Alnus*–cardamom plantation. Vertical bars represent s.e.

information on the impact of stand age on the performance of mixtures of N_2-fixing and non-N_2-fixing plants.

This paper examines biomass accumulation, net primary production and energetics in an age sequence of *Alnus*–

TABLE 2. *Biomass (t ha⁻¹) allocation in tree and cardamom components, and stand values in an age series of* Alnus–*cardamom plantation stands*

Plant components	Stand age (years) 5	10	15	20	30	40
Alnus						
Leaf and twig	1·84 ± 0·06	2·91 ± 0·12	2·64 ± 0·07	2·45 ± 0·29	1·82 ± 0·16	1·78 ± 0·02
Catkin	0·30 ± 0·04	0·45 ± 0·07	0·50 ± 0·07	0·55 ± 0·08	0·53 ± 0·07	0·53 ± 0·09
Branch	6·84 ± 0·67	8·71 ± 1·14	13·64 ± 3·35	17·61 ± 3·23	18·94 ± 3·36	25·91 ± 6·94
Bole	15·77 ± 2·93	20·13 ± 1·76	35·07 ± 9·97	48·08 ± 8·85	54·07 ± 10·16	80·47 ± 23·64
Root and root nodule	7·96 ± 1·19	8·09 ± 0·68	12·76 ± 4·32	17·93 ± 2·87	18·61 ± 2·73	20·67 ± 4·55
Total	32·71	40·29	64·61	86·62	93·97	129·36
Cardamom						
Leaf	0·62 ± 0·06	1·24 ± 0·29	2·33 ± 0·95	1·06 ± 0·16	1·20 ± 0·23	0·29 ± 0·09
Pseudo-stem	1·87 ± 0·02	3·72 ± 0·86	6·94 ± 2·88	3·18 ± 0·31	2·19 ± 0·68	0·88 ± 0·29
Root/rhizome	6·79 ± 0·66	13·48 ± 0·31	25·30 ± 5·13	10·79 ± 0·79	7·96 ± 2·47	1·73 ± 0·19
Total	8·72	18·44	34·57	15·03	11·35	2·90
Above-ground biomass	26·68 (64·39)	37·16 (63·27)	61·12 (61·63)	72·93 (71·75)	78·75 (74·77)	109·86 (83·06)
Below-ground biomass	14·75 (35·60)	21·57 (36·73)	38·06 (38·37)	28·72 (28·25)	26·57 (25·23)	22·40 (16·94)
Stand biomass	41·43	58·73	99·18	101·65	105·32	132·26

Values in parentheses represent percentage contribution.
Values are means of three site replicates.

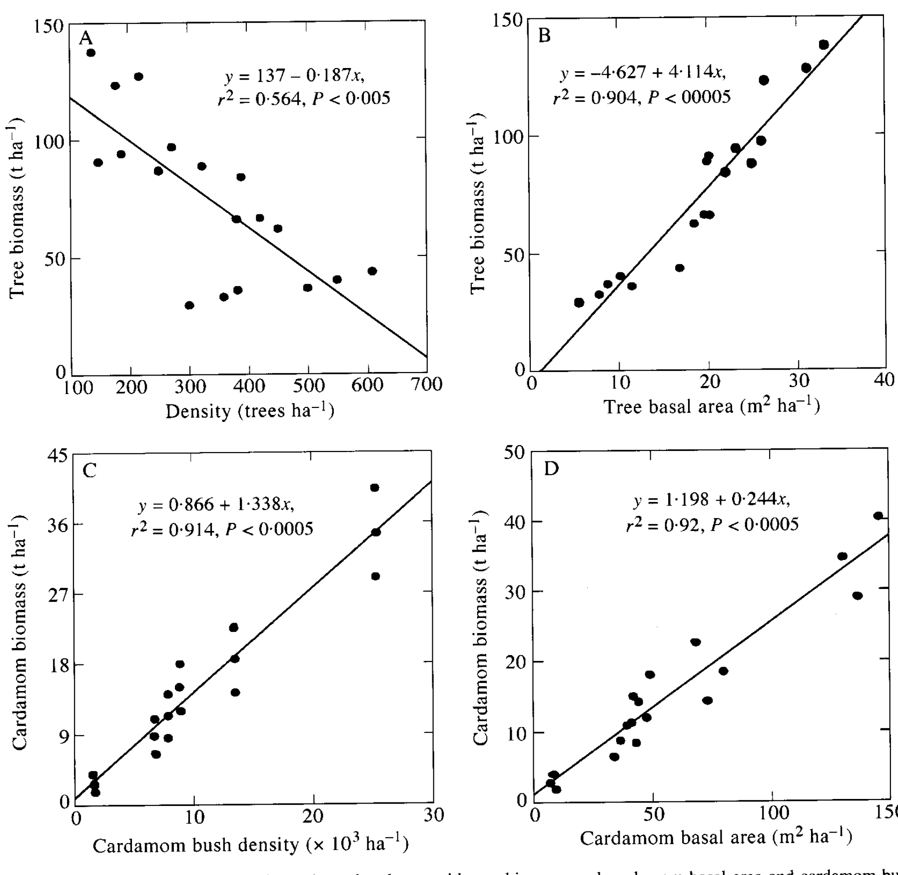

FIG. 2. Relationships between standing tree density and tree basal area with tree biomass, and cardamom basal area and cardamom bush density with cardamom biomass in an age series of *Alnus*–cardamom plantation stands.

TABLE 3. *Component-wise estimates of net primary productivity of* Alnus *tree and understorey cardamom (t ha*$^{-1}$ *per year) in an age series of* Alnus–*cardamom plantation stands*

Plant components	Stand age (years) 5	10	15	20	30	40
Alnus						
Leaf and twig	3·19 ± 0·06	4·07 ± 0·12	5·63 ± 0·07	4·77 ± 0·29	4·42 ± 0·16	3·17 ± 0·02
Catkin	0·30 ± 0·04	0·45 ± 0·07	0·50 ± 0·07	0·55 ± 0·08	0·53 ± 0·07	0·52 ± 0·09
Branch	1·82 ± 0·46	1·66 ± 0·22	1·25 ± 0·22	1·17 ± 0·23	1·13 ± 0·24	0·75 ± 0·01
Bole	3·47 ± 0·03	3·34 ± 0·89	2·88 ± 0·16	2·23 ± 0·57	1·78 ± 0·22	1·56 ± 0·51
Root and root nodule	2·75 ± 0·57	2·73 ± 0·92	2·35 ± 0·28	1·70 ± 0·09	1·35 ± 0·08	0·47 ± 0·05
Total	11·53	12·25	12·61	10·42	9·21	6·47
Cardamom						
Leaf	0·60 ± 0·29	0·93 ± 0·40	1·03 ± 0·15	0·45 ± 0·91	0·42 ± 0·71	0·10 ± 0·02
Pseudo-stem	1·79 ± 0·42	2·79 ± 0·43	3·09 ± 1·29	1·34 ± 0·35	1·25 ± 0·35	0·29 ± 0·05
Capsule	0·11 ± 0·02	0·23 ± 0·03	0·31 ± 0·04	0·36 ± 0·02	0·18 ± 0·11	0·04 ± 0·01
Root/rhizome	2·70 ± 0·39	3·37 ± 1·03	5·33 ± 1·89	2·19 ± 0·43	2·01 ± 0·60	0·43 ± 0·05
Total	5·20	7·32	9·77	4·30	3·85	0·86
Above-ground productivity	11·28 (67·42)	13·47 (68·83)	14·69 (65·58)	10·87 (73·84)	9·70 (74·27)	6·43 (87·48)
Below-ground productivity	5·45 (32·58)	6·10 (31·17)	7·68 (32·28)	3·85 (26·15)	3·36 (25·72)	0·90 (12·24)
Stand net primary productivity	16·73	19·57	22·38	14·72	13·06	7·33

Values in parentheses represent percentage contribution.
Values are means of three site replicates.

cardamom plantations. The specific objectives of the study were to determine: (1) component contribution to stand biomass and accumulation pattern; (2) component and total net primary production; (3) differences in component energy values, storage patterns and flow rates; (4) production efficiency and energy conversion efficiency; and (5) relationships between production efficiency, energy conversion efficiency and energy efficiency in N_2-fixation with respect to plantation age.

MATERIALS AND METHODS

Location and climate

The three experimental sites are located at Kabi (North District), Thekabong (East District) and Sumik (East District) in Sikkim of the eastern Himalaya. These sites extend from 27°15′05″ to 24°17′36·6″ N and from 88°28′6·9″ to 88°39′27·1″ E and range from 1350 to 1600 m asl. The study sites are more than 80 km apart and span the major areas of large cardamom cultivation in Sikkim. The study area is in the Indian monsoon region and has a temperate climate with three main seasons: winter (November–February), spring (March–May) and rainy (June–October). The mean monthly maximum temperature at the study sites ranges from 14·3 to 23·3 °C, the mean monthly minimum temperature from 5·4 to 15·8 °C and rainfall from 2500 to 3500 mm. Relative humidity varies between 80 and 95 % during the rainy season, decreasing to approx. 45 % in spring.

Plantations

Large cardamom is a shade-loving plant and is generally cultivated under shade trees; *Alnus* is used for this purpose in most new plantations. There is no rotation length as such for large cardamom plants in the traditional practice, and many old plantations are the least productive. The three experimental sites in Sikkim have several pure stands of *A. nepalensis* trees with understorey large cardamom plantations of different ages. Large cardamom and *Alnus* trees in a selected stand are the same age. *Alnus*–cardamom stands at each of the study sites were selected to represent plantations with the following age sequence: 5, 10, 15, 20, 30 and 40 years. These stands at each of the sites are closely comparable; the structural and functional differences are attributed to the ages of the plantations. The soil was acidic (pH 3·8–5·6) and pH varied greatly with depth; there was little variation in pH of surface soils between plantations. The soil was a sandy loam consisting of 11–30 % clay, 15–40 % silt and 34–65 % sand, depending on the horizon, to a depth of 1 m.

Methods

Sample plots 30 × 40 m were established for each of the six age series of plantation stands in all three sites, giving a total of 18 plots (0·36 ha per age group, totalling 2·16 ha). Tree diameter increment, litter production, decomposition and agronomic yield estimations were carried out in each plot. In the sample plots of all age groups each tree was marked and the diameter at breast height (d.b.h.) was measured in January 1998 and January 2000 (covering two annual cycles). Allometric relationships of tree component biomass on d.b.h. and below-ground biomass on above-ground biomass were used. These relationships had been developed by Sharma and Ambasht (1991) for *A. nepalensis* in the region. The component weight data of each tree in the sample plot were extrapolated using the allometric relationships and then expanded to stand values. Mean annual increment of above-ground components of the individuals

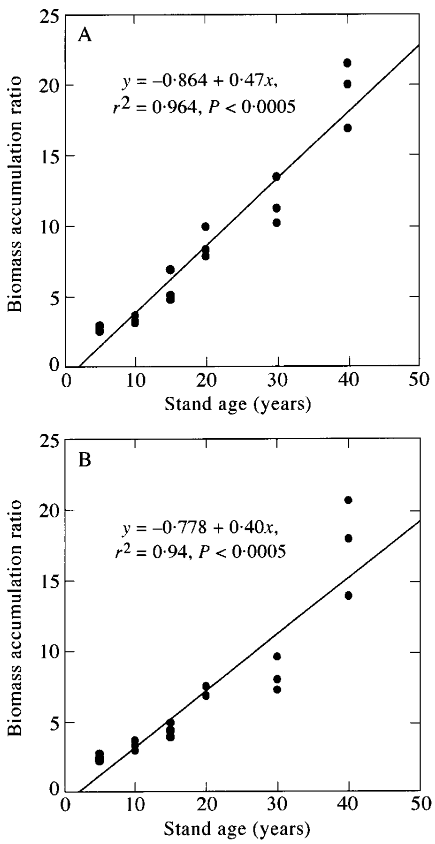

FIG. 3. Relationships between biomass accumulation ratio of *Alnus* (A) and cardamom (B) with stand age in the age series of *Alnus*–cardamom plantation stands. Values are means of three replicate sites.

in the sample plot was obtained by d.b.h. increment measurements. The below-ground biomass of individual trees was calculated using the regression equation of Sharma and Ambasht (1991) and the respective increment in above-ground biomass. The net change in the component biomass over a 1-year period yielded annual biomass accumulation and the sum of the different components gave net production of tree strata. Tree litterfall was estimated monthly for a 2-year period (1998–1999) using five litter traps with a collecting area of 1 m^2 in each sample plot; values were pooled to give annual totals. Floor-litter was sampled randomly in replicates (n = 5) in an area of 1 m^2 from each plot in January and extrapolated to stand values. *Alnus* root nodules of five average-sized trees from all 18 plots were recovered for estimation of biomass. Root nodule production was estimated using the method given by Sharma and Ambasht (1986).

In the sample plots of each age group, the total number of understorey cardamom bushes was recorded. The average number of tillers per bush was calculated using data from 20 bushes per plot. Total tiller number for the plot was calculated using the average number of tillers per bush and the total number of bushes per plot. Approx. 200 tillers from each plot were harvested, and height, leaf dry weight, pseudo-stem dry weight and bush root/rhizome dry weight were measured and mean values calculated. Tillers that fruit in the current year are removed after the harvest as a management practice because they do not fruit again. Therefore, the total numbers of tillers was recorded after the harvest and before the harvest in the next year. The difference in biomass values at these times provides a measure of current year leaf, pseudo-stem and root production. The agronomic yield of large cardamom was calculated by counting the tillers that fruited in the sample area of each stand prior to the harvest and multiplying this by the mean capsule weight per tiller. After the capsules had been harvested the tillers that had fruited in the current year were slashed and the leaf and pseudo-stem fractions estimated for their contribution to floor litter.

The ash content of different plant components was estimated by burning samples in a muffle furnace at 550 °C for 2 h. All energy estimations were made on an ash free mass basis. Calorific values of all plant components were estimated using an oxygen bomb calorimeter (Lieth, 1975). Photosynthetically active radiation (PAR) was recorded in an automatic weather station using a datalogger (Campbell Scientific Inc., Logan, UT, USA) during the study period. Component energy contents of *Alnus* trees and the cardamom crop were estimated as the product of mean energy value and component dry weight. Energy flow from tree leaf and twig, and cardamom leaf and pseudo-stem, to the floor litter was estimated through litterfall and slashed leaf and pseudo-stem, and their energy values. The mean energy content of floor litter was calculated by analysing the calorific content of different litter layers estimated during different intervals of decomposition for all age groups of plantations. The energy contents of the entire representative *Alnus* trees, cardamom crop and floor litter of sampled plots was summed to estimate total stand energy storage. Net energy fixation in trees and understorey cardamom was calculated as the total energy contained in the annual biomass production. Energy efficiency in N_2-fixation by *Alnus* was calculated following Schubert (1982) and Sharma and Ambasht (1988, 1991). N_2-fixation values given by Sharma *et al.* (2002) for the same stands were used.

Decomposition studies were carried out by enclosing litter fractions separately in nylon bags and the values of all the fractions were pooled, and annual mass loss per unit area was calculated. Summing heat release values of different stages of decomposing samples per year gave the total heat release from the floor litter. The energy loss from the root nodules of *Alnus* was estimated using root nodule turnover, a decomposition rate conversion factor (Sharma and Ambasht, 1986), and energy values in root nodules.

Energy content of firewood extracted from each plantation was estimated from total dry mass and its energy value. Energy in the agronomic yield was calculated as the product of capsule dry weight and energy value. Energy exit from

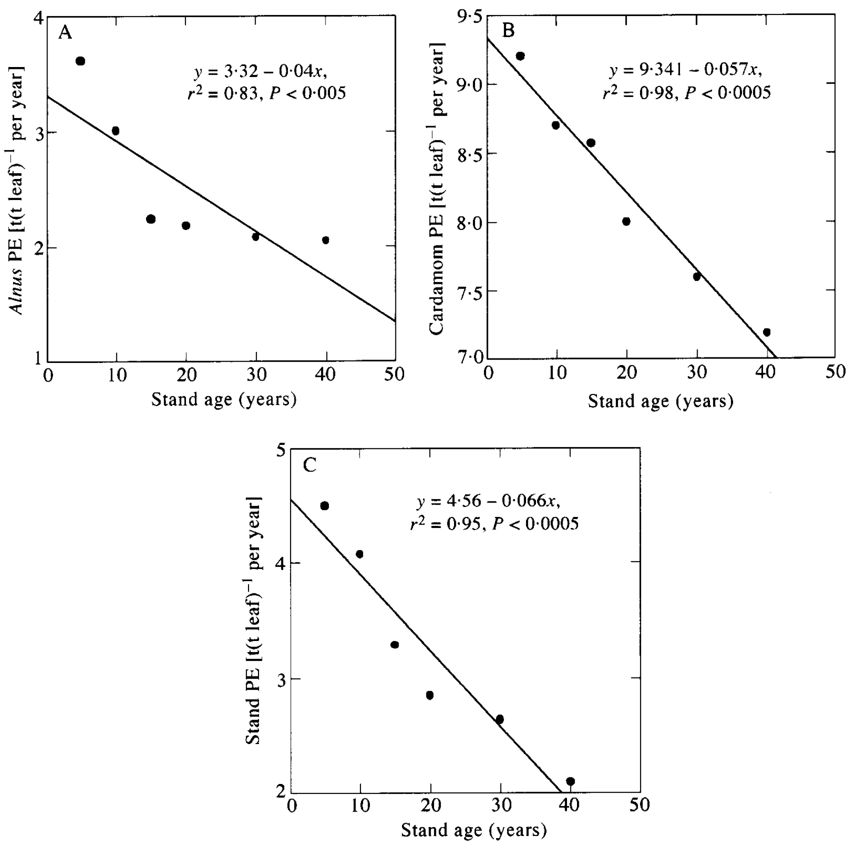

FIG. 4. Relationships between production efficiency (PE) of *Alnus* (A), cardamom (B) and stand total (C) with stand age in the age series of *Alnus*–cardamom plantation stands. Values are means of three site replicates.

TABLE 4. *Energy and ash concentration of different plant components of* Alnus *trees, cardamom crop and floor litter*

Plant components	Energy (kJ g^{-1})	Ash (%)
Alnus		
Leaf	20·92 ± 0·82	2·42 ± 0·59
Twig	20·44 ± 0·08	2·70 ± 0·67
Catkin	20·18 ± 0·35	2·43 ± 0·81
Branch	19·76 ± 0·66	2·82 ± 0·91
Bole	17·84 ± 0·02	2·01 ± 0·34
Root	17·54 ± 0·19	5·21 ± 0·71
Root nodule	21·25 ± 0·86	11·59 ± 2·10
Cardamom		
Leaf	19·93 ± 0·22	5·62 ± 2·10
Pseudo-stem	15·02 ± 0·07	3·72 ± 0·11
Rhizome	18·06 ± 0·76	10·92 ± 0·82
Root	18·84 ± 0·36	11·12 ± 0·90
Capsule	17·96 ± 0·58	12·13 ± 0·40
Floor litter*	15·06 ± 0·98	14·52 ± 0·60

Values are means ± s.e., $n = 6$.
* Includes values at different stages of decomposition.

the systems was the sum of energy in extracted firewood and agronomic yield.

RESULTS

Stand structure and litter production

Tree dimensions, cardamom density and basal areas are presented in Table 1. The d.b.h. range of *Alnus* was lowest in the 5-year-old stand and increased with age to reach a maximum in the 40-year-old stand. The basal area also increased with age, ranging from 8·3 m^2 ha^{-1} in the 5-year-old stand to 30·3 m^2 ha^{-1} in the 40-year-old stand. In contrast, tiller density and basal area of large cardamom increased from the 5- to the 15-year-old stand and then decreased to their lowest values in the 40-year-old stand (Table 1).

Average annual litterfall and slashed cardamom tillers ranged from 4·1 t ha^{-1} (40-year-old stand) to 10·3 t ha^{-1} (15-year-old stand). Plantation floor-litter increased from the 5-year-old stand, reached a peak in the 15-year-old stand

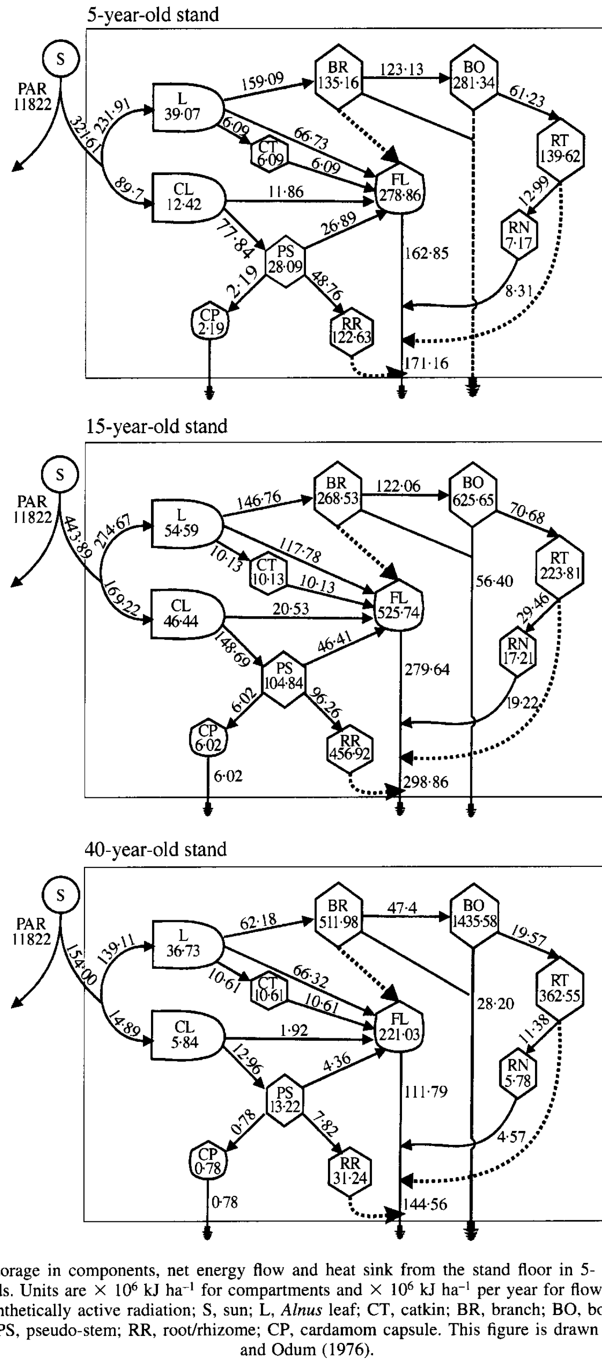

FIG. 5. Distribution of energy storage in components, net energy flow and heat sink from the stand floor in 5- (A), 15- (B) and 40- (C) year-old *Alnus*–cardamom plantation stands. Units are $\times 10^6$ kJ ha^{-1} for compartments and $\times 10^6$ kJ ha^{-1} per year for flows. Broken lines indicate that values are not estimated. PAR, Photosynthetically active radiation; S, sun; L, *Alnus* leaf; CT, catkin; BR, branch; BO, bole; RT, root; RN, root nodule; FL, floor litter; CL, cardamom leaf; PS, pseudo-stem; RR, root/rhizome; CP, cardamom capsule. This figure is drawn using the symbols given by Odum and Odum (1976).

TABLE 5. *Energy fixation, energetics and efficiencies in an age series of* Alnus–*cardamom plantations*

	Stand age (years)					
Energy/efficiency	5	10	15	20	30	40
Energy storage ($\times 10^6$ kJ ha^{-1})	1053	1435	2341	2288	2292	2635
Energy fixation ($\times 10^6$ kJ ha^{-1} per year)	322	389	444	305	261	154
Net energy allocation in agronomic yield ($\times 10^6$ kJ ha^{-1} per year)	2·19	4·47	6·02	7·05	3·40	0·78
Heat sink from the floor ($\times 10^6$ kJ ha^{-1} per year)	171	228	299	259	226	116
Energy exit ($\times 10^6$ kJ ha^{-1} per year)	2·20	56·56	56·40	18·80	22·18	28·20
Net ecosystem energy increment ($\times 10^6$ kJ ha^{-1} per year)	148·8	104·4	88·6	27·2	12·8	9·8
Energy accumulation ratio	3·27	3·69	5·27	7·5	8·78	17·11
Energy conversion efficiency (%)	2·72	3·29	3·76	2·58	2·21	1·30
Energy fixation efficiency (GJ GJ^{-1} leaf energy per year)	6·25	4·59	4·39	4·28	4·17	3·62
Energy efficiency in N_2-fixation* (g N_2 fixed 10^4 kJ^{-1} energy)	64	71	76	73	71	84
Energy utilized per kg N_2 fixed* ($\times 10^4$ kJ)	16	14	13	13	14	12

* N_2-fixation data from Sharma *et al.* (2002).

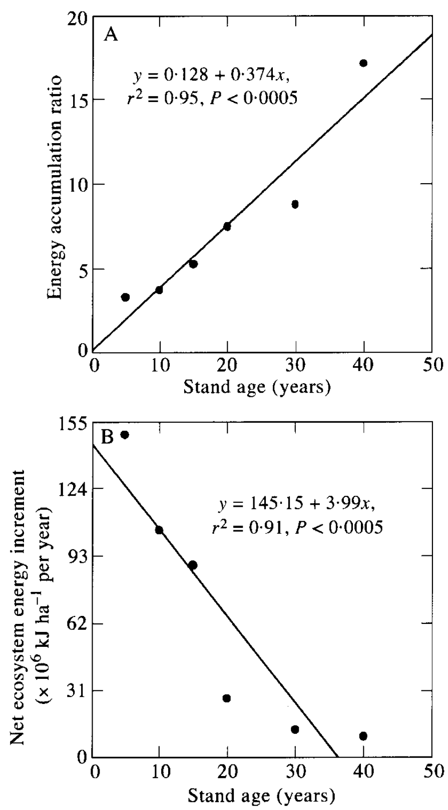

FIG. 6. Relationships between energy accumulation ratio (A) and net ecosystem energy increment (B) with stand age in the age series of *Alnus*–cardamom plantation stand. Values are means of three site replicates.

(35 t ha^{-1}) and then decreased to its lowest value in the 40-year-old stand (Table 1). The ratio of litter production to floor-litter was higher in the younger stands, and lowest in the 40-year-old stand (0·27).

Litter production occurred throughout the year with a marked seasonal distribution (Fig. 1). The quantity of litter produced was highly dependent on the age of the plantation stands. Approx. 66 % of annual litter production was recorded in a 4-month period (September–December). The seasonal distribution of litter production showed little difference between years or between plantation stands.

Standing biomass and net primary productivity

Total stand biomass in the age sequence of *Alnus*–cardamom plantations increased from 41 t ha^{-1} in the 5-year-old stand to 132 t ha^{-1} in the 40-year-old stand (Table 2). The bole accounted for 48–62 % of live biomass of the tree. The percentage contribution of branch biomass to total tree biomass remained fairly constant in all plantation stands while the contribution of bole biomass increased noticeably with plantation age.

The biomass contribution of *Alnus* to stand values ranged from 65 to 97 %; the contribution of *Alnus* decreased from the 5- to the 15-year-old stand, where it reached its lowest value, and then increased to its maximum value in the 40-year-old stand (Table 2). Above-ground stand biomass increased with stand age while below-ground biomass peaked in the 15-year-old stand; this was mainly due to the contribution of cardamom. The contribution of below-ground biomass ranged from 17 to 38 % of the stand total.

The standing biomass of trees showed a negative relationship with stand tree density while it was positive with tree basal area. However, in the case of cardamom biomass, positive relationships were obtained both with cardamom bush density and basal area (Fig. 2).

Net primary production rates of the age sequence of *Alnus*–cardamom plantations ranged from 7 to 22 t ha^{-1} per year, increasing to a peak in the 15-year-old stand before declining to a minimum in the 40-year-old stand (Table 3). Analysis of variance for stand net primary productivity showed significant variation between stand age ($F_{5,12} = 25$, $P < 0·0001$). Tukey's pairwise comparison tests showed significant variation between: 5- and 15-year-old stands ($P <$ 0·02); 10- and 20-year-old stands ($P < 0·06$); 30- and 40-year-old stands ($P < 0·0001$); and 40-year-old stands and

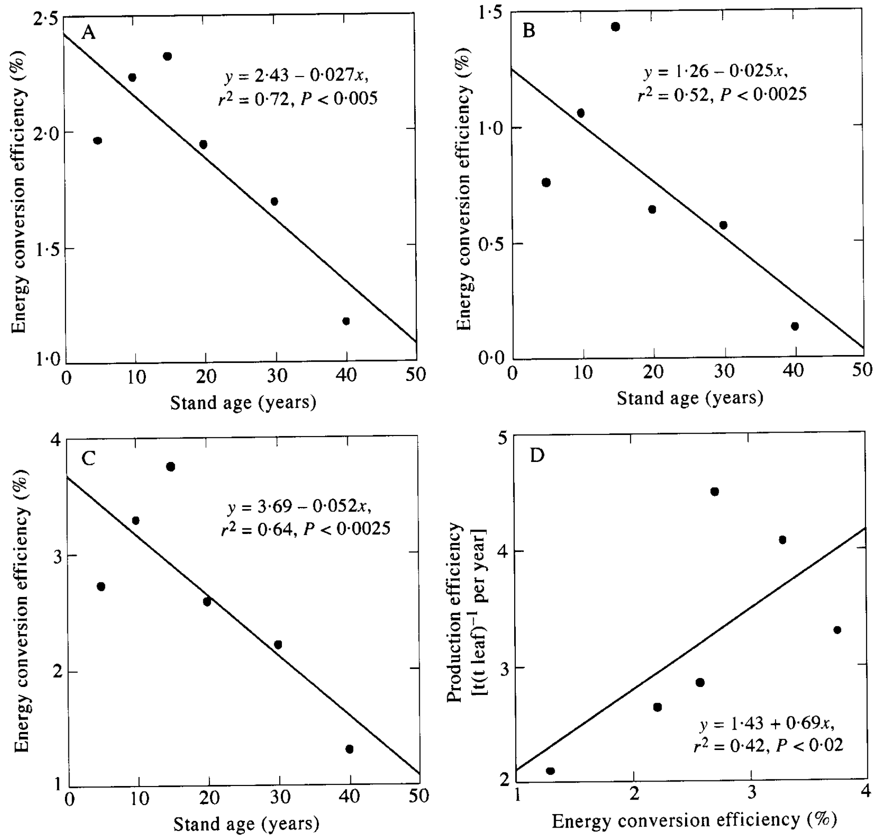

FIG. 7. Relationships between energy conversion efficiency with stand age of *Alnus* (A), cardamom (B) and stand total (C), and between production efficiency and energy conversion efficiency (D) in the age series of *Alnus*–cardamom plantation stands. Values are means of three site replicates.

20- and 30-year-old stands ($P < 0·004$). The contribution of above-ground productivity was around 65–69 % in younger stands and increased to a maximum value of 88 % in the 40-year-old stand. The contribution of cardamom net primary production to the stand value ranged from 12 (40-year-old stand) to 44 % (15-year-old stand). The agronomic yield increased from 110 kg ha^{-1} per year in the 5-year-old stand to reach a peak (360 kg ha^{-1} per year) in the 20-year-old stand, before declining in older stands to a minimum value of 40 kg ha^{-1} per year in the 40-year-old stand. Agronomic yield of large cardamom varied significantly with stand age ($F_{5,12}$ = 456, $P < 0·0001$). Tukey's pairwise comparison tests were significant between all combinations of stand age ($P < 0·0001$).

The biomass accumulation ratio (BAR; biomass/net primary production) was calculated for the stand total, and separately for the shade tree and understorey cardamom in the age sequence of *Alnus*–cardamom plantations. BAR of the stand and *Alnus* was lowest in the 5-year-old stand and increased with stand age to reach a maximum in the 40-year-old stand (approx. seven times greater than that of the 5-year-old stand). However, in the case of understorey cardamom, BAR was lowest (1·68) in the 5-year-old stand, increased to 3·54 in the 15-year-old stand and then remained similar in older stands. BAR of the stand total and *Alnus* trees showed strong positive relationships with stand age; however, in understorey cardamom it was significantly positive but feeble ($r^2 = 0·45$, $P < 0·05$) (Fig. 3).

Production efficiency is the net primary production per unit weight of leaf. It ranged from 2·97 to 8·38 t (t leaf)$^{-1}$ per year in cardamom and 3·63 to 6·27 t (t leaf)$^{-1}$ per year in *Alnus*. It was highest in the 5-year-old stand and lowest in the 40-year-old stand. Production efficiency showed highly negative relationships with plantation age for stand total and for both *Alnus* trees and understorey cardamom (Fig. 4). The efficiency curve tended to flatten with plantation age, especially in the case of *Alnus*.

Energy value, energetics and efficiencies

Energy and ash concentrations of different plant components of *Alnus*, cardamom and floor-litter are given

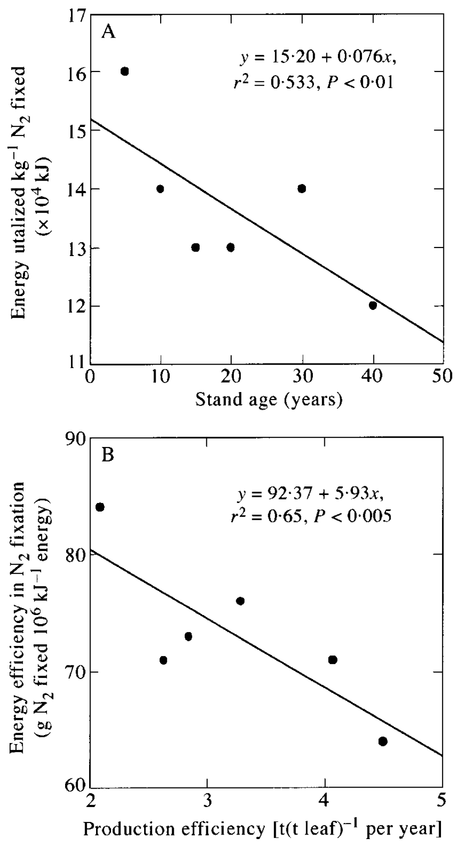

FIG. 8. Relationships between energy utilized per kg N_2 fixed with stand age (A), and energy efficiency in N_2 -fixation with production efficiency (B) in the age series of *Alnus*–cardamom plantation stands. Values are means of three site replicates.

in Table 4. Ash ranged from 2·01 to 11·59 % in *Alnus* and 3·72 to 12·13 % in cardamom components. The energy value of component parts ranged from 17·54 to 21·25 kJ g^{-1} in *Alnus* and 15·02 to 19·93 kJ g^{-1} in cardamom. The mean energy value of floor-litter, calculated using the values of different stages of decomposition, was 15·06 kJ g^{-1}.

Energy distribution and flow rates in the components of 5-, 15- and 40-year-old *Alnus*–cardamom plantation stands are presented in Fig. 5. Net annual energy fixation was lowest (154×10^6 kJ ha^{-1} per year) in the 40-year-old stand and highest (444×10^6 kJ ha^{-1} per year) in the 15-year-old stand. Annual energy fixation in the 15-year-old stand was 1·4 times that of the 5-year-old stand and 2·9 times that of the 40-year-old stand (Table 5). Energy allocation in agronomic yield of the large cardamom was highest (7·05 $\times 10^6$ kJ ha^{-1}per year) in the 20-year-old stand, which was 3·2 times greater than that of the 5-year-old stand and 9 times that of the 40-year-old stand. Allocation of stand annual energy fixation to shade tree and cardamom was, respectively, 72 and 28 % in the 5-year-old stand, 62 and 38 % in the 15-year-old stand, and 90 and 10 % in the 40-year-old stand. Energy storage was lowest in the 5-year-old stand and increased with plantation age to be 2·5 times greater in the 40-year-old stand (Table 5).

Component allocation of net energy fixation in the tree layer of the 5-year-old stand was more than that of the 15-year-old stand in the case of bole, branch and root, while the reverse was recorded for leaf and twig, root nodule and catkins. In the case of cardamom, all the components such as leaf, pseudo-stem, capsule and root/rhizome showed higher net energy allocation in the 15-year-old stand compared with the 5-year-old stand, while the lowest allocation was recorded in all the components of cardamom of the 40-year-old stand. Heat sink from the floor-litter and energy exit in terms of firewood and capsule are given in Table 5 and Fig. 5. Heat sink was highest in the 15-year-old stand and decreased in the order 15- > 20- > 10- > 30- > 5- > 40-year-old stand. Energy exit from the system was $2{\cdot}2 \times 10^6$ kJ ha^{-1} per year in the 5-year-old stand and increased to the greatest value in the 10- and 15-year-old stands before declining: 10- > 15- > 40- > 30- > 20- > 5-year-old stand.

Net ecosystem energy increment was highest in the 5-year-old stand (149×10^6 kJ ha^{-1} per year) and decreased with plantation age to a minimum value of 10×10^6 kJ ha $^{-1}$ per year in the 40-year-old stand. However, the energy accumulation ratio (energy storage/energy fixation) was lowest in the 5-year-old stand and increased with plantation age to reach a maximum value in the 40-year-old stand (Table 5). Net ecosystem energy increment showed a strong negative relationship with stand age while the energy accumulation ratio was positively related to stand age (Fig. 6). The best fit of net ecosystem energy increment and energy accumulation ratio curves was obtained using the natural logarithmic transformation of plantation age.

Energy conversion efficiency (ECE) at the autotrophic level is the ratio of energy captured by vegetation to the photosynthetically active radiation reaching an area over a period of time, expressed as a percentage. ECE increased from the 5-year-old stand (2·72 %) to peak in the 15-year-old stand (3·76 %). Thereafter it decreased with stand age to a minimum of 1·3 % in the 40-year-old stand. The relationship between ECE and stand age is strongly negative for *Alnus* trees, cardamom and stand total (Fig. 7). In all three situations, the curves showed a slight increase in the younger stands and then declined sharply in older stands. The production efficiency showed a positive relationship with energy conversion efficiency (Fig. 7). Both production and energy conversion efficiencies were high in the younger stands and decreased with stand age to reach minimum values in the 40-year-old stand.

The energy utilized per kg N_2 fixed was 16×10^6 kJ in the 5-year-old stand. This then decreased slightly with stand age and remained almost constant throughout, being 12×10^6 kJ in the 40-year-old stand. Energy utilized per kg N_2 fixed dropped sharply from the 5- to the 10-year-old stand and then more slowly thereafter. It showed a negative relationship with plantation age (Fig. 8). Energy efficiency in N_2-fixation was lowest (64 g N_2 fixed 10^4 kJ^{-1} energy) in the 5-year-old stand and increased to its highest value (84 g N_2

fixed 10^4 kJ^{-1} energy) in the 40-year-old stand. Efficiency in N_2-fixation between 10- and 30-year-old stands remained almost constant. Energy efficiency in N_2-fixation showed a significant negative relationship with production efficiency (Fig. 8), indicating greater energy efficiency in N_2-fixation in the 40-year-old stand when production efficiency was the lowest.

DISCUSSION

The annual variation of tree leaf litter and cardamom litter production within each plantation age during the 2-year study period was low. The temporal distribution of tree leaf-litter production was similar in all six age groups of stands, showing a regular pattern. Sharma *et al.* (1997) reported higher litter production under the influence of N_2-fixing *Alnus* trees in cardamom plantations compared with non-N_2-fixing mixed tree species. Tarrant *et al.* (1969) and Binkley (1992) also found much more litter production in mixed stands with N_2-fixing associates than in stands containing only non-N_2-fixing trees. Bormann and DeBell (1981) reported a floor-litter value as high as 39 t ha^{-1} in a 40-year-old *A. rubra* stand, and indicated a possibility of reaching equilibrium at 25 years of age. However, the equilibrium of litter accumulation could not be firmly established in the present study due to large cardamom crop management practice.

The stand total biomass, and tiller number, basal area and biomass of the cardamom crop were much higher under the influence of *Alnus* (Sharma *et al.*, 1994). Binkley *et al.* (1992) also reported that the biomass of *Alnus*–conifer stands exceeded by 69 % that of pure conifer stands at a low fertility site in the USA. The total biomass in the age sequence of pure *A. nepalensis* plantations increased from 106 t ha^{-1} in a 7-year-old stand to 606 t ha^{-1} in a 56-year-old stand (Sharma and Ambasht, 1991). In the age sequence of mixed *Alnus*–cardamom plantations, a biomass accumulation trend similar to that of above study was recorded, although smaller in magnitude. It was mainly influenced by the *Alnus* tree associate. The biomass accumulation ratio is used to categorize the production conditions of forests/plantations (Whittaker and Woodwell, 1969). It expresses the amount of biomass accumulated per unit of net production. The change in biomass accumulation ratio is caused by the differences in site characteristics and wood increment rates as affected by environmental conditions and age of the trees. The biomass accumulation ratio ranged from 2·5 to 18·0 in the age sequence of *Alnus*–cardamom plantations. Smith (1977) also reported a low average biomass accumulation ratio (2·86) in an immature (8–10-year-old) *A. rubra* stand, consistent with the findings of Sharma and Ambasht (1991) and the present study.

Sharma and Ambasht (1991) reported net annual production rates of 13–25 t ha^{-1} per year in the age sequence of pure *Alnus* plantations, which decreased with age and closely matched the trend in total net primary productivity of the *Alnus* associates in the *Alnus*–cardamom plantations, ranging from 6·5 to 12·6 t ha^{-1} per year. Immature stands often have net primary production rates more than double those of mature stands (Johnson and Risser, 1974). This is also the case in the present study, which showed that the net production rate in the 40-year-old plantations was approx. 33 % of that in the 15-year-old stand. Rodin and Bazilevich (1967) reported net productivity within a broad range (3·6–20 t ha^{-1} per year) for temperate deciduous forest, and values from the present study were within this range. Productivity of *Alnus* was almost constant until the stand reached 15 years of age, and then declined with stand age. However, under the influence of *Alnus*, cardamom productivity doubled in the 15-year-old stand compared with that in the 5-year-old stand; thereafter it decreased sharply with stand age to reach its lowest value in the 40-year-old stand. *Alnus* trees are not growing well by 40 years of age, and litterfall has dropped by half. Large cardamom, being a shade-tolerant plant, does not perform well upon opening of the canopy, as observed after 30 years of age, and the other factor could be its ageing impact.

Net annual energy fixation was reported to be highest in a young stand and declined sharply with plantation age in pure *A. nepalensis* in the region (Sharma and Ambasht, 1991). In the present study, annual energy fixation and flow rates increased from the 5-year-old stand to a peak in the 15-year-old stand, and then declined sharply. This clearly indicates that energy flows and fixation were optimum for both *Alnus* and cardamom up to the 15-year-old stand age. The production efficiency and energy conversion efficiencies of the age sequence of *Alnus*–cardamom plantations showed a significant positive relationship, with the younger stands performing more efficiently compared with mature stands. The production efficiency of the plantation was highest in the 5-year-old stand and decreased with advancing age, having a similar trend in both *Alnus* as well as cardamom components. The energy fixation efficiency of cardamom decreased with advancing age; it remained fairly high up to the 20-year-old stand supporting the system efficiency until this age. The energy efficiency of stands, and separately for the *Alnus* and cardamom components, was highest in the youngest stand and decreased with increasing plantation age. The energy conversion efficiency of cardamom increased from the 5- to the 15-year-old stand and then decreased to its lowest value in the 40-year-old stand. The energy accumulation ratio of *Alnus* increased with stand age, becoming almost five times greater in the 40-year-old stand than in the 5-year-old stand, whereas it was almost constant after 15 years of age in the case of cardamom. Energy conversion efficiency in N_2-fixation and production efficiency of the *Alnus*–cardamom plantations were shown to have an inverse relationship. Younger stands with a higher production efficiency showed least efficiency in N_2-fixation. However, as the stands matured the production efficiency decreased and the system suddenly switched to increased energy efficiency in N_2-fixation. The inverse relationships of production efficiency, energy conversion efficiency and energy utilized in N_2-fixation against stand age, and the positive relationship between production efficiency and energy conversion efficiency suggest that younger plantations are the most productive systems, while intermediate and mature plantations are relatively less and least productive, respectively. The performance of large cardamom under the influence of N_2-fixing *Alnus* in an age sequence of plantations with regards to net primary productivity, agronomic yield, net energy fixation rates, production efficiency, energy conversion efficiency and energy efficiency in N_2-fixation suggest the optimal rotational cycle is 15–20 years. Sharma *et al.* (1994) suggested that *Alnus* is an excellent associate of large cardamom, increasing its performance compared with non-N_2-fixing mixed tree associates. This study reveals that the *Alnus*–cardamom plantation system could be sustainable by adopting a rotational cycle of 15–20 years.

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LITERATURE CITED

Adhikary PK, Gurung N, Mukhia DK, Nepal DR, Sampang T, Singh HC, Young S. 1993. An investigation of the market systems for Sikkim horticultural products: Fruits, vegetables, ginger and cardamom. *Report of the Rapid Market Appraisal*. Indo-Swiss Project, Sikkim, India.

Binkley D. 1983. Ecosystem production in Douglas-fir plantations: Interaction in red alder and site fertility. *Forest Ecology and Management* **5**: 215–227.

Binkley D. 1992. Mixtures of nitrogen-fixing and non-nitrogen-fixing tree species. In: Cannell MGR, Malcolm DC, Robertson PA, eds. *The ecology of mixed species stands of trees*. Oxford: Blackwell Scientific Publications, 99–123.

Binkley D, Sollim P, Bell R, Sachs D, Myrold D. 1992. Biogeochemistry of adjacent conifer and alder/conifer stands. *Ecology* **73**: 2022–2035.

Bormann BT, DeBell DS. 1981. Nitrogen content and other soil properties related to age in red alder stands. *Soil Science Society American Journal* **45**: 428–432.

Cole EC, Newton M. 1986. Nutrient, moisture, and light relations in 5-year-old Douglas-fir plantations under variable competition. *Canadian Journal of Forest Research* **16**: 727–732.

Cote B, Camire C. 1987. Tree growth and nutrient cycling in dense plantings of hybrid poplar and black alder. *Canadian Journal of Forest Research* **17**: 516–523.

DeBell DS, Whitesell C, Schubert TH. 1989. Using N_2-fixing *Albizia* to increase growth of *Eucalyptus* plantations in Hawaii. *Forest Science* **35**: 64–75.

Gupta PN, Naqvi AN, Mishra LN, Sen T, Nigam MC. 1984. Gas chromatographic evaluation of the essential oils of different strains of *Amomum subulatum* Roxb. growing wild in Sikkim. *Sonderdruck aus Parfumeric und kodmetik* **65**: 528–529.

Heilman P. 1990. Growth of Douglas-fir and red alder on coral spoils in western Washington. *Soil Science Society of America Journal* **54**: 522–527.

Johnson FL, Risser PG. 1974. Biomass, annual net primary production and dynamics of six mineral elements in a post oak-blackjack oak forest. *Ecology* **55**: 1246–1258.

Lieth H. 1975. Measurement of calorific values. In: Lieth H, Whittaker RH, eds. *Primary productivity of the biosphere*. Berlin: Springer-Verlag, 119–129.

Newton MBA, Hassan El, Zavitkovski J. 1968. Role of red alder in western Oregon forests succession. In: Trappe JM, Franklin JF, Tarrant RF, Hassans GM, eds. *Biology of alder*. Portland Oregon: USDA Forest Service, PNW Forest Range Experimental Station, 73–83.

Odum HT, Odum EC. 1976. *Energy basis for man and nature*. New York: McGraw-Hill, 337.

Rodin LE, Bazilevich NI. 1967. *Production and mineral cycling in terrestrial vegetation*. Edinburgh: Oliver and Boyd.

Schubert KR. 1982. *The energetics of biological nitrogen fixation*. Rockvile, Maryland: American Society of Plant Physiologists.

Sharma E, Ambasht RS. 1984. Seasonal variation in nitrogen fixation by different ages of root nodules of *Alnus nepalensis* plantations in the eastern Himalayas. *Journal of Applied Ecology* **21**: 265–270.

Sharma E, Ambasht RS. 1986. Root nodule age-class transition, production and decomposition in an age sequence of *Alnus nepalensis* plantation stands in the Eastern Himalayas. *Journal of Applied Ecology* **23**: 689–701.

Sharma E, Ambasht RS. 1988. Nitrogen accretion and its energetics in Himalayan alder plantations. *Functional Ecology* **2**: 229–235.

Sharma E, Ambasht, RS. 1991. Biomass, productivity and energetics in Himalayan alder plantations. *Annals of Botany* **67**: 285–293.

Sharma E, Sharma R, Pradhan M. 1998. Ecology of Himalayan alder (*Alnus nepalensis* D. Don). *Proceedings of the Indian National Science Academy B* **64**: 59–78.

Sharma E, Sharma R, Singh KK, Sharma G. 2000. A boon for mountain populations: Large cardamom farming in the Sikkim Himalaya. *Mountain Research and Development* **20**: 108–111.

Sharma G, Sharma R, Sharma E, Singh KK. 2002. Performance of an age series of *Alnus*–cardamom plantations in the Sikkim Himalaya: Nutrient dynamics. *Annals of Botany* **89**: 273–282.

Sharma R, Sharma E, Purohit AN. 1994. Dry matter production and nutrient cycling in agroforestry systems of cardamom grown under *Alnus* and natural forest. *Agroforestry Systems* **27**: 293–306.

Sharma R, Sharma E, Purohit AN. 1997. Cardamom, mandarin and nitrogen-fixing trees in agroforestry systems in India's Himalayan region. I. Litterfall and decomposition. *Agroforestry Systems* **35**: 235–253.

Smith NJ. 1977. *Estimates of above-ground biomass, net primary production and energy flows in 8–10-year-old red alder (*Alnus rubra*, Bong.) ecosystems*. MSc Thesis, The University of British Columbia, Canada.

Tarrant RF, Lu KC, Bollen W, Franklin JF. 1969. Nitrogen enrichment of two forest ecosystems by red alder. United States Forest Service Research Paper PNW-76.

Whittaker RH, Woodwell GM. 1969. Structure, production and diversity of the oak pine forest at Brookhaven, New York. *Journal of Ecology* **57**: 155–174.