Productivity and Nutrient Cycling in an Age Series of *Alnus*-Cardamom Agroforestry in the Sikkim Himalaya

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By

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Dedicated to my beloved grandfather

Late Shri D.P. Banstola

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"All failed be lost but not all lost the unconquerable will"

- Robert Frost

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In Sikkim more than 80% of the population have farming as primary livelihood. In recent years, the population growth and consequent fragmentation of farmland in Sikkim has caused reduction in per capita holdings and has forced farmers to cultivate cash crops such as potatoes, ginger, mandarin and large cardamom. This study on cardamom based agfororestry aims to address the fulfilment of the concept of "sustainable agriculture" which would be an example of how local mountain niche can be exploited sustainably.

Investigations on "Productivity and nutrient cycling in an age series of *Alnus*-cardamom agroforestry in the Sikkim Himalaya" was undertaken with the following broad objectives to examine (i) biomass, productivity, energetics and efficiencies, (ii) nitrogen fixation efficiency and energetics, (iii) litter production, decomposition, and nutrient and energy release, (iv) seasonal soil nutrient dynamics, fluxes and availability, and (v) retranslocation, use efficiency and biogeochemical cycling of nutrients; in the age sequence of *Alnus*-cardamom agroforestry plantations in the Sikkim Himalaya.

Three experimental sites selected during the study period (1997–2000) are located at Kabi (North District), Thekabong (East District) and Sumik (East District) in Sikkim of the Eastern Himalaya. These sites fall within 27° 15′ 05″ and 24° 17′ 36.6″ N latitude and 88° 28′ 6.9″ and 88° 39′ 27.1″ E longitude with a range of elevation between 1350–1600 m asl. These study sites are more than 80 km distance apart and relates to the major areas of large cardamom cultivation in Sikkim. The study area is in the Indian monsoon region with a temperate climate having the three main seasons; viz., winter (November-February), spring (March-May) and rainy (June-October). Mean monthly maximum temperature ranged from 14.3–23.3°C, mean monthly minimum temperature from 5.4–15.8°C, and rainfall between 3000–4500 mm at the study sites. Relative humidity varied between 80–95% during the rainy season and decreased to about 45% in spring.

Large cardamom (*Amomum subulatum* Roxb.) is a perennial cash crop cultivated under the shade trees predominantly in association with *Alnus nepalensis*. All the three experimental sites in Sikkim have several pure stands of *A. nepalensis* tree with understorey large cardamom plantations of different age classes. Large cardamom and *Alnus* trees in a selected stand are of the same age, therefore age designation to the stand refers to the same age for both large cardamom and *Alnus*. The selected *Alnus*-cardamom stands at each of these sites represented plantations of an age sequence of 5-, 10-, 15-, 20-, 30- and 40-years numbering a total of 18 (6 plots × 3 sites). These stands at each of the sites are closely comparable; the structural and functional differences are attributed to the age of the plantations. Soil was acidic (pH 3.8–5.6) and pH varied widely with depth; the variation in pH of surface soils was small between plantations (17%). The soil was sandy loam ranging in horizons from 11–30% clay, 15–40% silt and 34–65% sand in a 1 m profile.

Salient findings of the research

1. Tree height and DBH range of *Alnus* were lowest in the 5-year stand that increased with age to be highest in the 40-year stand. The basal area also increased with age ranging from 8.3 m^2 ha^{-1} in the 5- to 30.3 m^2 ha^{-1} in the 40-year stand. In contrary, the tiller density as well as basal area of cardamom increased from the 5-year, was highest in the 15-year and then decreased to lowest value in the 40-year stand.

2. Annual litter production of both *Alnus* and slashed cardamom tillers increased from 5.9 t ha^{-1} (5-year) to 10.3 t ha^{-1} (15-year) and declined down to 4.1 t ha^{-1} (40-year). Plantation floor-litter increased from the 5-year (19 t ha^{-1}) stand that peaked at the 15-year stand (35 t ha^{-1}) and then decreased in the 40-year (15 t ha^{-1}) stand. Stand total biomass increased from 41 t ha^{-1} (5-year) to 132 t ha^{-1} (40-year). The standing tree biomass showed negative relationship with stand tree density, while it was positive with the tree basal area. Biomass accumulation ratio of the stand total and *Alnus* tree showed strong positive relationship with stand age, however, in understorey cardamom it was significant though

feeble. Net primary production was lowest (7 t ha^{-1}) in the 40-year stand and was 22 t ha^{-1} (highest) in the 15-year stand. Agronomic yield of large cardamom peaked at 20-year plantation stand. Cardamom production doubled in the 15-year stand compared to the 5-year stand and then declined with age. Production efficiency showed highly negative relationships with plantation age for stand total, and for both *Alnus* tree and understorey cardamom.

3. Net energy storage ranged between $1053-2635 \times 10^6$ kJ ha^{-1} with lowest value in the 5-year and highest value in the 40-year stand. Annual net energy fixation was highest (444×10^6 kJ ha^{-1} $year^{-1}$) in the 15-year which was 1.4 times that of the 5-year and 2.9 times that of the 40-year stand. Net ecosystem energy increment showed a strong negative relationship with stand age while energy accumulation ratio showed a positive relationship with stand age. Energy conversion efficiency with stand age was negatively related in all the three cases such as *Alnus*, cardamom and stands total. Both energy fixation efficiency and net ecosystem energy increment were highest in the 5-year stand and decreased with advancing age. N_2-fixation efficiency was lowest (64 g N_2 fixed 10^4 kJ^{-1} energy) in the 5-year and increased by 1.3 times in the 40-year stand. It showed a significant negative relationship with production

efficiency. Inverse relationship of production efficiency, energy conversion efficiency and energy utilized in N_2-fixation against stand age; and positive relationship between production efficiency and energy conversion efficiency suggest that the younger plantations are more productive.

4. Annual root nodule production was highest (165 kg ha^{-1}) in the 10-year stand and lowest in the 30-year (18 kg ha^{-1}) and 40-year (14 kg ha^{-1}) stands. Annual production of inactive root nodule (1.43−73.54 kg ha^{-1}) was lower than the active root nodule (13−110 kg ha^{-1}). Range of seasonal nitrogenase activity was lower in 5-year (4−28 C_2H_4 µmoles g^{-1} d.wt. nodules h^{-1}), higher in 15-year (5−52 C_2H_4 µmoles g^{-1} d.wt. nodules h^{-1}) and highest in the 40-year (3−65 C_2H_4 µmoles g^{-1} d.wt. nodules h^{-1}) stand. Peak activity was recorded during rainy (11−65 C_2H_4 µmoles g^{-1} d.wt. nodules h^{-1}) and minimum activity was recorded in winter (3−21 C_2H_4 µmoles g^{-1} d.wt. nodules h^{-1}). Diurnal variation showed peak activity (37−58 C_2H_4 µmoles g^{-1} d.wt. nodules h^{-1}) during 8.00−14.00 h. Altitudinally, activity was lowest (26 and 34 C_2H_4 µmoles g^{-1} d.wt. nodules h^{-1}) at 2100 m and 500 m elevations and highest (51−71 C_2H_4 µmoles g^{-1} d.wt. nodules h^{-1}) between 1100−1700 m in *Alnus*-cardamom plantations.

5. Annual N fixation was highest in the 15-year (155 kg ha^{-1}) and lowest in the 5-, 30- and 40-year stands (51–58 kg ha^{-1}) with maximum fixation (64–74%) during rainy and autumn, and minimum (24–26%) during winter and spring seasons. Nitrogen fixation contributed 39–66% of the total N uptake. Energy utilized per kg N_2-fixed was 16×10^4 kJ in 5-year that decreased by 1.3 times in the 40-year stand. N_2-fixation efficiency showed a negative relationship with energy conversion efficiency. The quantum of energy input in nodulation for N_2-fixation was optimum until 20 years and reduced with decline in energy conversion efficiency. *Alnus* contributes substantial amount of N in the younger plantations than older, and it controls N dynamics in the *Alnus*-cardamom agroforestry systems. Inverse relationship between energy input for unit N_2-fixation with stand age; energy efficiency in N_2-fixation with energy fixation efficiency and energy conversion efficiency suggests that plantations until 20 year functions most efficiently.

6. Decomposition and ash-free mass loss were not conspicuous during first three month and showed 15–20% of the initial mass loss. In the first six month >30–40% of initial mass was lost. The half life and turnover time of ash-free mass was lowest (9.55–13.41; 12.76–19.35) in the 15-year stand with high

decomposition constant (0.62–0.94). Ash free mass of decomposing litter remaining at different retrieval dates was associated with narrowing of the C:N ratio. The single exponential decay functions show that the *k* values decreased with plantation stand maturity, indicating that loss was faster in younger stands.

7. Seasonal rates of decomposition, nutrient and energy release were distinct, with highest (30–40%) rate in the first six months (warm rainy season) followed by subsequent seasons of the year. Among the stands, decomposition rate was highest in 10- and 15-year stands (stand with dense canopy). Decomposition was slow at high lignin:N and C:N ratios. Inverse curvilinear relationships exist between *k* values on ash-free mass and N expressed as a function of initial lignin to initial N concentration.

8. The quantities of nutrients and energy released per unit area in 24 months were highest in the 15-year stand (N 36.6 g m^{-2}; P 3.9 g m^{-2}; energy 55024 kJ m^{-2}) and lowest in the 40-year (N 14.5 g m^{-2}; P 1.3 g m^{-2}; energy 21626 kJ m^{-2}) stand. The relative loss rate of ash-free mass, nutrient and energy content was strongly related to C:N ratio, litter temperature and litter moisture. Relative loss rate of ash-free mass and nutrients of

the litter fractions depended more strongly on litter quality followed by litter temperature and then litter moisture, whereas in the case of energy, litter temperature had greater effect than C:N ratio and litter moisture. The magnitude of release of nutrients and energy in the younger stands were rapid indicating accelerated nutrient cycling through litter production, decomposition and heat sink than older stands beyond 20 years age.

9. Soil was acidic and acidity increased with age. The influence of *Alnus* on acidity in the *Alnus*-cardamom plantation stands showed less chances of soil neutralization capacity and accumulation of base cations as the plantation age progressed. There was a decrease in SOM, organic carbon with consistent decrease in litter accumulation and productivity in the 20-, 30- and 40-year stands. SOM was negatively related to soil pH. Total-N, total-P, inorganic-P, organic-P and available-P contents increased until 15-year and decreased thereafter with increase in stand age indicating limitations of these nutrients in older plantations.

10. Net rate of N-transformation through N-mineralization and nitrification were more than twice in the younger plantations up to 20 years and consequently more is available for plant

uptake. Both N-mineralization and net nitrification were inversely related to soil moisture and SOM, and positively related to soil pH. Soil N-availability indexed by *in situ* field incubation revealed a strong pattern of stand age effect with highest (24−61 kg ha^{-1}) at 15-year which was 1.7 and 2.2 fold increase compared to 5- and 40-year stands, respectively. The 15-year stand showed the lowest C:N ratio indicating higher N availability. The C:N ratio was inversely proportional to mineralization. The potential net rate of N-transformation through N-mineralization and nitrification were more than twice in the younger plantations than the oldest and consequently more is available for plant uptake in the younger plantations.

11. In the soil total-P, most of the P was in organic form. Availability of phosphorus was highly dependent on pH and showed a positive relationship in different stands. Secondarily fixed phosphates in the forms of Ca-P, Al-P, Fe-P and occluded Fe-P were fractionated. Seasonal fluctuation and lower concentrations of Ca-P, Al-P, Fe-P, and occluded Fe-P with increasing acidity in the older plantations resulted into lower available–P in the older plantations. In contrast, among all the fractionated forms, occluded Fe-P was 14−47 times greater than other forms which would be a potential source of

available-P in *Alnus*-cardamom plantations. In course of stand aging, the processes of N-transformation and P solubilization declined with time and showed lower availability in the older plantations after 20 years. Thus, N and P budgets and availability is mainly controlled by N_2-fixing *Alnus* and it tends to be a successful associate in the *Alnus*-cardamom agroforestry.

12. Foliar concentration of nutrients showed inverse relationships with stand age. Standing states of nutrients including that of floor-litter was recorded lower (N 554 kg ha^{-1}; P 37 kg ha^{-1}) in 5-year and highest (N 1084 kg ha^{-1}; P 48 kg ha^{-1}) in 15-year, and decreased thereafter with advancing age. Nutrient uptake was lowest in the 40-year and highest in the 15- and 5-year stands. Nutrient storage in cardamom was very high up to 31% N and 59% P in 15-year of the total vegetative components of stand. Total nutrient input through litter production ranged from 3.6 kg ha^{-1} $year^{-1}$ P and 62 kg ha^{-1} $year^{-1}$ N in the 40-year stand to 7 kg ha^{-1} $year^{-1}$ P and 163 kg ha^{-1} $year^{-1}$ N in 15-year. Nutrient use efficiency was higher (with faster turnover times) in younger stands and decreased with increase in plantation age.

13. Nitrogen retranslocation showed positive relationship while P showed negative relationship with stand age. Nitrogen uptake that included addition through biological fixation was lowest in the 5-year (90 kg ha^{-1}) and highest in the 15-year (239 kg ha^{-1}) stand. Annual return of N to the soil through decomposition to that of uptake ranged from 32–58% being higher in the younger stands whereas P ranged from 44–66% being higher at 15- and 20-year stands. Nutrient standing state and return were highest in 15-year and lowest in the 40-year stand. The poor nutrient conservation of *Alnus* and malleability of nutrient cycling under its influence also make it an excellent associate promoting greater availability and faster nutrient cycling. Nitrogen and P cycling were balanced due to the influence of *Alnus*. Nutrient cycling and dynamics indicated that the *Alnus*-cardamom performed well between 15 and 20 years.

14. Traditional stand tree density management should be slightly improved by planting more than 600 *Alnus* trees per hectare at the time of establishment. Reduction of tree density by heavy thinning should be avoided. Density of 500–600 trees ha^{-1} with subsequent gap filling by planting cardamom would be appropriate for higher energy conversion efficiency, production efficiency, nitrogen fixation and dynamics of

nutrient cycling balance. This will also ensure substantial yield and provide additional income in the form of timber and fuel-wood from the harvested trees at the end of rotational cycle.

15. Appropriate shade conditions and canopy interference of light are the determining factors for humidity and moisture retention, as cardamom requires both of these at high percentage. Cardamom requires diffuse light radiation that minimizes evapotranspiration. High canopy of tall trees beyond 12 m height results in-canopy wind flows which is also not suitable for large cardamom.

16. The inclusion of N_2-fixing *Alnus* in the cardamom plantations helped in maintaining ecosystem functioning through accelerated biogeochemical cycling of nutrients and energy dynamics. It is concluded that the performance of *Alnus*-cardamom plantations is ecologically and economically beneficial up to 20 years of age. It is suggested that the agroforestry stands which are old should be replaced by replantation. Adoption of replantation cycle of 20 years for both *Alnus* and cardamom would be highly beneficial and this will ensure the practice to be sustainable ❖

1.1 The context

As global concerns focus on environmental protection, natural resource management and the world's ability to feed ever-growing population, the interdependence between nations and scientific disciplines is greater than ever before. The sustainability of agricultural and natural resources has taken centre stage among researchers, the public and policy makers as a key issue in global change, biodiversity preservation and the welfare of rural people.

The concept of 'sustainable agriculture' really constitutes acceptance of a broadened agenda for agricultural research. It represents a shift in balance, greater environmental concern and renewed importance given to biological and social interpretation. The management actions were focused at a field scale over a time period of a few crop cycles, with a single objective: yield maximization. Recently, global concerns have broadened this view to include biodiversity, nutrient budgets and water quantity and quality forming a more complex interactive perspective. Farming system that have existed for long periods have been, by definition, sustainable. To continue this sustainable, they must evolve to meet the needs and constraints of future generation just they have evolved from the past.

In large areas of the mountains, the resource base of plantation forestry are often established on land on which other forms of land uses have failed good economic viability due to mismanagement or severe environmental constraints. This has been manifested by a decline in the per capita availability of cropland, reduced availability of village commons also called support-land and a decline in carrying capacity of these areas. Development concerns in the Himalaya revolve around the clock how resources of the region could be managed for conserving/improving the environmental values of the region together with socio-economic development of the mountain people. Conservation of natural resources figures as top priority on the agenda of environmentalists thinking about the development of the mankind in a wider perspective. Ways of building upon the economic potential linked to infrastructure development, introduction of advanced technology and increased cash flows through market economy are the primary concerns to the deprived and desperate rural hill dweller.

1.2 Sikkim perspective

Farming and tourism are the primary livelihood options for mountain people in the Hindu-Kush Himalayan region. Tourism in Sikkim, a small Indian state in the eastern Himalaya, has become popular only since 1990; the main focus is on ecotourism. Only a small segment of the population is engaged in this sector, however.

More than 80% of the population depends on agriculture. The developmental measures of the "green revolution" implemented in other Indian states were not successful in the Himalayan region because adequate fertilizers were never available on time, irrigation could not be developed, and soils are very fragile. Population growth and consequent fragmentation of farmland in Sikkim have caused a reduction in per capita holdings. This has forced farmers to cultivate cash crops such as potatoes (*Solanum tuberosum*), ginger (*Zingiber officinale*), and mandarin oranges (*Citrus reticulata*). The latter two have caused rapid nutrient depletion of the soil. Production of another cash crop, large cardamom (*Amomum subulatum*), a plant native to the Sikkim Himalaya, has been a boon to the mountain people of the area. Large cardamom is a perennial cash crop grown beneath the tree cover on marginal lands. Its cultivation is an example of how local mountain niche can be exploited sustainably.

1.3 Approach to agro-ecosystem studies

There seems to be lack of proper understanding of the basic principles underlying the functioning of agro-ecosystems. Whereas ecosystem research has expanded our understanding of ecosystem functioning, it has mainly been directed towards natural or undisturbed ecosystems. Integrated ecosystem studies have been carried out in managed forests, but few if any have been conducted with a view of gaining on the understanding of basic principles regulating the productivity of agricultural land. Such investigation are vital but must be supplemented by more basic studies, which should be carried out in an ecological framework and on ecosystem context. Such an approach calls for cooperation of scientists from a multitude of disciplines, such as eco-physiology, crop husbandry, soil science, microbiology, hydrology, plant pathology and ecology.

An integrated approach to agro-ecosystem studies is especially needed with regard to energy flow and nutrient cycling. Nitrogen and P are the main limiting factors for agricultural production, and as a consequence, the uses of N_2-fixing trees have been tried to augment the system. Large cardamom based plantation with N_2-fixing *Alnus nepalensis* as shade tree forms a popular agroforestry system is Sikkim that is a good example to carry out such study.

1.4 Hypotheses and objectives

The hypotheses of the present investigation were drawn from the regular queries and field interactions with the farmers of different parts of the cardamom-growing region of the Eastern Himalaya. Their experience and expertise refined through generations since the inception of the cardamom domestication were recorded through personal contact and field visits. These information's were useful for planning the work.

Hypothesis I

Productivity potential of both *Alnus* and cardamom plants peak at a certain age and then decrease with aging.

Objectives for Testing Hypothesis I

- Estimation of agronomic yield and productivity in an age series of *Alnus*-cardamom stands to find out an appropriate age for replantation.
- Energy fixation efficiency and compartmental flows in an age series of *Alnus*-cardamom stands.
- Net primary productivity stratification by girth classes from all ages of *Alnus nepalensis* trees.
- Estimation of tiller number and fruiting frequency relationship with cardamom age.

Hypothesis II

Symbiotic N_2-fixation by *Alnus nepalensis* increases the nitrogen availability in the soil benefiting the understorey large cardamom associate.

Objectives for Testing Hypothesis II

- Estimation of N_2-fixation by *Alnus nepalensis* in an age series of *Alnus*-cardamom stands.
- Seasonal estimation of total nitrogen and inorganic nitrogen (NH_4^+-N and NO_3^--N) in different ages of *Alnus*-cardamom stands.

- To quantify the rates of soil nitrogen mineralization in an age series of *Alnus*-cardamom stands.

Hypothesis III

Accelerated nutrient cycling under the influence of N_2-fixing *Alnus* retards after certain age affecting the stand nutrient dynamics. Nutrient use efficiency of both *Alnus* and cardamom drop when the nutrient cycling retards after a certain age.

Objectives for Testing Hypothesis III

- To quantify different forms of nitrogen (total-N, organic-N, inorganic-N, NH_4^+-N and NO_3^--N) and phosphorus (total-P, organic-P, inorganic-P, available-P and fractionated-P) in soil pool in an age series of *Alnus*-cardamom stands.
- To estimate the quantities of nutrients (N and P) in different compartments of *Alnus* and cardamom, and also in litter component.
- To estimate the nutrient (P and P) flows such as uptake from soil, translocation in different plant components and nutrient release through litter decomposition in an age series of *Alnus*-cardamom stands.
- Estimation of N and P uptake separately by *Alnus* and cardamom in different ages of *Alnus*-cardamom stands.

- To establish the relationship between uptake of nutrients and net primary productivity in different *Alnus*-cardamom stands.

Agroforestry systems are man-made ecosystems— so called agro-ecosystems— which in most instances depends on intensive management for sustained productivity. Despite all the extensive agricultural research carried out over a century, surprisingly only a few studies have been undertaken in which the agroforestry system have been an integrated ecological unit. In order to assure sustained or increased agro-economic yields from the system it is necessary to gain a better understanding of how production can be optimized while possible negative environmental consequences are minimized. This can only be attained by integrated studies aimed at understanding the basic properties of the systems. Such studies call for co-operation between the workers in the basic or fundamental sciences and those in the applied sciences.

Plantation sustainability is most likely if there is a maximum alignment between interdependent variables that include (a) ecological capabilities of the site, (b) intensity of management, (c) soil water and other environment values, and (d) economic benefit and social goals.

Information on large cardamom and *Alnus nepalensis* based agroforestry system with respect to the plantation age and maturity of both cardamom and *Alnus* is lacking. *Alnus*-cardamom plantations in the Sikkim Himalaya is a good example for understanding the impact of stand age on performance of mixtures of N_2-fixing and non-N_2-fixing plants. This study was conceptualized to see the influence of both *Alnus* and cardamom age on the crop yield, biomass, productivity, energy dynamics and biogeochemical cycling of nutrients to examine the sustainability of the system and practice. Extensive research on influences of N_2-fixing tree species on soil fertility and stand performance in an integrated farming system of the Himalaya is hardly few. Thus, the study provides information on stand dynamics with regard to soil fertility as a focus in actinorhizal based N_2-fixer in cardamom agroforestry systems.

This research incorporates an approach on the biological aspects of productivity and soil fertility. The approach derives from an ecosystem-level perspective and focuses on developing an understanding of the mechanistic process regulating soil fertility, nutrient dynamics, productivity increase and soil fertility. An equally important reason for the adoption of this research has been an increasing concern for land management, resource conservation and economic benefit in the region ❖

Sustained agriculture production has gradually become the cornerstone of development policies in tropical, subtropical and mountainous zones. The increase in agriculture production was based on the introduction of new high yielding varieties of crops, which required the use of large amounts of pesticides and chemical fertilizers, in addition to irrigation. This policy was successful in some of the privileged sectors of agriculture but it did not benefit any of the less favoured areas where adequate fertilizers are not available and irrigation cannot be developed or where soils are so fragile and deficient in nutrients (especially N and P). This policy, that implies the Green Revolution techniques are not appropriate/adequate and do not even serve to maintain soil fertility (Subba Rao and Rodriguez-Barrueco 1993). Therefore, the management practices were developed in which N_2-fixing species were extensively utilized. In recent years, interest in the use of nitrogen fixing trees has rapidly increased, especially in all areas where the introduction or reintroduction of nitrogen fixing trees can sustain and possibly increase productivity (Subba Rao and Rodriguez-Barrueco 1993).

There are 24 genera from eight angiosperm families that have been described as possessing actinorhizal nodules (Dixon and Wheeler 1986, Schwintzer and Tjepkema 1990). The genus *Alnus* for temperate regions stand out as excellent example for the benefits it provides to the ecosystem by way of nitrogen inputs. It can adapt itself to grow under most diverse environmental conditions and geographic zones (Quispel *et al.* 1993). The microsymbiont in actinorhizal nodules is an actinomycete and has been collectively designated as *Frankia* (Becking 1970). Most nurseries and field sites have sufficient natural populations of infective and effective strains of *Frankia*. These strains have been available from pure cultures since 1978 (Callaham *et al.* 1978), and laboratory production and large scale distribution of the inoculum in a nursery is relatively simple (Perinet *et al.* 1984, Stowers and Smith 1985). In the Himalaya actinorhizal plants such as *Alnus, Hippophae, Myrica, Elaeagnus,* and *Coriaria* are found (Sharma and Ambasht 1986a)

Nitrogen accretion through biological fixation depends on the amounts of active nodule biomass in field and its efficiency. *Alnus* spp are the most extensively studied actinorhizal plant for both nodule biomass and annual N_2-fixation. A few estimates have been published for alder nodule biomass under field conditions (Zavitkovski and Newton 1968, Akkermans and Van Dijk 1976, Binkley 1981, Sharma and Ambasht 1986b). Root nodule biomass in field of the same species and of similar age also differs much depending on plant growth performance, soil fertility, climatic conditions, etc (Sharma and Ambasht 1986b). *A. nepalensis* stands showed lower standing nodule biomass and higher production rate (i.e. faster nodule turnover) than the *A. glutinosa* studied by

Akkermans and Van Dijk (1976). Sharma and Ambasht (1986b) classified active root nodules into three age-classes to investigate age-to-age transition. They found that the percentage of nodule age-class transition and transition to inactive nodules were functions of the season, nodule age and their nitrogen-fixing potential. The highest percentage of active nodule transition to inactive nodule occurred in winter, when the nitrogen fixing activity was low (Sharma and Ambasht 1984, 1986b). Schwintzer *et al.* (1982) reported that 88% of the field nodules of *Myrica gale* were 1-3 years old, comparable to 82% in *A. nepalensis* as reported by Sharma and Ambasht (1986b).

Nitrogen accretion in *Alnus* spp has been found distinctly higher than other actinorhizal plants. Red alder (*Alnus rubra*) is the species which has been investigated in greater details with respect to both biology and management (Trappe *et al.* 1968, Briggs *et al.* 1978, Gordon *et al.* 1979, Hibbs *et al.* 1994). About 15 estimates of nitrogen-fixation rates are recorded in the literature for forest dominated by red alder with rates ranging from no fixation in 0- to 4-year-old stand (Cole and Newton 1986) to a high value of 320 kg ha^{-1} $year^{-1}$ (Newton *et al.* 1968). Most rates fell within the range of 100–200 kg ha^{-1} year $^{-1}$ (Binkley *et al.* 1994). Nitrogen accretion studies in the Himalayan alder plantations in an age sequence revealed that highest fixation of 117 kg ha^{-1} $year^{-1}$ was recorded in the youngest stand of 7 years age which decreased with alder age and fixed just 29 kg ha^{-1} $year^{-1}$ in the oldest stand of 56 years. The efficiency of production and nitrogen fixation in Himalayan alder decreases with age (Sharma and Ambasht 1988).

Most of the studies on mixtures of actinorhizal N_2-fixing and non-N_2-fixing trees have been dealt with red alder (*Alnus rubra*) mixed with either Douglas-fir (*Pseudotsuga menziesii*) or black cottonwood (*Populus trichocarpa*) as reported by Binkley (1992). Large cardamom based agroforestry with and without N_2-fixing *Alnus nepalensis* tree associate has been extensively investigated for biomass, productivity and nutrient dynamics (Sharma 1995; Sharma *et al.* 1994, 1997a, 1997b). An age sequence of *Alnus nepalensis* mono-culture plantations were also thoroughly studied (Sharma 1985, 1993; Sharma and Ambasht 1984, 1986b, 1987, 1988, 1991).

The potential increase in productivity of plants growing near nitrogen fixing plants has been recognized for centuries. The effects of N_2-fixing trees on interplanted non-N_2-fixing trees have most often been characterized in terms of heights and diameters (Berntsen 1961, Newton *et al.* 1968, Miller and Murray 1978, Mikola *et al.* 1983, 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. On nitrogen-deficient sites, mixed stands present an ecological opportunity for increasing both the total stand growth and the growth of the non-N_2-fixing trees (Binkley 1992). Mixture of N_2-fixing and non-N_2-fixing trees differs from other sets of species by the direct and indirect effects of increased nitrogen supply. In stands where nitrogen availability would limit production in the absence of N_2-fixation, these effects typically include increased nitrogen mineralization, nutrient uptake, leaf area, biomass production and nutrient leaching. The key features of mixed stand depend upon the magnitude of these increases and how some of the increases are apportioned between the N_2-fixing and non-N_2-fixing trees. Binkley (1992) summarized the observed rates of N_2-fixation and subsequent cycling in mixed stands relative to single species stands, and then examined other biogeochemical aspects followed by description of components that determine productivity and a discussion of silvicultural opportunities.

Studies on litter production and decomposition dynamics of managed agroforestry systems are limited. There has been a growing effort of inclusion of N_2-fixing species in plantation agroforestry systems in tropics and temperate regions, which in regard is a new intervention for influencing the soil fertility and quick nutrient dynamics. There are reports of much greater litter production in mixed stands of tree plantations with N_2-fixing associate than in stands containing only non-N_2-fixing trees

(Tarrant *et al.* 1969; Binkley *et al.* 1992b). The litter of N_2-fixing species generally decomposes faster and the addition of N_2-fixing tree litter may accelerate the decomposition of non-N_2-fixing litter types (Taylor *et al.* 1989). The ratio of lignin:N and C:N ratio predicts litter decomposition well in temperate forests (Berg and McClaugherty 1987). The decomposition of N_2-fixing species litter is typically much higher than those of other species, although decomposition rates can vary substantially among N_2-fixing trees (Sankaran *et al.* 1993; Mwiinga *et al.* 1994).

The inclusion of N_2-fixing species with non-N_2-fixing species has 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 (Giardina *et al.* 1995; Binkley 1997; Binkley and Ryan 1998; Binkley *et al.* 1999). Mixtures of N_2-fixing and non-N_2-fixing trees typically show increased rates of cycling of nutrients such as N and P (DeBell *et al.* 1989; Binkley *et al.* 1992a & 1992b; Binkley 1983; Cote and Camire 1987). N_2-fixing trees may increase supply of available-N in the soil benefiting both the N_2-fixing and non-N_2-fixing associates. N_2-fixing tree species can have variable feedback effects on soil P supplies; increases in P supply could enhance long term growth of the N_2-fixer (Binkley *et al.* 1999).

Sharma *et al.* (1997b) reported greater soil nutrient dynamics in *Alnus*-cardamom agroforestry compared to non-N_2-fixing forest-cardamom stand of similar age. Reports on accelerated cycling of N and P in the mixed stands of N_2-fixing *Alnus* and *Albizia* in North America and Hawaii are available (Binkley *et al.* 1992b; Cote and Camire 1987; Tarrant *et al.* 1969). The greater N content of the litter in the N_2-fixing stands is attributable to N_2-fixation while greater P cycling in mixed cropping with N_2-fixing species hence been explained as: greater rooting depth (Maklcom *et al.* 1985), rhizospheric acidification (Gillespie and Pope 1990), production of low molecular weight acid and chelates (Ae *et al.* 1990), and increased phosphatase activity (Ho 1979). The N_2-fixing species conserves less nutrient compared to non-N_2-fixing species and hence, contributed more of these nutrients in their litter which results in greater cycling (Sharma *et al.* 1994, 1995).

Alnus nepalensis has been an important fellow species in the jhum system which improves soil fertility through rapid cycling of nutrients with faster turnover of leaves and high rates of N_2-fixation (Ramakrishnan 1992). *A. nepalensis* coppices readily as observed in Nagaland jhum systems and may be harvested after the same-5-year interval thus providing farmer with marketable poles and restore the soil fertility at the same time (Ramakrishnan 1992, 1994).

Alnus-cardamom intercrop grown in middle hills of eastern Nepal was studied as a model highland agroforestry system (Zomer and Menke 1993). Large cardamom based agroforestry system is an age old practice and yield reduces substantially on aging of stands (Singh *et al.* 1989; Zomer and Menke 1993). Cardamom is adapted to local soil conditions with very low soil and nutrient loss from the system compared to other cropped area (Rai and Sharma 1998). Large cardamom farming in the Sikkim Himalaya is a boon for the mountain populations (Sharma and Sharma 1997; Sharma E *et al.* 2000). The use of N_2-fixing *Alnus* as an associate shade tree in cardamom agroforestry has been highly beneficial in terms of stand production, cardamom yield and nutrient cycling (Sharma *et al.* 1994, 1997a & 1997b). In the current scenario of a very fast rate of the forest depletion in the fragile mountains, a cash crop with a strong forestry component (such as large cardamom agroforestry) meeting the basic requirements of fuel, fodder, timber and high economic return provides comparative advantage both ecologically and economically over other livelihood options (Sharma R *et al.* 2000).

There is no information on large cardamom and *Alnus nepalensis* based agroforestry system with respect to aging of both cardamom and *Alnus*. Therefore, this study has been planned to see the influence of both *Alnus* and cardamom age on the crop yield, biomass, productivity and nutrient dynamics to examine the sustainability of the combination and practice. Measurements of influences of N_2-fixing tree species on soil fertility and stand performance in integrated farming systems in the Himalaya is lacking. This study provides information on stand dynamics with regard to soil fertility as a focus in actinorhizal based N_2-fixer in cardamom agroforestry systems and draw management strategies for sustainable agriculture to lay foundations for an agro-ecological approach to soil fertility ❖

Chapter III

STUDY AREA, CARDAMOM AGROFORESTRY AND STAND CHARACTERISTICS

3.1 Prelude

The Himalaya (Sanskrit *Hima-* snow, *Aalaya-* house) constitutes a unique geographical and geological entity comprising diverse social, cultural and environmental set up. It is a cradle of unique and important biodiversity elements known for their economic and ecological importance. The growing concerns for deteriorating environment sustainability and formulation of appropriate land-use policies in planning research and developmental activities over the last four decades seem to have cause and effect arguments, and are plunging very fast towards environmental and socio-economic collapse. These unwitting influences have been manifested in the form of deforestation, landslides, down-stream flooding, uncontrolled population growth, poverty and malnutrition and poor management strategies. Progress towards these goals can, in principle, be monitored through out-come oriented codes. Anthropogenic stress on natural ecosystem has triggered large-scale disasters throughout the Himalaya. Undirected spread of subsistence agriculture (for per capita increase) to support the growing undernourished population and corresponding increase of grazing pressures that out-strip the carrying capacity of the forest, continue to abridge supportive ecosystem by various means.

Management practices can do much to conserve or improve biological resources in the Himalayas. The dynamic accomplishment of an ecologically sound and environment friendly, new green revolution is possible only when rural farming families learn to optimally manage their valuable geo- as well as bio-resources.

3.2 The Sikkim Himalaya

The traditional definition of the Himalaya, *sensu stricto,* is that great range of mountains that separates India, along its north-central and north-eastern frontier, from China (Tibet), and extends between latitudes 26^0 20′ and 35^0 40′ North, and between longitudes 74^0 50′ and 95^0 40′ East. The region extends from the Indus Trench below Naga Parbet (8,125 m) in the west to the Yarlungtsangpo-Bramhaputra gorge below Namchee Barwa (7,756 m) in the east, covering the political administrative regions of Afghanistan, Pakistan, India, Nepal, Bhutan, and China (Ives and Messerli 1989). The Himalaya lying in the Indian territory stretches over a length of about 2,500 km and a width of 220–300 km covering partially or fully 12 states/provinces of the Indian Union with the Himalayan kingdom of Nepal and Bhutan. It has been classified into five major geographical divisions' viz. (a) The eastern Himalaya (Sikkim-Darjeeling-Bhutan and Arunachal Pradesh), (b) The Central Himalaya (eastern and central Nepal), (c) The Western Himalaya (Kumaon-Garhwal, Himachal Pradesh, Western Nepal), (d) North-West Himalaya (Kashmir-Afghanistan), and (e) The North-West Himalaya (Sino-Tibet). This is the highest and youngest mountain system formed out of the bed of the Tyeth

Sea during continental drift sometimes by the end of the tertiary period. The Indian Himalaya covers a total geographical area of approximately 591000 km^2 and is inhabited by about 51 million persons (Rao and Saxena 1994) with a multiple ethnic composition. Geographically speaking the snow clad mountainous range of the Eastern Himalaya and the highly precipitous hilly terrain of Himalayan amphitheater happens to be at a closer proximity to the Bay of Bengal to receive more rainfall than Central and Western Himalayas. The vividly marked tangled series of interlacing ridges with indifferent gigantic mountainous barriers and diversified vegetation green cover , is geomorphologically varied with immense climatic differences even at a closer distance.

Sikkim or the "New House" is situated in the eastern Himalaya (88^0 03′ 40″ to 88^0 57′ 19″ East longitude and 27^0 03′ 47″ to 27^0 07′ 34″ North latitude) sandwiched between the Himalayan kingdoms of Nepal and Bhutan in the west and east, bounded by the vast stretches of Tibetan Plateau on the North and shares southern border with Darjeeling Gorkha Hill Council of West Bengal. The mountain terrain is spread over 7096 km^2 with elevations ranging from 250–8,595 m above msl. Administratively, there are 440 villages, eight towns and four districts and is a cornucopia of four major ethnic groups' viz. *Lepcha (s), Nepalese, Bhutia (s)* and *Limbu (s).*

The climate of the state varies from cold temperate and alpine in the northeast to subtropical in the south. The main livelihood option of the people is agriculture. The state abounds by more than 6000 plant species and more than 4000 species are flowering plants. About 12% of the land is available for cultivation and the main occupation of the hill people is farming. The net state domestic product of Sikkim at constant prices increased by three times from 1981 to 1991 and per capita income doubled during the period. The state earns about 47% of its GDP from agriculture (Anonymous 1981).

3.3 Large cardamom

3.3.1 Agroforestry

Large cardamom locally called "alainchii" is believed to be one of among the oldest spices known and its Ayurvedic preparations dates back to 6th century BC as mentioned by Sashruta. It was known to Greeks and Romans as "*Amomum*" during the 4th century BC and was recorded by Theophrastus the Greek philosopher. The aboriginal inhabitants of Sikkim- *The Lepchas*- were believed to be the first to collect cardamom capsules from natural forests, and these forests eventually converted into ownership and the crop was domesticated.

The seeds are sometimes administered orally for curing certain ailments and acts as carminative; stomachic, diuretic, an effective cardiac stimulant and is a remedial medicine for throat and respiratory troubles. The seeds contain about 3% essential oil rich in cineole (Gupta *et al.* 1984), which is used as flavoring agent and spice.

A total of 16,949 cardamom holdings have been recorded in Sikkim state, most of which are smaller than 1 ha. About 30% of the total area under cultivation is 1–3 ha large (Sharma and Sharma 1997; Sharma E *et al.* 2000). Figure 1 shows the major cardamom growing areas of Sikkim.

The cultivation area of large cardamom has increased by 2.3 times in the past 20 years. Large cardamom is the most perennial cash spinner native crop of Sikkim grown mostly in private holdings. However, about 1316 ha of the reserved forest in Sikkim is still used for under-canopy large cardamom cultivation on lease to farmers with no rights of cutting the trees (Sharma *et al.* 1994). The crop usually grows as understorey vegetation below the tree canopy and requires an annual rainfall of 1500–3500 mm. During the last 5-6 decades, a large area of agricultural land has been converted to *Alnus*-cardamom agroforestry using monocultures of N_2-fixing *Alnus nepalensis* as shade tree.

3.3.2 Local cultivars and ecological amplitude

The cultivated species is *Amomum subulatum* Roxb. and belongs to the family Zingeberaceae. Seven wild species such as *A. linguiforme, A. kingii, A. aromaticum, A. corynostachyum, A. dealbatum, A. costatum* and *A. plauciflorum* are naturally occurring in the region. The cultivated species has six local cultivars (varieties) suitable for cultivation at different elevations and adapted to various other environmental factors such as water deficit and frost. The common occurrence of local cultivars grown in Sikkim varies according to their altitudinal adaptability. Local varieties such as 'Ramsai', 'Sawney', 'Bharlng' and 'Ramla' are cultivated above 1500 m whereas 'Sawney', 'Chibey' and 'Ramnang' are grown within 1000–1500 m and 'Golsai', and 'Saramna' below 1000 m elevations.

In large plantations of the cardamom agroforestry the shade tree is N_2-fixing Himalayan alder (*Alnus nepalensis* D. Don). Some other common shade trees are *Schima wallichi, Engelhardtia spicata, Eurya acuminata, Leucosceptrum canum, Maesa chisia, Symplocos theifolia, Ficus hookeri, Nyssa sessiliflora, Osbeckia paniculata, Viburnum cordifolium, Litsaea polyantha, Macaranga pustulata* etc. Large cardamom agroforestry thus supports conservation of tree biodiversity in the region though the use of *Alnus*-cardamom systems has recently proved more profitable.

3.3.3 Economics

Only 12.3% of the land in Sikkim is available for cultivation, including currently used and other fallow land. Forest cover account for 41.9% while a large area of 25.4% is barren and uninhabited. About 26,734 ha area is under cardamom cultivation in Sikkim while about 3,274 ha area is under cardamom plantation in adjoining Darjeeling District of West Bengal (Spices Board, Government of India 2001).

The greatest percentage increase of cultivated land was recorded for cereals, followed by large cardamom, oil seeds, vegetables, oranges, pulses, ginger, and potatoes. Percentage increase in state production in the past 20 years clearly show that crops such as cereals, vegetables, ginger, and potatoes performed very well. The percentage contribution of large cardamom production was proportionally small, as it is low volume crop that nevertheless has high economic value. Large cardamom's share in the state's gross income was proportionally very high: 16.58% in 1995–1996, which was second to the 31.14% contribution of cereals. Of the total gross income of the state, large cardamom contributed more than 80% in 1975–1976; this decreased to about 58% in 1985-1986 and to about 38% in 1995–1996.

The gross income from large cardamom cultivation in Sikkim increased from US$ 1.9 million in 1975–1976 to 5.7 million in 1985–1986 and 6.4 million in 1995–1996 (conversion at a fixed rate of US$ 1 = Rs 42). In recent years, the contribution of ginger has increased tremendously, but the net income from large cardamom is still higher. A study that compared two systems, one dominated by large cardamom and the other by maize and potatoes, showed that household income and per person per day income were almost double in the large cardamom system (Sharma and Sharma 1997).

The cash-benefit analysis after three years of plantation of *Alnus*-cardamom crop is given in Table 3.1. Large cardamom is a perennial crop that gives yield form 3rd year of plantation. In the first year the plantation around Rs. 25000 ($538) per hectare is required for planting material and labour. Refilling of gaps and weeding requires Rs. 3500 ($75) per hectare in the second year. After this, from third year onwards weeding, harvest and post-harvest labour costs are the only cash inputs required for the system.

The cash-benefit analysis shows that large cardamom provides excellent income until 15- to 20-year of plantation. The timber and fuel-wood monetary return by the harvest of *Alnus* tree before replanting with a rotational cycle of 20-year would be around Rs. 576000.00 ($12387) per hectare. This is in addition to cash income from large cardamom after 3-year onwards.

3.3.4 Ecological sustainability and future perspective

Besides its high-income value and low demand in labour, large cardamom is also a low-volume and non-perishable crop; this is a great advantage in an area where accessibility and transportation are restricted. Furthermore, cardamom agroforestry is almost a closed system that does not depend on external inputs.

The cardamom crop is well adapted to the local soil conditions and soil loss (30 kg ha^{-1}), overland flow (2.17% of precipitation), and nutrient loss (nitrogen 0.41 kg ha^{-1}; total phosphorus 0.02 kg ha^{-1}, organic carbon 1.86 kg ha^{-1}) were very low in large cardamom agroforestry compared to other forming practice (Rai and Sharma 1988). The ecological sustainability is even greater with cardamom when shade tree used is the Himalayan alder (*Alnus nepalensis*), which regenerates naturally on landslide-affected areas and grows within the same agroclimatic range of cardamom. The agroforestry under the influence of *A. nepalensis* is more productive because of higher nutrient cycling rates. The poor conservation and low nutrient use efficiency of the *Alnus*, together with the malleability of nutrient cycling under its influence make it an excellent associate for cardamom plantation (Sharma *et al.* 1994, 1995). By comparison with other cash crops, large cardamom is thus low input crop, and nutrient exit through agronomic yield is very minimal, making it an excellent crop for this fragile mountain ecosystem.

Large cardamom is almost a self sufficient system. The post-harvest technology continues to be largely traditional. Farmers have devised indigenous ways of processing cardamom. The capsules are dried in traditional kilns. Fuel-wood is consumed in the ratio of 4:1 for cured cardamom; about 800 kg ha^{-1} of wood are required to cure 200 kg ha^{-1} of finished product. Recently, some institutions have developed improved kilns and gasifiers for curing as well as capsule tail cutting and polishing machines for value addition. Farmers are yet to adopt these technologies.

3.3.5 The future of large cardamom farming

The most worrying factor in large cardamom farming is the decrease in yield per hectare recorded in recent years. The yield of the large cardamom depends upon the age and that most of the plantations (about 10,000 ha) that existed before 1975 are very old and have actually not been producing more than 100 kg ha^{-1} capsules. But the majority of new plantations (about 13,500 ha) are well maintained and produce between 250–350 kg ha^{-1}. New plantations should replace the older ones. Large cardamom starts producing from the 3rd year after planting, and yield declines considerably after the 20th year. Filling the gaps created by withering cardamom bushes and carrying out selective felling of old trees is not enough.

Another cause of decline in large cardamom yield has been infestation mainly by viral diseases viz. "Chirkey" and "Phurkey". This is one of the reasons for production decrease. Uprooting and burning of all the infected plants has been the only possible alternative to control these viral diseases. The Dzongu Golsai variety has been found to be resistant to these diseases. Until now cardamom hybrids have not been developed by any research and development institutions.

In conclusion, cash crop farming holds the key to maintaining the viability of small and marginal farmers in the mountain region. Further expansion of the landholding size is almost impossible. The potentiality for sustainable management of a marginal/fragile mountain land needs serious evaluation.

3.4 Site Characteristics

3.4.1 Study area

3.4.1.1 Location and climate

Three experimental sites selected for the study are located at Kabi (North District), Thekabong (East District) and Sumik (East District) in Sikkim of the Eastern Himalaya. These sites extend within 27° 15′ 05″ to 24° 17′ 36.6″ N latitude and 88° 28″ 6.9″ to 88° 39′ 27.1″ E longitude with an elevation distribution between 1350–1600 m asl. These study sites are more than 80-km distance apart and relates to the major areas of large cardamom cultivation in Sikkim. The study area is in the Indian monsoon region with a temperate climate having the three main seasons: winter (November-February), spring (March-May) and rainy (June-October). Mean monthly maximum temperature ranged from 14.3–23.3°C, mean monthly minimum temperature from 5.4–15.8°C (Fig. 3.2). Mean monthly minimum soil temperature ranged from 6.34−17.61°C and mean monthly maximum soil temperature from 11.48−20.98°C (Fig. 3.2). Total rainfall varied with maximum during monsoon season and minimum in winter season and ranged between 3000–4500 mm per year in the study sites (Fig. 3.3). Relative humidity varied between 80–95% during the rainy season and decreased to about 45% in spring (Fig. 3.3).

Photosynthetically active radiation (PAR) was recorded during 1998–1999 (Fig. 3.3). Mean PAR was highest (655 μ mol m^{-2} sec^{-1}) in April and lowest in September (357 μ mol m^{-2} sec^{-1}).

3.4.1.2 Plantations

All the three experimental sites in Sikkim have several pure stands of *A. nepalensis* tree with understorey large cardamom plantations of different age classes. Large cardamom and *Alnus* trees in a selected stand is of the same age, therefore age designation to the stand refers to the same age for both large cardamom and *Alnus*. The selected *Alnus*-cardamom stands at each of these sites represented plantations of an age sequence of 5-, 10-, 15-, 20-, 30- and 40-years numbering 18 plots altogether. These stands at each of the sites are closely comparable; the structural and functional differences are attributed to the age of the plantations. Soil was acidic (pH 3.8–5.6) and pH varied widely with depth; the variation in pH of surface soils was small between plantations (17%). The soil was sandy loam ranging in horizons from 11–30% clay, 15–40% silt and 34–65% sand in a 1 m profile. The per cent clay and porosity decreased along the soil depth while per cent sand increased down the depth (Table 3.2).

The selection of three sites and stand ages were based on the available information and history of plantations maintained by the cardamom growers. The selection of sites at three different locations was exercised to minimize the heterogeneity and arbitrarity of ecophysiological and microclimatic variations.

3.4.2 Geology

The Sikkim Himalaya is constituted, by the physiographic or geologic terrain's viz. the Tibetan Himalayan Zone, Higher Himalaya, Lower Himalaya etc. It has the world's third highest mountain peak Mt. Kanchandzonga, (8598 m) and other mountain systems.

The Sikkim Himalaya enjoys a wide range of climate, physiography, geology and vegetation that influence the formation of different kind of soil. The soils are in general, acidic in reduction due to heavy rainfall and leaching of bases from surface soil to represent Typhic Hapludolls and Dystric Eutrochrepts largely under the temperate forests. On the other hand, steep slopes (30–50%) with Umbric Dystrochrepts and Cumulic Hapludolls experiences Thermic soil temperature regime and found largely under paddy, maize, cardamom and temperate forests (Mukhopadhyay 1998).

The soil throughout the cardamom based agroforestry stands consists of humus, sandy loam, and dark brown to yellowish brown in colour. Red and yellowish podzolic soils are found in some of the agroforestry stands of higher elevations. The humus layer at the upper soil horizon is due to the deposition of dead organic residue.

3.4.3 Bulk density

The bulk density of the soil horizon (0-15, 15-30 cm) in the age series of *Alnus*-cardamom plantations varied distinctly with higher values at lower depths than upper. The bulk density in the lower depths of all the sites showed lower values indicating the most compact soil in this horizon (Table 3.3). Bulk density varied significantly ($P<0.0001$) within sites, stand ages and soil depths. Interactions between the sites, stand ages and depths were also significant ($P<0.0001$). Older plantation stand showed higher bulk density which is an indication of greater soil compactness.

3.5 Stand structure

3.5.1 Diameter at breast height (DBH)

DBH is the one of the important dimension used in factors determining individual tree volume and value. It is generally known to be strongly influenced by stand density and has therefore been investigated in several alder spacing and thinning studies (Bormann 1985; Hibbs *et al.* 1989). DBH is widely used to estimate biomass and production through selective harvest or predictions of established regressions.

Mean DBH of *Alnus* trees in the age series is presented in Table 3.4. DBH of *Alnus* ranged between 8–77 cm in 5- to 40-year stand. Variation within the stand at age 5-year was 8–25 cm, 15-year 18–40 cm and 40-year 37–77 cm. It increased with the increase of age of the plantations.

3.5.2 Tree height

Tree height increased with increase in age of the plantations and basal area (Table 3.5). Mean tree height increased with the advancement of age and ranged between 15 m in 5-year to 35 m in the 40-year stand.

The analysis of tree height within the optimal range or 26 m or below in the *Alnus*-cardamom stand showed that the performance of understorey cardamom was well with greater productivity and agronomic yield. In stands older than 25- to 30-years, height growth and area increase showed considerably above the optimal range of the shade required for better performance of cardamom.

3.5.3 Tree density, parabolic volume and conic surface

Density of trees was highest in 10-year stand and lowest in 40-year stand. Density, parabolic volume and conic surface of *Alnus* trees are presented in Table 3.4. Parabolic volume of the stem is one-half basal area times tree height and conic surface is one-half girth at breast height multiplied by tree height. Parabolic volume of the trees in the age series increased form 70 m^3 ha^{-1} (5-year) to 543 m^3 ha^{-1} (40-year) (Table 3.4). Increase in parabolic volume showed a negative relationship with tree density and in the age series (Fig. 3.5b). Increase in tree density also showed a negative relationship with DBH (Fig. 3.4a). This was because of higher basal area of *Alnus* trees at stands with lower tree density than at higher tree density stands. Increase in DBH showed considerable increase in parabolic volume. Linear regression between parabolic volumes with basal area showed a positive relationship (Fig. 3.5a).

Conic surface of the sampled trees in the age series ranged from 1406 m^2 ha^{-1} (5-year) to 4528 m^2 ha^{-1} (40-year). Conic surface is also related to diameter at breast height and tree height. Parabolic volume and conic surface were comparatively much higher in 30- and 40-year plantation stand than other younger stands (Table 3.4).

3.5.4 Tree basal area

The basal area of the *Alnus* trees on per hectare basis was obtained from the DBH (π $DBH^2/4$) of the individual trees on per hectare basis. Mean basal area of the *Alnus* trees are presented in Table 3.4. Basal area of the individual tree ranged between 0.013 m^2 in 5-year to 0.523 m^2 in 40-year plantation stands. Basal area of a stand largely depends on the tree density and plantation age (Fig. 3.5b).

Stand total basal area on per hectare basis was highly dependent on the basal area of the understorey cardamom. Stand basal area increased from 45 m^2 ha^{-1} (5-year) to 156 m^2 ha^{-1} (15-year) and decreased consistently in the increasing age to a reduced value of 40 m^2 ha^{-1} (40-year). This was due to the small tree density and small number of cardamom bushes in the older stands.

3.5.5 Cardamom bush density, tiller number and basal area

Cardamom bush density increased with increase in plantation age. One possible reason may be gap filling of the cardamom as a management practice. Number of cardamom bush ranged from 10−260x10^2 bush ha^{-1} in 5- to 40-year plantation stands (Table 3.6). This was followed by increase in tiller number in the increasing age groups of plantations. Range of tiller density increased form 5-year (130−160x10^3 tillers ha^{-1}) to a maximum at the 15-year (550−630x10^3 tillers ha^{-1}) and lowest (20−40x10^3 tillers ha^{-1}) in the 40-year stand.

Basal area of cardamom was calculated on tillers per bush and bushes per hectare basis. Basal area of understorey cardamom increased form the 5- (30−37 m^2 ha^{-1}) to 15-year (128−147 m^2 ha^{-1}) and decreased (5−10 m^2 ha^{-1}) in the 40-year stand (Table 3.6). It decreased with increase in age beyond 15 years with corresponding decrease in the number of cardamom tillers and bushes.

3.5.6 Canopy architecture and shade effect

The canopy architecture of a stand is determined by the number, spacing, height and size of the trees. The relationships between leaf area and stand age depend on species, and water and nutrient availability. In plantations, a key issue is the management of canopies to maximize interception of light throughout the rotation. The arrangement of foliage and branches throughout the canopy determines structure. Structure determines penetration of light through the canopy and distribution of micro-environmental factors such as leaf and air temperature, vapour pressure deficit and wind speed.

Canopy cover, canopy volume and canopy depths of different girth classes of *Alnus* are presented in Table 3.5. The range of canopy cover was 14.52 m^2 $tree^{-1}$ (5-year) to 70.85 m^2 $tree^{-1}$ (40-year). Similarly, canopy volume increased consistently from 106 (5-year) to 978 m^3 $tree^{-1}$ (40-year). Due to the highest tree density in the 15-year stand, canopy cover on per hectare basis was highest as compared to other plantations while it was least in older plantations. Canopy depth also increased consistently from 5-year (7.31 m $tree^{-1}$) to 40-year (13.80 m $tree^{-1}$) plantation.

Light interception by the canopy was recorded during full canopy and least canopy stage. Light intensity was recorded in all the stand ages using Lux meter. Light intensity reaching the understorey cardamom was substantially low in the higher tree density stands than in lower tree density stands. In 10-year stand, light intensity received was 86 μmol m^{-2} sec^{-1} while it was 479 μmol m^{-2} sec^{-1} in 40-year stand (Table 3.7).

Appropriate shade conditions and canopy interference of light are the determining factors for humidity and moisture retention, as cardamom requires both of these at high percentage. Cardamom requires diffuse light radiation that minimizes evapotranspiration. High canopy of tall trees beyond 12 m height results in-canopy wind flows which is also disadvantageous for large cardamom. The performance of cardamom was found highly promising within 18–22% of the PAR reaching the understorey cardamom.

3.5.7 Stand tree density management

Two important conclusions are drawn from the traditional stand density management practice. First, stand densities at the time of establishment probably need to be higher than 600–650 trees ha^{-1} to avoid height growth loss due to wide spacing. Second, a reduction of tree density after heavy thinning has been found in stands after 10- to 15-years. This leads to a substantial reduction in tree and stand volume. Densities within 500–600 trees ha^{-1} with subsequent gap filling by cardamom plantation would be appropriate for higher energy conversion efficiency, production efficiency, nitrogen accretion and dynamics of nutrient cycling. This will also ensure sustained yield, nutrient balance, and provide additional income at the end of rotational cycle by harvesting *Alnus* ❖

Table 3.1. Annual cash-benefit analysis and monetary evaluation per hectare (amount in US\$ 1 = 46.50 rupees) of large cardamom after three years of plantation in Sikkim. (First year plantation cost =\$538 ha^{-1} for planting material and labour; 2nd year =\$75.27 ha^{-1} for refilling of gaps and weeding; 3rd year onwards cardamom gives yield and after this weeding, harvest and post harvest cost are cash inputs)

Cost evaluation	Plantation age (year)				
	3	4 – 6	7 – 12	13 – 16	17 – 20
Cost	77.42	120.43	161.29	133.33	124.73
Output	80.65	806.45	1427.73	1532.90	953.76
Benefit/cost ratio	1.04	6.69	8.83	8.49	7.64

The timber and monetary return by the harvest of *Alnus* tree before replanting (20-year rotational cycle) =\$12387. This is in addition to cash income from large cardamom yield from 3rd year onwards.

Table 3.2. Soil physical properties under the age series of *Alnus*-cardamom plantation stands. Values are (replicates of three sites) ±SE n=6

Soil depth	Clay (%)	Silt (%)	Sand (%)	Porosity (%)
0–40	22.69±2.98	25.62±4.57	43.93±7.76	69.43±7.08
20–40	25.04±3.55	26.98±3.11	43.64±4.89	68.58±2.87
40–60	21.73±2.88	27.06±4.36	44.57±6.56	66.28±4.68
60–80	18.39±2.39	29.04±4.73	46.35±7.03	62.35±4.91
80–100	17.38±2.51	28.51±5.82	48.52±7.47	58.96±4.65

Table 3.3. Bulk density (g cm^{-3}) at two soil depths at three sites in age series of *Alnus*-cardamom plantation stands.. Values are mean ±SE, n=5

Stand age (year)	Soil depth (cm)	Study sites		
		Thekabong	Sumik	Kabi
5	0-15	0.93±0.04	0.71±0.05	0.64±0.18
	15-30	1.10±0.05	0.77±0.07	0.77±0.28
10	0-15	1.09±0.06	0.63±0.03	0.64±0.08
	15-30	1.12±0.06	0.79±0.03	0.73±0.03
15	0-15	0.68±0.03	0.81±0.09	0.92±0.10
	15-30	1.19±0.06	0.94±0.08	1.02±0.24
20	0-15	0.57±0.02	0.81±0.04	0.62±0.03
	15-30	1.26±0.05	0.97±0.05	0.92±0.03
30	0-15	0.58±0.02	0.64±0.07	0.94±0.06
	15-30	1.14±0.02	1.07±0.03	1.08±0.03
40	0-15	0.61±0.25	0.69±0.03	0.65±0.03
	15-30	1.07±0.49	1.10±0.04	1.09±0.05

ANOVA: Sites $F_{2,72}$ = 25.91, P<0.0001; Stand age $F_{5,72}$ = 4.25, P<0.0001; Depth $F_{1,72}$ = 48.06, P<0.0001; Site x Stand age $F_{10,72}$ = 6.38, P<0.0001; Site x Depth $F_{2,72}$ = 1.25, P<0.0001; Stand age x Depth NS; Site x Stand age x Depth $F_{10,72}$ = 7.45, P<0.0001; LSD (0.05) = 0.05

Table 3.4. Stand tree density, DBH, basal area, parabolic volume and conic surface in the age series of *Alnus*–cardamom plantations. Values are means of three site replicates.

Stand age (year)	Tree density (trees ha^{-1})	DBH (cm)	Basal area (m^2 ha^{-1})	Parabolic volume (m^3 ha^{-1})	Conic surface (m^2 ha^{-1})
5	347	18.05±2.65	8.30±1.45	69.61±18.5	1406±204
10	553	24.00±3.12	12.03±2.11	97.04±18.1	2067±340
15	417	30.14±4.59	19.51±2.89	183.68±53.1	2779±506
20	321	36.13±5.67	22.29±2.36	312.61±66.2	3912±637
30	204	48.80±6.97	23.12±2.68	386.62±60.3	4169±262
40	180	60.25±7.58	30.25±4.16	542.72±170.9	4528±708

Table 3.5. Canopy cover, canopy volume and canopy depth of *Alnus nepalensis* in the age series of *Alnus*-cardamom plantation stands. Values are means ±SE, n=10

Stand age (year)	Tree height (m)	Canopy cover (m^2 $tree^{-1}$)	Canopy volume (m^{-3} $tree^{-1}$)	Canopy depth (m $tree^{-1}$)
5	15.19±1.03	14.52±1.36	106±23	7.31±0.46
10	15.40±1.09	29.88±1.62	269±43	9.06±0.53
15	19.60±1.51	34.89±4.26	414±54	11.86±1.34
20	26.57±4.48	46.08±6.51	570±35	12.37±0.97
30	32.06±4.43	66.00±8.98	854±66	12.95±1.28
40	34.99±1.42	70.85±10.26	978±75	13.80±2.78

Table 3.6. Stand cardamom bush number, tillers density and understorey basal area in the age series of *Alnus*-cardamom plantations. Values are replicates of three sites.

Stand age (year)	Bush number ($x10^2$ bush ha^{-1})	Tiller density ($x10^3$ tillers ha^{-1})	Basal area (m^2 ha^{-1})
5	60–70	130–160	30–37
10	130–140	280–330	66–77
15	240–260	560–630	128–147
20	80–100	180–230	42–53
30	70–90	160–200	37–46
40	10–20	20–40	5–10

Table 3.7. Light intensity at the understorey cardamom in the age series of *Alnus*-cardamom plantations. The data were collected between 10.00 to 12.00 hours during sunny days in August 1998, to show the comparative values between the stands.

Stand age (year)	Light intensity under the canopy ($\mu mol\ m^{-2} sec^{-1}$)
5	139.12±43.32
10	86.35±24.65
15	98.96±35.23
20	257.59±65.36
30	478.51±78.69
40	389.68±53.25

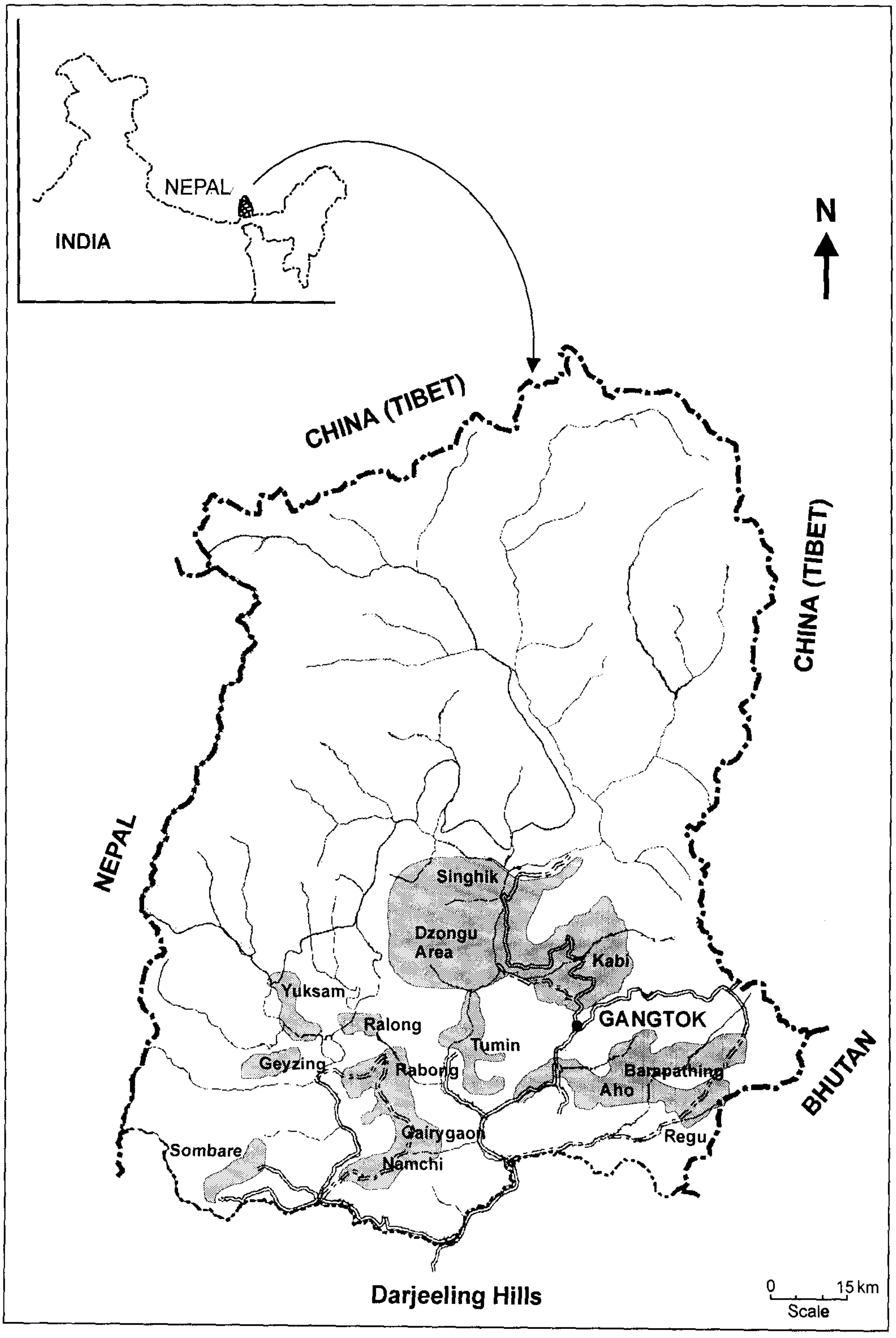
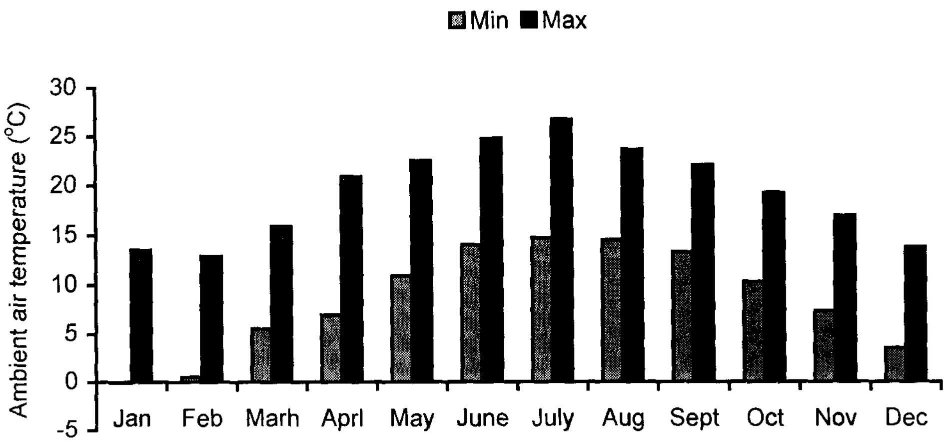


Fig. 3.1. Major cardamom growing areas of Sikkim.



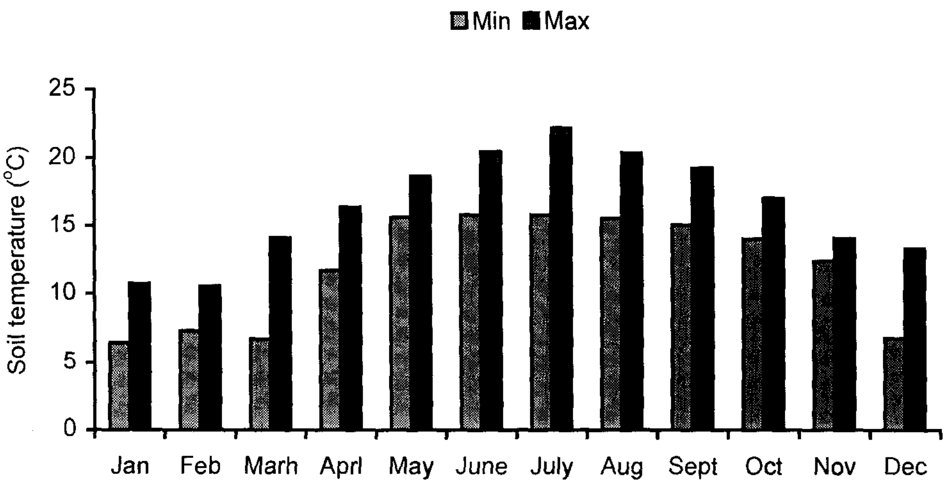


Fig. 3.2. Monthly variation in ambient air and soil temperature at the study sites during 1998.

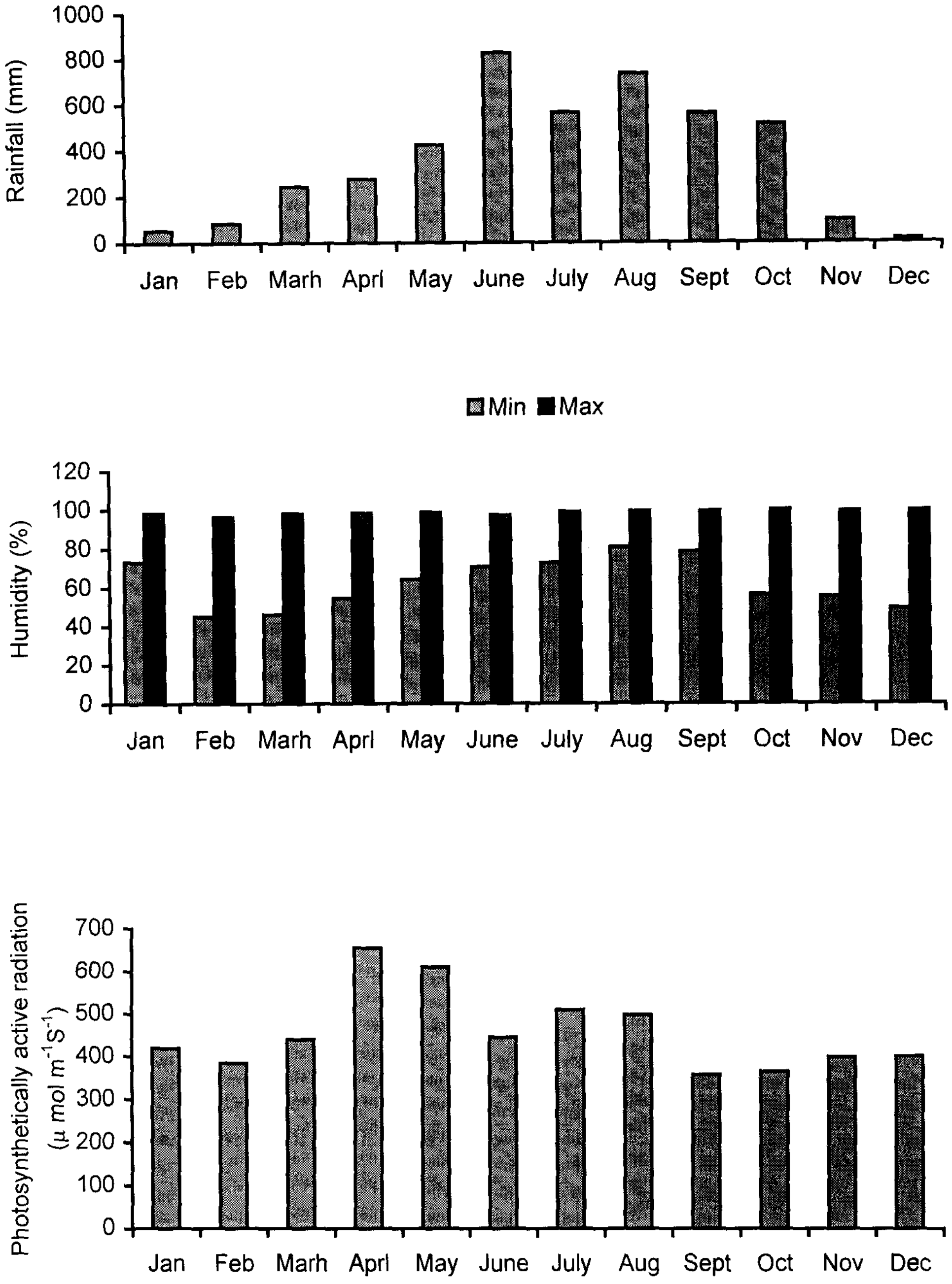
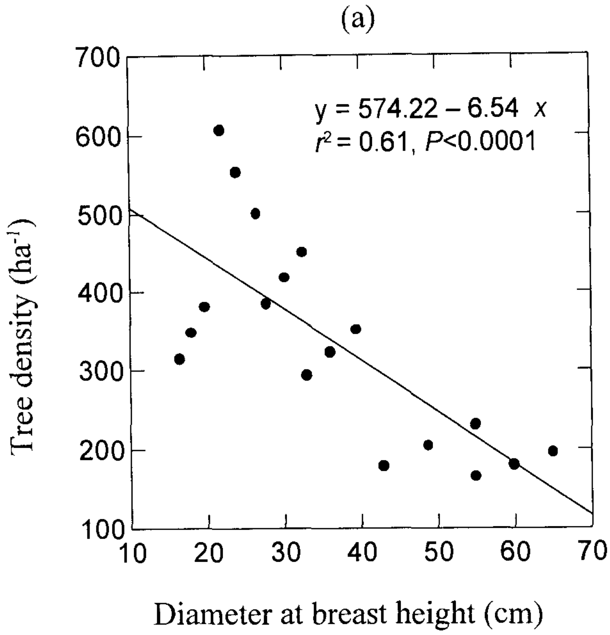


Fig 3.3. Monthly variation in rainfall, relative humidity and photosynthetically active radiation in the study sites during 1998.



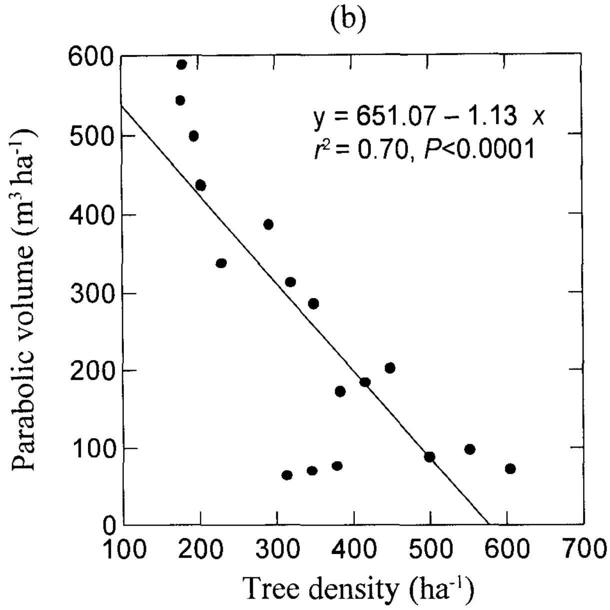


Fig. 3.4. Relationships between (a) tree density and diameter at breast height, and (b) parabolic volume and tree density in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

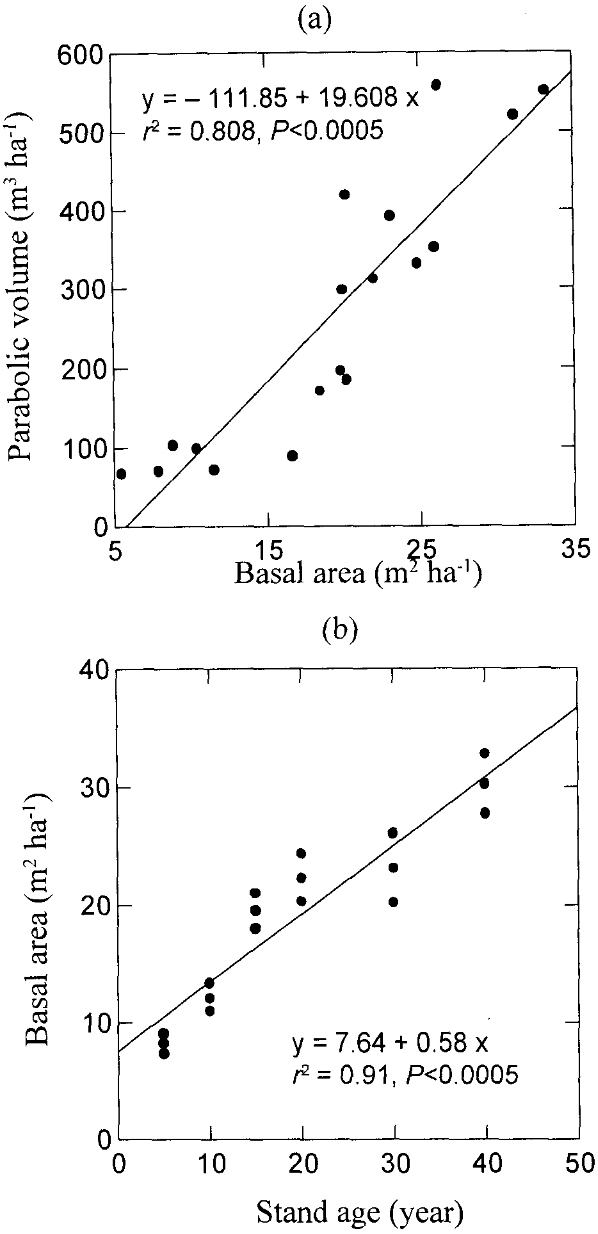


Fig. 3.5. Simple linear regression between (a) parabolic volume and basal area, and (b) basal area and stand age in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

PRODUCTIVITY, ENERGETICS AND EFFICIENCIES

4.1. Introduction

Intensively managed plantations in temperate and tropical regions have been established largely on such agroclimatic zones where temperature, humidity and rainfall are conducive to higher plantation productivity. Experience in fast growing plantations in temperate regions shows that scientifically based, intensive management practices can increase and sustain productivity (Nambiar 1990, 1996; Beets *et al.* 1994; Sharma *et al.* 1994).

Biomass, productivity and yield in agroforestry systems are related to inputs, outputs and cycling of nutrients consequently affecting soil fertility in the system. The potential role of N_2-fixers as associate species has been realized in the eastern Himalaya which is prevalent in both the cardamom and mandarin agroforestry systems. Studies have been made on site index, biomass and productivity estimates in eastern Nepal by Zomer and Manke (1993). Few reports are available on agroforesrty system functioning from the Central and Sikkim Himalaya (Rahlan *et al.* 1991; Singh *et al.* 1989; Sundriyal *et al.* 1994).

The potential increased productivity of plants growing near N_2-fixing species has been recognized for long. 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.* 1992a & 1992b). 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 shade tree compared to non-N_2-fixing tree associates (Sharma *et al.* 1994). However, there is no information available on mixtures of N_2-fixing and non-N_2-fixing stands with respect to their stand age and maturity. *Alnus*-cardamom plantations in the Sikkim Himalaya is a good example for understanding the impact of stand age on performance of mixtures of N_2-fixing and non-N_2-fixing plants.

This chapter examines biomass accumulation, net primary production and energetics in an age sequence of *Alnus*-cardamom plantations. The specific objectives of the study were to determine: (a) component contribution to stand biomass and accumulation pattern; (b) component and total net primary production; (c) differences in component energy values, storage pattern and flow rates; (d) production efficiency and energy conversion efficiency, and (e) relationships between production efficiency, energy conversion efficiency and energy efficiency in N_2-fixation with respect to plantation age function.

4.2. Materials and methods

4.2.1 Biomass, productivity and litter production

Sample plots of 30×40 m were marked at each of the six age series of plantation stands in all the three sites, numbering 18 plots altogether (0.36 ha per each age group totaling to 2.16 ha). Tree diameter increment, litter production, decomposition and agronomic yield estimations were carried out in the above sample plots. Each tree in the sample plots of all age groups was marked and DBH measured in January 1998 and January 2000 (covering two annual cycles). Allometric relationships of tree component biomass on DBH, and belowground biomass on aboveground biomass developed by Sharma and Ambasht (1991) for *A. nepalensis* in the region were used (Table 4.1). 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 aboveground components of the individuals in the sample plot was obtained by DBH increment measurements. The belowground biomass of individual trees was calculated using regression equation given by Sharma and Ambasht (1991) and the respective increment in the aboveground biomass (Table 4.1). The net change in the component biomass over one year period yielded annual biomass accumulation and the sum of the different components gave net production of tree strata. Monthly tree litterfall estimations were carried out for a 2-year period (1998-1999) using five litter traps of 1 m^2 collecting area in each sample plot and pooled to annual values. Floor-litter was randomly sampled 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 the 18 plots were recovered for estimation of biomass. Root nodule production was estimated using method given by Sharma and Ambasht (1986b).

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

4.2.2 Caloric content, energy fixation and efficiencies

Per cent ash content of different plant components was estimated by burning samples in muffle furnace at 550°C for two hours. All energy estimations were made on ash free mass basis. Caloric values of all plant components were estimated using oxygen bomb calorimeter (Lieth 1975). Photosynthetically active radiation (PAR) was recorded by the automatic weather station using dataloger-based Campbell Scientific Inc., USA. Component energy contents of *Alnus* trees and cardamom crop were estimated by taking 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 analyzing the caloric content of different litter layers estimated during different intervals of decomposition for all age groups of plantations. The energy contents of the entire representative components such as

Alnus trees, cardamom crop and floor litter of sampled plots were added together in deriving the 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 are presented in Chapter V.

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 on unit area basis was calculated. Details on litter decomposition and energy contents of different components and nutrient and energy release estimated are given in Chapter VI. The sum of the heat release values from different stages of decomposing samples per year presented the total heat release from the floor litter. The energy loss from the root nodules of *Alnus* was estimated using root nodule turnover and decomposition rate conversion factor (Sharma and Ambasht 1986b), 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 a product of capsule dry weight and energy value. Energy exit from the system was the sum of energy in extracted firewood and agronomic yield.

Regression equations and graphical presentations were made using Systat 1996. Analysis of variance was carried out for stand net primary productivity and cardamom yield between stand ages, and comparison between means was done by Tukey's pair wise comparison probabilities (Systat 1996).

4.3. Results

4.3.1. Stand structure and litter production

Tree dimensions, cardamom density and basal area are presented in Table 4.2. The DBH range of *Alnus* showed lowest group in the 5-year stand that increased with age to be highest in the 40-year stand. The basal area also increased with age ranging from 8.3 m^2 ha^{-1} in the 5-year stand to 30.3 m^2 ha^{-1} in the 40-year stand. In contrast, the tiller density as well as basal area of large cardamom increased from 5-year to be highest in 15-year and then decreased to the lowest value in the 40-year stand (Table 4.2).

Average annual litterfall and slashed cardamom tiller ranged from 4.1 t ha^{-1} (40-year stand) to 10.3 t ha^{-1} (15-year stand). Plantation floor-litter increased from the 5-year stand to a peak at age 15-year (35 t ha^{-1}), and then decreased to the lowest value in the 40-year stand (Table 4.2). The ratio of litter production to floor-litter was higher in the youngest and oldest stands, and lowest in the 15-year stand (0.24).

Litter production occurred throughout the year with a marked seasonal distribution (Fig. 4.1). Quantity of the litter production was highly dependent on age of the plantation stands. About 66% of annual litter production was recorded between a four-month period (September-December). Seasonal distribution of litter production showed little difference between year 1 and year 2, or between plantation stands.

4.3.2. 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 stand to 132 t ha^{-1} in the 40-year stand. A range from 48–62% of the live biomass of the tree stratum was contributed by bole. Per cent contribution of branch biomass to total tree biomass remained nearly the same in all the plantation stands while the bole biomass contribution increased conspicuously with plantation age. The relationships between the DBH of the increasing age series and their respective component biomass of *Alnus* and relationships between cardamom root biomass and shoot biomass were highly significant (Fig. 4.2 & 4.3)

Biomass contribution of *Alnus* to stand values ranged from 65–97%, whose contribution was higher in the 5-year stand that decreased to the lowest value at the 15-year stand and then further increased to be highest at the 40-year stand (Table 4.3). Stand aboveground biomass increased with stand age while the belowground biomass peaked in the 15-year stand that was mainly attributed to cardamom contribution. The contribution of belowground biomass ranged from 17–38% of the stand total. The standing biomass of trees showed a negative relationship with the stand tree density, while it was positive with the tree basal area. However, in the case of cardamom biomass positive relationships were obtained both with cardamom bush density and basal area (Fig. 4.4).

The net primary production rates of the age sequence of *Alnus*-cardamom plantations ranged from 7–22 t ha^{-1} year^{-1}, increasing to a peak at the 15-year stand, and then declining to the lowest value in the 40-year stand (Table 4.4). Analysis of variance for stand net primary productivity showed significant variation between stand age ($F_{5,12}$=25, P<0.0001). Tukey's pair wise comparison probabilities showed significant variation between– 5-year with 15-year (P<0.02); 10-year with 20-year (P<0.06), 30-year and 40-year stands (P<0.0001) and 20-year and 30-year with 40-year stand (P<0.004). Contribution of aboveground productivity hovered around 65–69% in younger stands and increased to a highest value of 88% in the 40-year stand. Contribution of cardamom net primary production to the stand value ranged from 12% (40-year stand) to 44% (15-year stand). The agronomic yield of cardamom increased from 110 kg ha^{-1} year^{-1} in the 5-year stand with a peak value of 360 kg ha^{-1} year^{-1} in the 20-year stand which sharply declined in older stands to a minimum value of 40 kg ha^{-1} year^{-1} in the 40-year stand. Analysis of variance for agronomic yield of large cardamom varied significantly between stand age ($F_{5,12}$=456, P<0.0001). Tukey's pair wise comparison probabilities were significant between all combinations of stand age (P<0.0001).

Biomasss accumulation ratio (BAR, Biomass/net primary production) was calculated for the stand total and separately for the shade tree in the age sequence of *Alnus*-cardamom plantations (Fig. 4.5). The BAR of the stand and the *Alnus* tree was lowest in the 5-year stand and increased with stand age to be highest in the 40-year stand which was about 7-times greater than the 5-year stand. However, in the case of understorey cardamom, it was lowest (1.68) in the 5-year stand and increased to 3.54 in the 15-year stand that remained nearly the same thereafter in older stands. The BAR of the stand total and *Alnus* tree showed strong positive relationships with stand age, however in understorey cardamom it was significantly positive but feeble (r^2=0.45, P<0.05).

The net primary production per unit weight of leaf is the production efficiency, and it ranged from 2.97–8.38 t t leaf^{-1} year^{-1} in cardamom and 3.63–6.27 t t leaf^{-1} year^{-1} in *Alnus* tree. It was highest in the 5-year stand and lowest in the 40-year stand. It showed highly negative relationships with plantation age for stand total and for both *Alnus* tree and understorey cardamom (Fig. 4.6). The efficiency curve tended to flatten with plantation age especially in the case of *Alnus* tree.

Compartment model showing the distribution of biomass and net primary production in the age series of *Alnus*-cardamom plantation stands are presented in Figure 4.7a, b & c. Values in the compartments are biomass and arrows show net flow rate. The differences of the values on the arrows of either side of a compartment give the component net production. A comparative account of the six stand ages of plantations showed high biomass build up with stand age maturity especially of perennial parts like bole, branch and belowground parts. The biomass build up in the cardamom recorded until 15 years of plantation age and then declined with increase in stand age.

4.3.3. Energy value, energetics and efficiencies

Energy and ash concentrations of different plant components of *Alnus*, cardamom and floor-litter are given in Table 4.5. Ash ranged from 2.01–11.59% in *Alnus* and 3.72–12.13% in cardamom components. It was highest in root nodules of *Alnus* tree while underground parts and capsule in the case of cardamom. Floor-litter showed the highest (14.52%) ash concentration (Table 4.5). The energy value of component parts of the *Alnus* trees ranged from 17.54–21.25 kJ g^{-1} and 15.02–19.93 kJ g^{-1} in cardamom (Table 4.5). The mean energy value of floor-litter, calculated using the values of different stages of decomposition, was 15.06 kJ g^{-1}.

Compartment model showing the details of energy storage net energy flow and heat sink through the stand floor due to decomposition in the age series of plantation stands are presented in Figure 4.8a, b & c. Values in the compartments are energy storage and annual net energy flow rate is indicated by arrows.

The net energy contents in the standing biomass of *Alnus*-cardamom plantations followed the biomass build up trend. It increased from 774×10^6 kJ ha^{-1} $year^{-1}$ in the 5-year stand to 2414×10^6 kJ ha^{-1} $year^{-1}$ in the 40-year stand (Table 4.6). Per cent energy content in tree biomass ranged from 79–98 whereas cardamom contributed 2–21% in the age series of plantations. Energy contribution by cardamom decreased sharply after 15-year plantations.

Component wise transfer of energy to the stand floor through litter production is presented in Table 4.8. Contribution of litter by *Alnus* ranged between 73×10^6 kJ ha^{-1} $year^{-1}$ (5-year) to 128×10^6 kJ ha^{-1} $year^{-1}$ (15-year). Similarly, contribution of litter production by cardamom ranged between 6.29×10^6 kJ ha^{-1} $year^{-1}$ (40-year, lowest) to 66.94×10^6 kJ ha^{-1} $year^{-1}$ (15-year, highest). The 15-year stand added significant amount of energy to the stand.

Net annual energy fixation was lowest (154×10^6 kJ ha^{-1} $year^{-1}$) in the 40-year stand and highest (444×10^6 kJ ha^{-1} $year^{-1}$) in the 15-year stand (Table 4.7). Annual energy fixation in 15-year stand was 1.4 times that of 5-year stand and 2.9 times that of the 40-year stands. Energy allocation in agronomic yield of the large cardamom was highest (7.05×10^6 kJ ha^{-1} $year^{-1}$) in 20-year stand which was 3.2 times greater than that of 5-year stand and 9 times that of 40-year stand. Allocation of stand annual energy fixation to shade tree and cardamom was respectively, 72% and 28% in 5-year stand, 62% and 38% in 15-year stand, and 90% and 10% in 40-year stand. Energy storage was lowest in 5-year stand and increased with plantation age to be 2.5 times greater in 40-year stand (Table 4.9).

Component allocation of net energy fixation in the tree layer of the 5-year stand was more than 15-year 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 stand compared to the 5-year stand while the least allocation was recorded in all the components of cardamom of 40-year stand. Heat sink from the floor-litter and energy exit in terms of firewood and capsule are given in Table 4.9 and Fig. 4.8a, b & c. Heat sink was highest in the 15-year stand and decreased in the order 15>20>10>30>5>40 year stand. Energy exit from the system in the case of 5-year stand was 2.2×10^{6} kJ ha^{-1} $year^{-1}$ which increased to the greatest value in 10- and 15-year stands and then declined in the order 10>15>40>30>20>5 year stand.

Net ecosystem energy increment was highest in the 5-year stand (149×10^{6} kJ ha^{-1} $year^{-1}$) which decreased with plantation age to a minimum value of 10×10^6 kJ ha^{-1} $year^{-1}$ in the 40-year stand. However, the energy accumulation ratio (energy storage/energy fixation) was lowest in the 5-year stand and increased with plantation age to the greatest value at the 40-year stand (Table 4.9). Net ecosystem energy increment showed strong negative relationship with stand age while the energy accumulation ratio was positively related with stand age (Fig. 4.9). The best fit of net ecosystem energy increment and energy accumulation ratio curves was obtained using the natural logarithmic form 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 percentage. The ECE increased from 5-year stand (2.72%) to peak at the 15-year stand (3.76%) thereafter decreased with stand age to a minimum of 1.3% in the 40-year stand. Relationship between ECE with stand age is strongly negative in all the three cases such as *Alnus* tree, cardamom and stand total (Fig. 4.10a, b & c). In all these three situations, curves showed slight increase in the younger stands and then sharply declined with older stands. The production efficiency showed a positive relationship with energy conversion efficiency (Fig. 4.10d). Both production and energy conversion efficiencies were high in the younger stands and decreased with stand age to the lowest value at 40-year stand.

Energy utilized per kg N_2 fixed was 16×10^4 kJ in the 5-year stand which slightly decreased with stand age and remained almost similar throughout with the value of 12×10^4 kJ in the 40-year stand. Energy utilized per kg N_2 fixed dropped sharply from 5-year to 10-year stand and then more slowly thereafter. It showed negative relationship with plantation age that was converted into natural logarithmic form (Fig. 4.11). Energy efficiency in N_2-fixation was lowest (64 g N_2 fixed 10^4 kJ^{-1} energy) in the 5-year stand and increased to be highest (84 g N_2 fixed 10^4 kJ^{-1} energy) in the 40-year stand. Efficiency in N_2-fixation between 10- to 30-year stands remained almost similar. Energy efficiency in N_2-fixation showed a significant negative relationship with production efficiency (Fig. 4.11), indicating greater energy efficiency in N_2-fixation in the 40-year stand when production efficiency was the lowest.

4.4. Discussion

The annual variation of tree leaf litter and cardamom litter production within each plantation age during the two-year study period was low. The temporal distribution of tree leaf-litter production was similar in all the six age groups of stands showing a regular pattern. Sharma *et al.* (1997a) reported higher litter production under the influence of N_2-fixing *Alnus* tree in cardamom plantations compared to non-N_2-fixing mix tree species. Tarrant *et al.* (1969) and Binkley (1992) also found much more litter production in mix 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 *A. rubra* stand, and indicated a possibility of reaching equilibrium at 25-year 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, tiller number, basal area and biomass of cardamom crop were much higher under the influence of *Alnus* (Sharma *et al.* 1994). Binkley *et al.* (1992a) have also reported that at a low fertility site in USA biomass of *Alnus*-conifer stands exceeded by 69% to that of pure conifer stands. The total biomass in the age sequence of pure *A. nepalensis* plantations increased from 106 t ha^{-1} in the 7-year stand to 606 t ha^{-1} in 56-year stand (Sharma and Ambasht 1991). In the age sequence of mixture of *Alnus*-cardamom plantations, the biomass accumulation trend similar to that of above study was recorded although of a lower magnitude. The *Alnus* tree associate mainly influenced it. The biomass accumulation ratio is used for categorizing 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 between 2.5–18.0 in the age sequence of *Alnus*-cardamom plantations. Smith (1977) has also reported low average rates of 2.86 biomass accumulation ratio in immature 8–10-year-old A. *rubra* stand, consistent with report made by Sharma and Ambasht (1991) and in the present study.

Sharma and Ambasht (1991) reported net annual production rates of 13–25 t ha^{-1} $year^{-1}$ in the age sequence of pure *Alnus* plantations which decreased with age closely matching the trend in the total net primary productivity of the *Alnus* associates in the *Alnus*-cardamom plantations ranging form 6.5–12.6 t ha^{-1} $year^{-1}$. Immature stands often have net primary production rates more than twice as great as mature stands (Johnson and Risser 1974). This is also true in the present study, which showed that the net production rate in the 40-year plantations was about 33% of the 15-year stand. Rodin and Bazilevich (1967) have given a broad range of 3.6–20 t ha^{-1} $year^{-1}$ net productivity for temperate deciduous forest and the present study values were within this range. Productivity of *Alnus* was almost similar up to 15-year stand and then declined with age. However under the influence of *Alnus*, cardamom productivity doubled in 15-year stand compared to the 5-year stand, thereafter it decreased sharply with stand age to a lowest value in the 40-year stand. Performance of cardamom in the association of N_2-fixing *Alnus* remained beneficial until 20 years.

Net annual energy fixation was reported highest in a young stand and declined sharply with plantation age on pure *A. nepalensis* in the region (Sharma and Ambasht 1991). In the present study annual energy fixation and flow rates increased from 5-year stand to a peak at the 15-year stand and then sharply declined. This clearly indicated that energy flows and fixation were optimum for both *Alnus* and cardamom up to the 15-year stand age. The production efficiency and energy conversion efficiencies of the age sequence of *Alnus*-cardamom plantations showed a significant positive relationship where the younger stands performed more efficiently compared to mature stands. The production efficiency of the plantation was highest in the 5-year old stand that decreased with advancing age having similar trend in both *Alnus* as well as cardamom components. The energy fixation efficiency of cardamom decreased with advancing age which remained fairly high up to 20-year old stand supporting the system efficiency until this age. The energy efficiency of stands and separately for *Alnus* and cardamom components was highest in the youngest stand and decreased with advancing plantation age. The energy conversion efficiency of cardamom increased from the 5-year stand up to the 15-year stand and then decreased to the lowest efficiency in the 40-year stand. Energy accumulation ratio of *Alnus* increased with stand age almost reaching more than 5 times in 40-year stand compared to 5-year stand, whereas it was almost similar after 15-year age in the case of cardamom. The relationships of energy efficiency in N_2-fixation with production efficiency of the *Alnus*-cardamom plantations showed inverse function. Younger stands with 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 the N_2-fixation. The inverse relationships of production efficiency, energy conversion efficiency and energy utilized in N_2-fixation against stand age, and positive relationship between production efficiency and energy conversion efficiency suggest that younger plantations function as the most productive system, while the intermediate and mature plantations relatively less and least productive, respectively. Performance of large cardamom under the influence of N_2-fixing *Alnus* in an age sequence of plantation 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 20 years age. Sharma *et al.* (1994) suggested *Alnus* as an excellent associate with cardamom promoting higher performance compared to non-N_2-fixing mix tree associates. This study reveals that the *Alnus*-cardamom plantation system could be sustainable by adopting rotational cycle of 20 years ❖

Table 4.1. Logarithmic regressions relating component biomass with the function of tree diameter at breast height, and beloewground biomass with aboveground biomass, of the harvested sample alder trees ('E' is the antilog of the standard error of the logarithm of the y-value and 'r' is the coefficients of correlation).

Regression equation	d.f	r^{Ψ}	E
$\log_{10}$ TLDW = 2.963 + 0.628 $\log_{10}$ DBH	21	0.977	1.011
$\log_{10}$ CDW = 1.348 + 1.281 $\log_{10}$ DBH	20	0.998	1.005
$\log_{10}$ BrDW = 1.455 + 2.216 $\log_{10}$ DBH	21	0.993	1.021
$\log_{10}$ BDW = 1.532 + 2.461 $\log_{10}$ DBH	21	0.977	1.016
$\log_{10}$ BgDW = 0.916 + 0.720 $\log_{10}$ AgDW	21	0.992	1.018

DBH = diameter at breast height (range, 18–80 cm); TLDW = twig and leaf dry wt. (g); CDW = catkin dry wt. (g); BcDW = aboveground dry wt. (g); BDW = bole dry wt. (g); BrDW = branch dry wt. (g); AgDW = aboveground dry wt. (g); and BgDW = belowground dry wt. (g). $^{\Psi}$ Significant at $P < 0.001$.
(After Sharma and Ambasht 1991)

Table 4.2. Tree dimensions, number of understorey cardamom tillers and bushes, basal area, litter production and floor-litter in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

Parameters	Plantation stands (year)					
	5	10	15	20	30	40
Tree (*Alnus nepalensis*)						
Density (trees ha^{-1})	347 ±20	553 ±65	417 ±17	321 ±33	204 ±29	180 ±9
DBH 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 (*Amomum subulatum*)						
Bush (number ha^{-1})	6786 ±655	13484 ±3100	25316 ±1706	8797 ±1733	7962 ±2467	1733 ±186
Tiller density (x 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} $year^{-1}$)	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
Litter production: floor litter	0.32	0.36	0.29	0.28	0.27	0.27

Table 4.3. Biomass (t ha^{-1}) allocation in tree and cardamom components, and stand values in the age series of *Alnus*-cardamom plantation stands. Values in the parentheses are per cent contribution. Values are means of three site replicates.

Plant components	Stand age (year)					
	5	10	15	20	30	40
Tree						
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						
Cardamom ieaf	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
Aboveground 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)
Belowground 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

Table 4.4. Component wise estimates of net primary productivity of *Alnus* tree and understorey cardamom (t ha^{-1} $year^{-1}$) in the age series of *Alnus*-cardamom plantation stands. Values in the parenthesis are percent net contribution. Values are means of three site replicates.

Plant components	Stand age (year)					
	5	10	15	20	30	40
Tree						
Leaf & 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						
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
Aboveground 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)
Belowground 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

Table 4.5. Energy and ash content of different plant components of *Alnus* tree, cardamom crop and floor litter. Values are mean ±SE, $n = 6$

Plant components	Energy (kJ g^{-1})	Ash (%)
Tree		
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

£ Analyzed from different stages of decomposition

* Analyzed from different stages of development

Table 4.6. Energy content (x 10^6 kJ ha^{-1}) of different plant components of trees and cardamom in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

Plant components	Stand age (year)					
	5	10	15	20	30	40
Tree						
Leaf and twig	39.07 ±5.37	59.99 ±11.15	54.59 ±6.21	50.06 ±5.86	37.70 ±5.41	36.73 ±4.08
Catkin	6.09 ±0.79	9.04 ±1.39	10.13 ±1.45	11.08 ±1.58	10.72 ±4.42	10.61 ±1.89
Branch	135.16 ±13.04	172.11 ±22.53	269.53 ±66.19	347.97 ±63.82	374.25 ±66.39	511.98 ±137.13
Bole	281.34 ±52.27	359.12 ±31.39	625.65 ±177.86	857.75 ±157.88	964.61 189.82	1435.58 ±421.74
Root	139.62 ±20.87	142.00 ±11.99	223.81 ±75.77	314.49 ±50.34	326.42 ±47.88	362.55 ±79.81
Root nodule	7.17 ±1.11	15.65 ±2.83	17.21 ±3.21	13.07 ±2.38	7.12 ±1.38	5.78 ±2.11
Total	608.5 ±72.4	757.90 ±49.70	1200.9 ±340.1	1594.9 ±286.3	1720.8 ±319.8	2363.23 ±615.9
Cardamom						
Cardamom leaf	12.42 ±1.13	24.71 ±5.45	46.44 ±17.85	21.13 ±3.01	24.81 ±4.32	5.84 ±1.86
Pseudo-stem	28.09 0.30	55.87 ±12. 91	104.84 ±43.25	47.26 ±4.67	32.89 ±10.25	13.22 ±4.49
Root/rhizome	122.63 ±11.91	243.45 ±5.60	456.92 ±92.65	194.87 ±14.26	143.76 ±44.61	31.24 ±3.36
Capsule	2.19 ±0.27	4.47 ±0.59	6.02 ±0.74	7.05 ±0.34	3.40 ±0.20	0.78 ±0.04
Total	165.33 ±39.29	328.50 ±75.76	614.22 ±101.50	270.81 ±57.59	204.86 ±50.57	51.08 ±19.79
Net stand energy content	774	1086	1815	1866	1926	2414

Table 4.7. Component wise net energy fixation (x 10^6 kJ ha^{-1} $year^{-1}$) of different plant components of trees and undersotrey cardamom in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

Plant components	Stand age (year)					
	5	10	15	20	30	40
Tree						
Leaf and twig	66.73 ±1.24	85.14 ±2.48	117.78 ±1.44	99.78 ±5.99	92.47 ±3.31	66.32 ±0.41
Catkin	6.09 ±8.07	9.04 ±1.41	10.13 ±1.41	11.08 ±1.61	10.72 ±1.42	10.61 ±1.82
Branch	35.96 ±9.09	32.80 ±4.34	24.70 ±4.35	23.12 ±4.54	22.33 ±4.74	14.78 ±0.20
Bole	61.90 ±0.54	59.59 ±15.87	51.38 ±2.85	39.78 ±10.16	31.76 ±3.92	27.83 ±9.09
Root	48.24 ±9.99	47.88 ±16.13	41.22 ±4.91	29.82 ±1.57	23.68 ±1.40	8.19 ±0.87
Root nodule	12.99 ±1.23	28.85 3.43	29.46 ±2.76	25.32 ±7.68	13.09 ±3.54	11.38 ±2.12
Total	231.91 ±15.16	263.33 ±35.05	274.67 ±24.42	228.90 ±24.23	194.05 ±11.62	139.11 ±12.80
Cardamom						
Cardamom leaf	11.86 ±0.59	18.59 ±0.79	20.53 ±2.98	8.97 ±1.79	8.27 ±1.30	1.93 ±0.39
Pseudo-stem	26.89 ±6.30	41.91 ±6.33	46.41 ±9.37	20.12 ±5.25	18.78 ±5.24	4.36 ±0.75
Root/rhizome	48.76 ±7.04	60.86 ±18.60	96.26 ±34.13	39.55 ±7.76	36.30 ±10.83	7.82 ±0.92
Capsule	2.19 ±0.36	4.47 ±0.53	6.02 ±0.71	7.05 ±0.35	3.40 ±1.97	0.78 ±0.10
Total	89.70 ±16.11	125.83 ±21.91	169.22 ±38.20	75.69 ±10.51	66.75 ±1.64	14.89 ±1.99
Stand total	321.61 ±12.72	389.16 ±30.28	443.89 ±42.00	304.59 ±10.15	260.80 ±28.01	154.00 ±8.26

Table 4.8. Component wise transfer of energy ($\times 10^6$ kJ ha^{-1} $year^{-1}$) to the stand floor through litter production in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

Plant components	Stand age (year)					
	5	10	15	20	30	40
Tree						
Leaf and twig	66.73 ±1.25	85.14 ±2.51	117.78 ±1.40	99.78 ±6.07	92.47 ±3.35	66.32 ±4.18
Catkin	6.09 ±0.81	9.04 ±1.41	10.13 ±1.41	11.08 ±1.61	10.72 ±1.43	10.61 ±1.82
Total	72.82 ±3.41	94.18 ±2.10	127.91 ±3.45	110.86 ±4.65	103.19 ±5.43	76.93 ±4.34
Cardamom						
Cardamom leaf	11.86 ±5.84	18.59 ±7.95	20.53 ±3.06	8.97 ±1.81	8.27 ±1.42	1.93 ±0.48
Pseudo-stem	26.89 ±6.32	41.91 ±6.50	46.41 ±9.37	20.12 ±5.24	18.78 ±5.44	4.36 ±0.69
Total	38.75 ±7.54	60.50 ±4.45	66.94 ±5.21	29.09 ±2.32	27.05 ±2.11	6.29 ±0.56
Total	111.57 ±8.73	154.68 ±25.90	194.85 ±3.69	139.95 ±5.67	130.24 ±2.18	83.22 ±8.13

Table 4.9. Energy fixation, storage, allocation in agronomic yield, heat sink, release and exit, and efficiencies in an age series of *Alnus*-cardamom plantations.

Energy/efficiency	Stand age (year)					
	5	10	15	20	30	40
Energy storage ($\times 10^6$ kJ ha^{-1})	1053	1435	2341	2288	2292	2635
Stand energy content ($\times 10^6$ kJ ha^{-1})	774	1086	1815	1866	1926	2414
Energy Fixation ($\times 10^6$ kJ ha^{-1} $year^{-1}$)	322	389	444	305	261	154
Net energy allocation in agronomic yield ($\times 10^6$ kJ ha^{-1} $year^{-1}$)	2.19	4.47	6.02	7.05	3.40	0.78
Floor litter energy content ($\times 10^6$ kJ ha^{-1} $year^{-1}$)	279	349	526	422	366	221
Heat sink from the floor ($\times 10^6$ kJ ha^{-1} $year^{-1}$)	171	228	299	259	226	116
Energy exit ($\times 10^6$ kJ ha^{-1} $year^{-1}$)	2.20	56.56	56.40	18.80	22.18	28.20
Energy conversion efficiency (%)	2.72	3.29	3.76	2.58	2.21	1.30
Energy fixation efficiency (GJ GJ^{-1} leaf energy $year^{-1}$)	6.25	4.59	4.39	4.28	4.17	3.62
Net ecosystem energy increment ($\times 10^6$ kJ ha^{-1} $year^{-1}$)	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 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

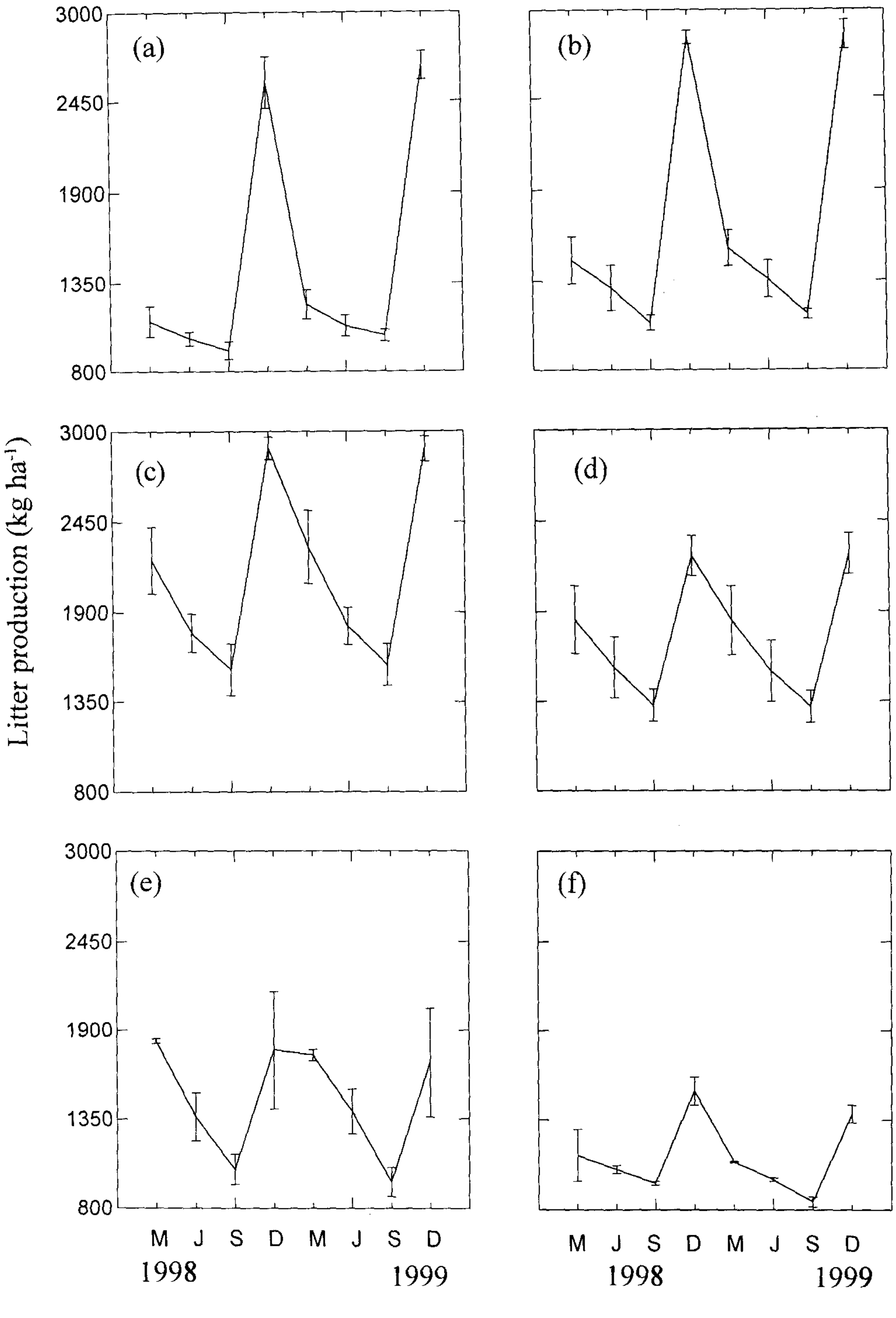


Fig. 4.1. Temporal distribution of litter production in (a) 5-year, (b) 10-year, (c) 15-year, (d) 20-year, (e) 30-year and (f) 40-year of *Alnus*-cardamom plantation stands. Vertical bars represent standard errors.

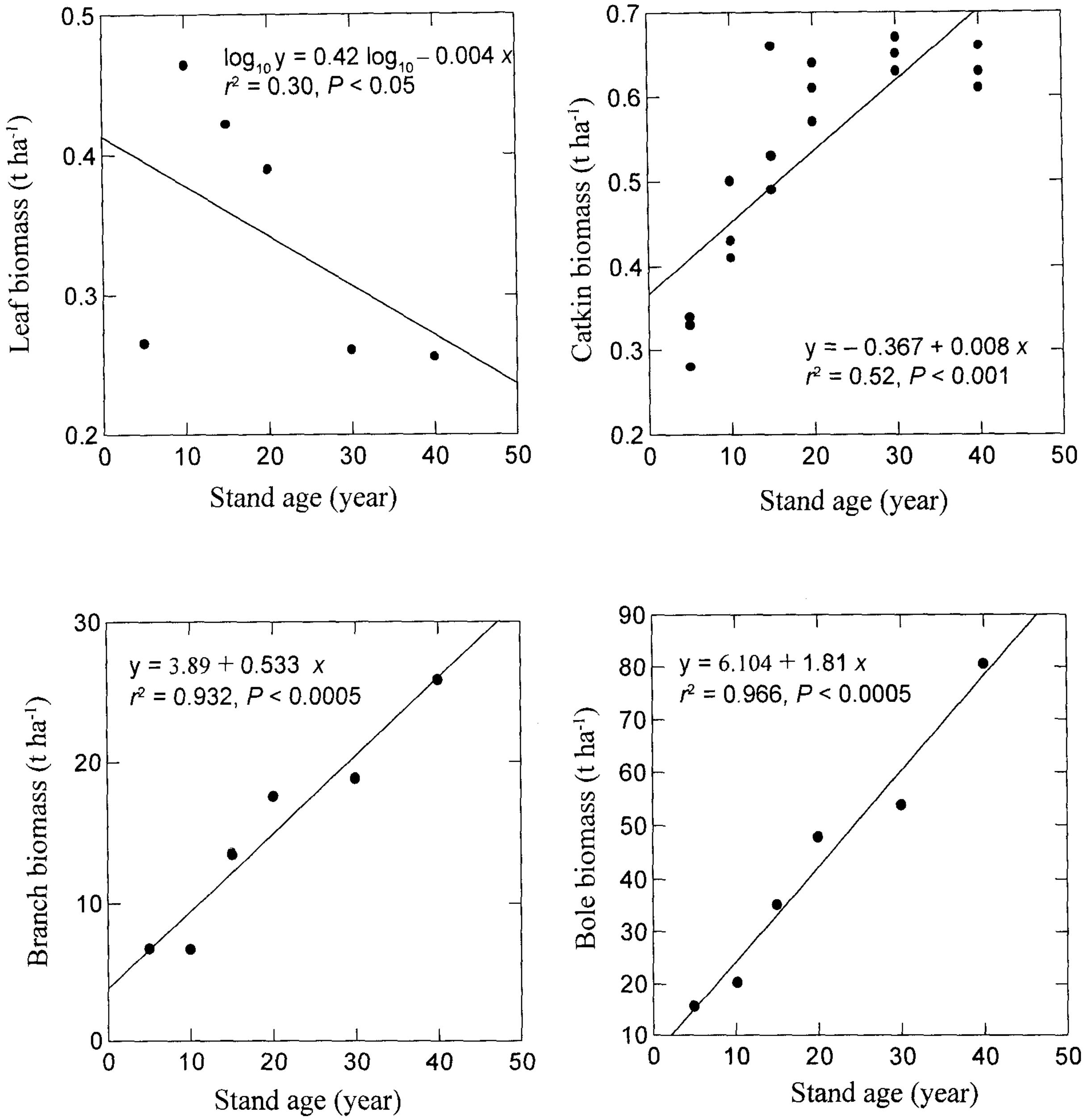


Fig. 4.2. Logarithmic relationship between *Alnus* leaf biomass with stand age, and simple relationships between catkin, branch and bole biomass of *Alnus* with stand age in the age series of *Alnus*-cardamom palntation stands.Values are means of three site replicates.

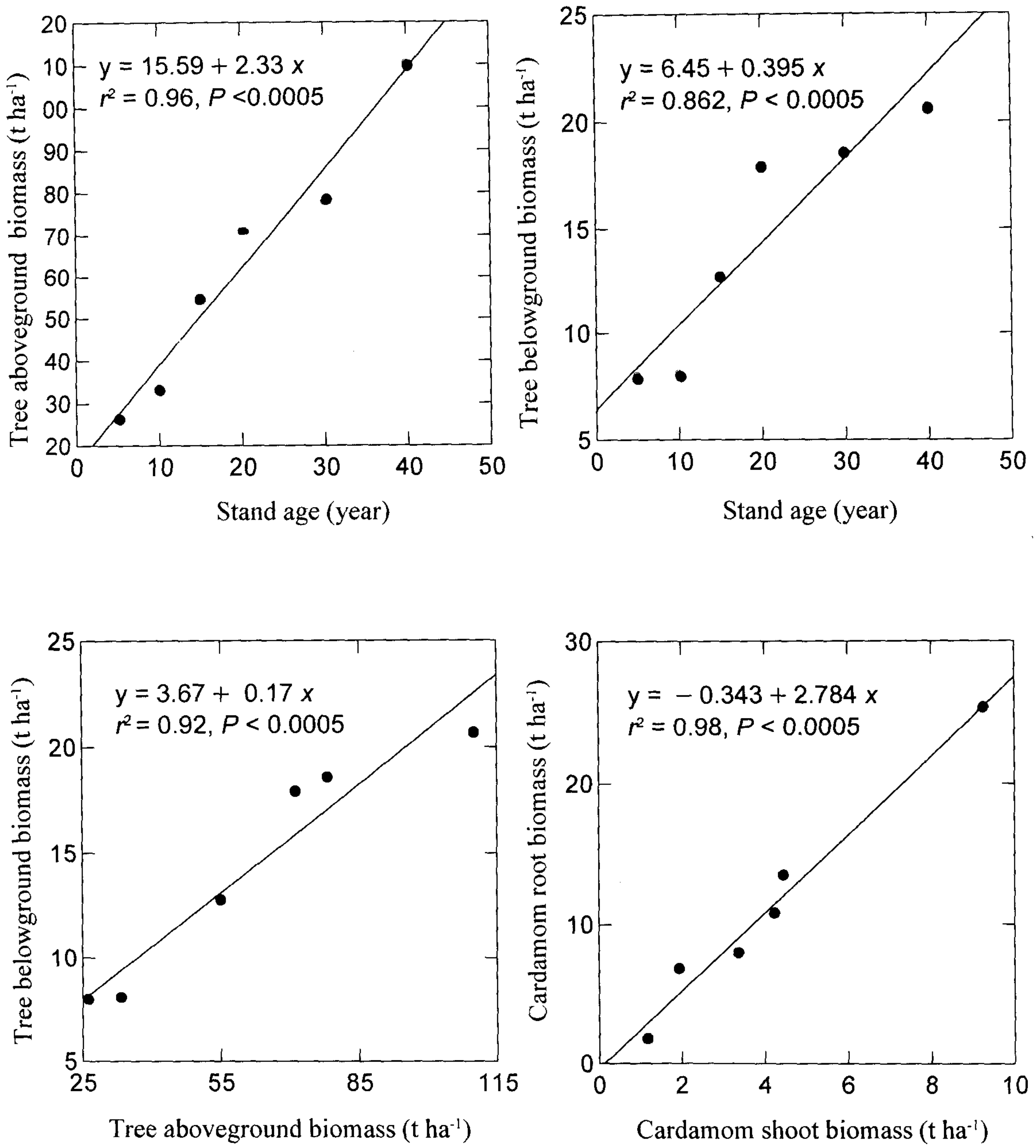


Fig. 4.3. Relationships between abovegound and belowground tree biomass with stand age, tree belowground biomass with aboveground biomass, and cardamom root biomass with cardamom shoot biomass in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

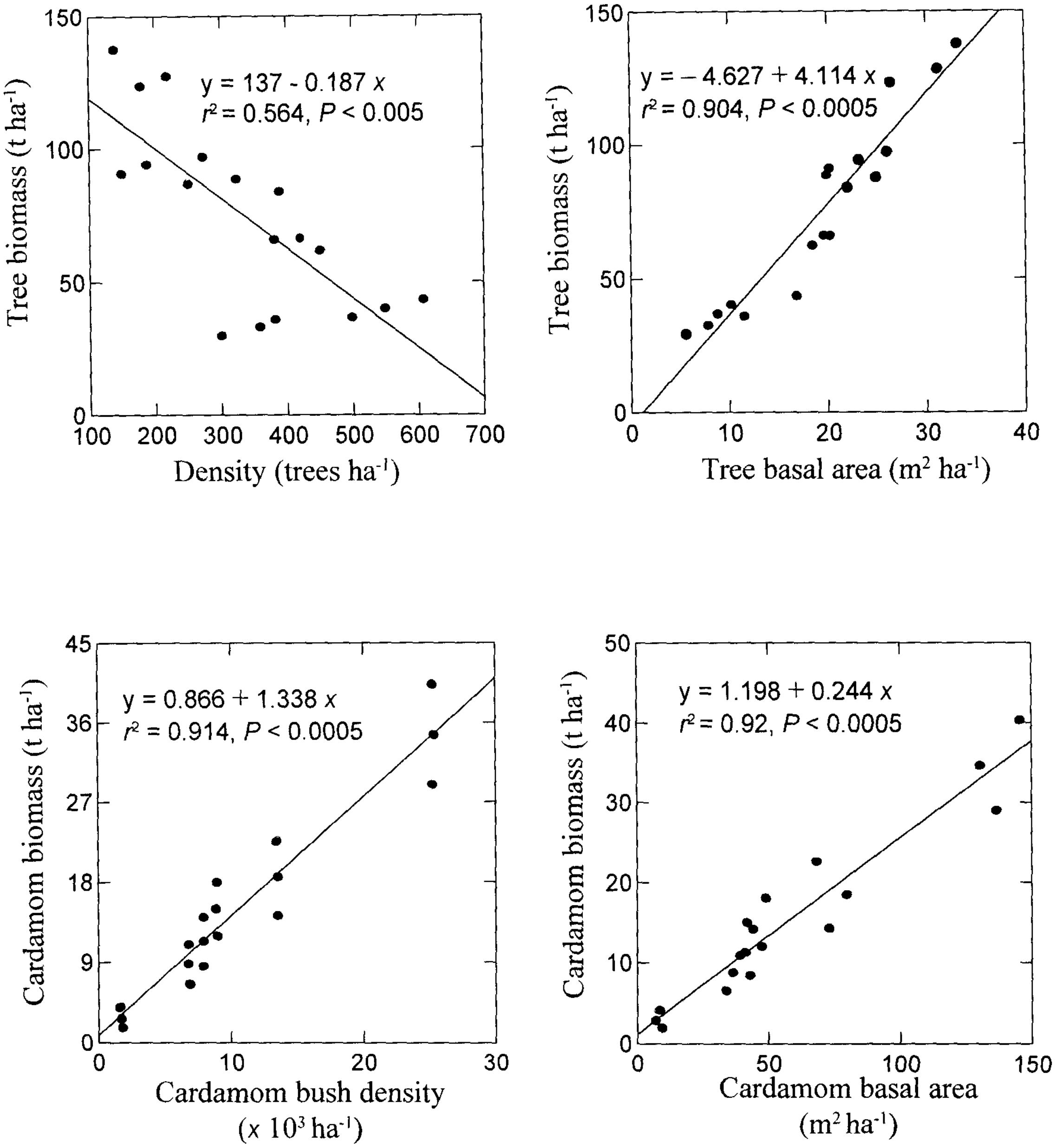


Fig. 4.4. Relationships between standing tree density and tree basal area with tree biomass, and cardamom basal area and cardamom bush density with cardamom biomass in an age seires of *Alnus*-cardamom plantation stands.

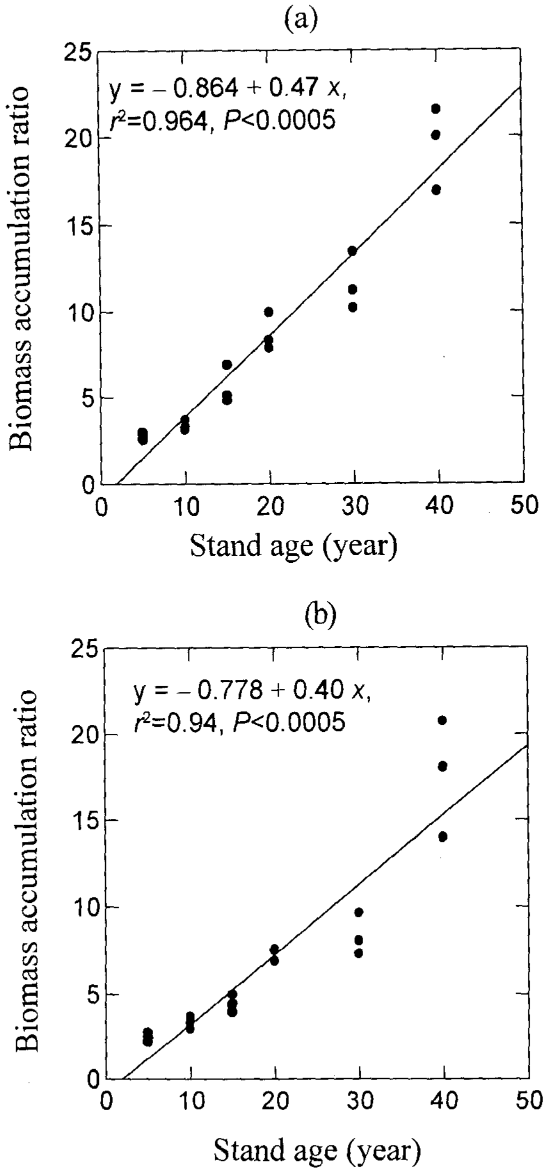


Fig. 4.5. Relationships between biomass accumulation ratio of (a) *Alnus* and (b) stand total with stand age in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

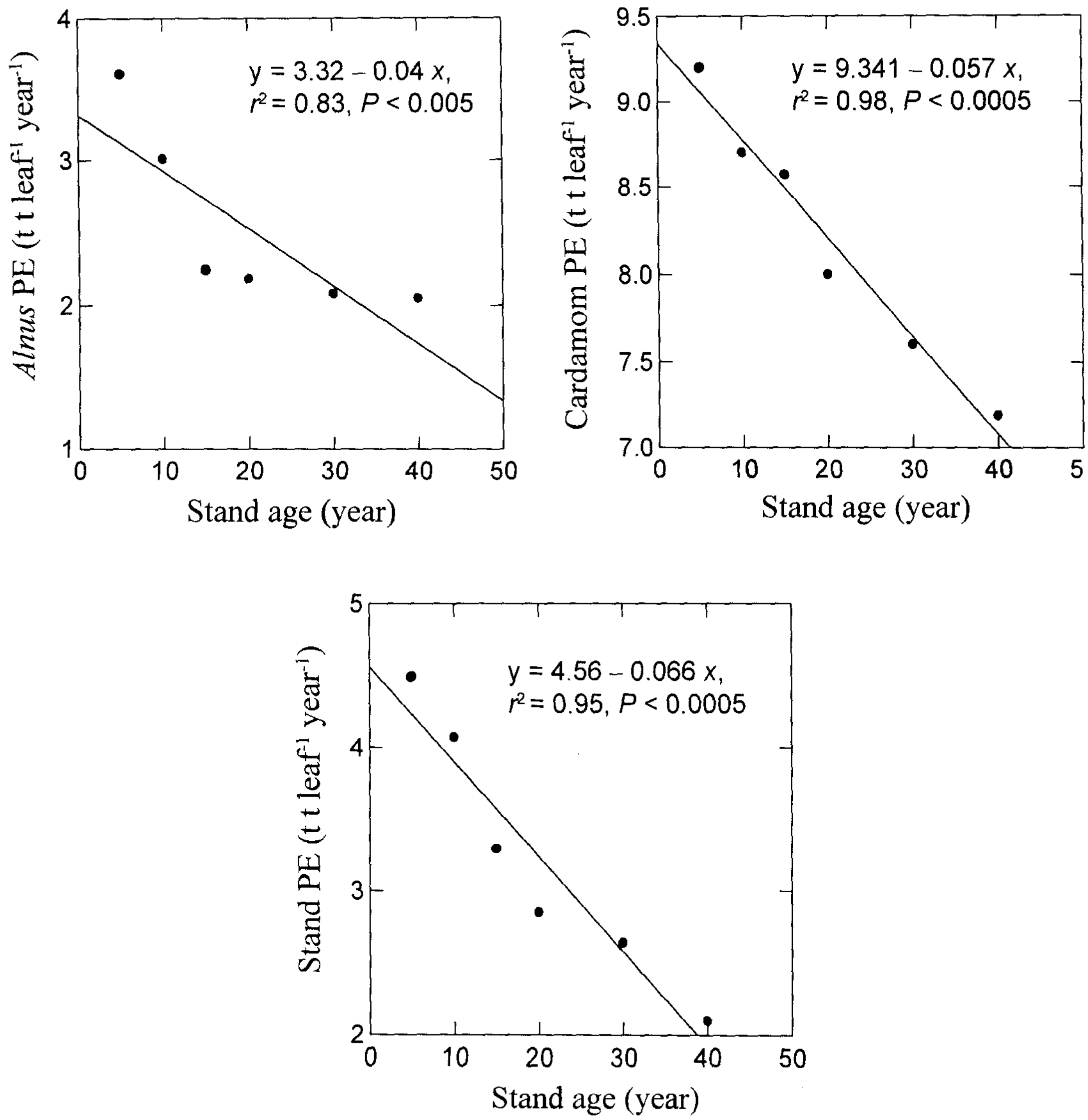
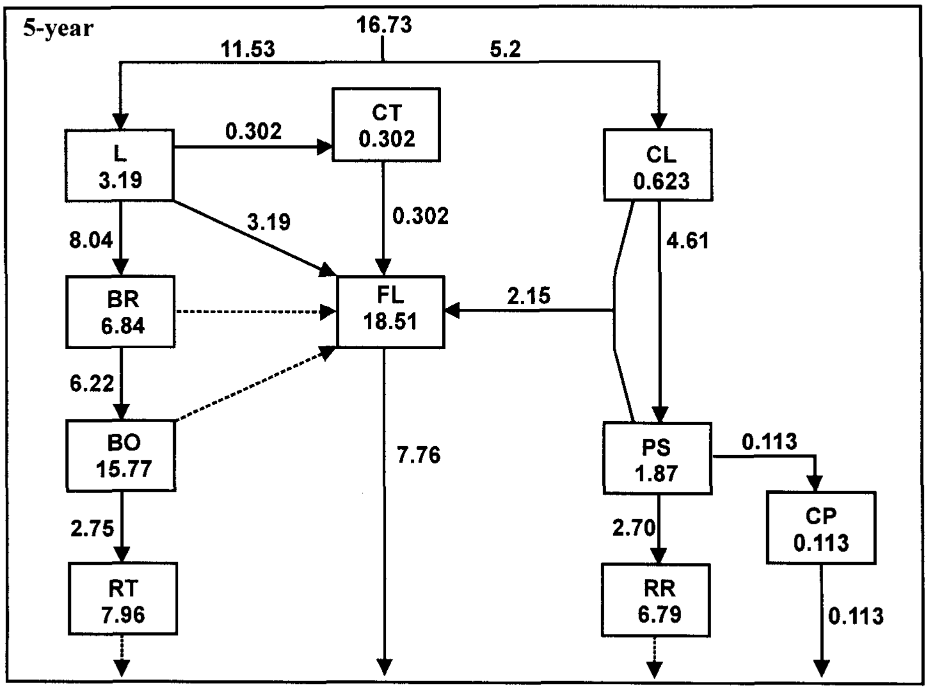


Fig. 4.6. Relationships between production efficiency (PE) of shade tree *Alnus*, cardamom and stand total with stand age in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

Fig. 4.7a. Compartment model showing distribution of dry matter biomass, net primary production, litter disappearance rate and cardamom capsule harvest in 5- and 10-year stand of *Alnus*-cardamom plantations. Broken lines indicate that values are not estimated. Units are t h^{-1} for compartments and t ha^{-1} $year^{-1}$ for flows. L= leaf, BR= branch, BO= bole, RT= root, CT= catkin, FL= floor litter, CL= cardamom leaf, PS= pseudo-stem, RR= root/rhizome, CP= cardamom capsule.


5-year
16.73
11.53
5.2
L
3.19
0.302
CT
0.302
CL
0.623
3.19
0.302
8.04
4.61
BR
6.84
FL
18.51
2.15
6.22
BO
15.77
7.76
PS
1.87
0.113
CP
0.113
2.75
2.70
RT
7.96
RR
6.79
0.113

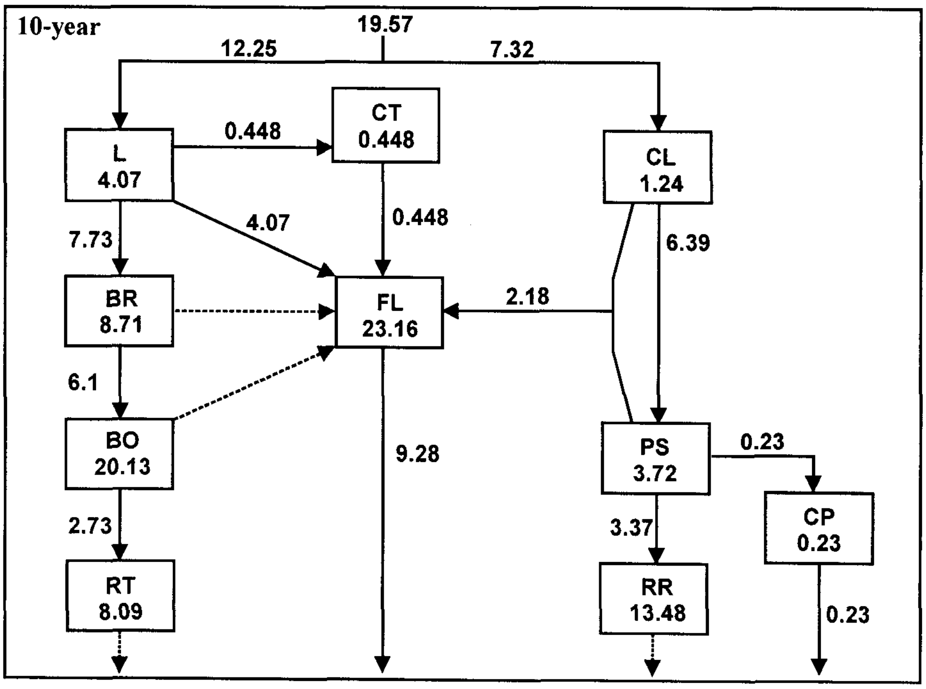
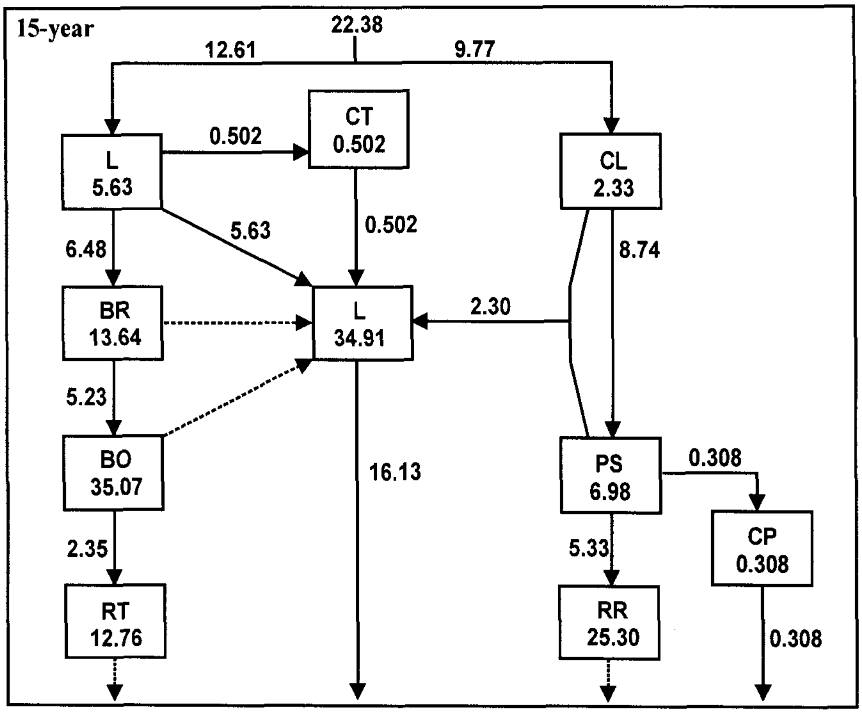

10-year
19.57
12.25
7.32
L
4.07
0.448
CT
0.448
CL
1.24
4.07
0.448
7.73
6.39
BR
8.71
FL
23.16
2.18
6.1
BO
20.13
9.28
PS
3.72
0.23
CP
0.23
2.73
3.37
RT
8.09
RR
13.48
0.23

Fig. 4.7b. Compartment model showing distribution of dry matter biomass, net primary production, litter disappearance rate and cardamom capsule harvest in 15- and 20-year stand of *Alnus*-cardamom plantations. Broken lines indicate that values are not estimated. Units are t h^{-1} for compartments and t ha^{-1} $year^{-1}$ for flows. L= leaf, BR= branch, BO= bole, RT= root, CT= catkin, FL= floor litter, CL= cardamom leaf, PS= pseudo-stem, RR= root/rhizome, CP= cardamom capsule.


15-year
22.38
12.61
9.77
L
5.63
0.502
CT
0.502
CL
2.33
5.63
0.502
6.48
8.74
BR
13.64
L
34.91
2.30
5.23
BO
35.07
16.13
PS
6.98
0.308
2.35
5.33
CP
0.308
RT
12.76
RR
25.30
0.308

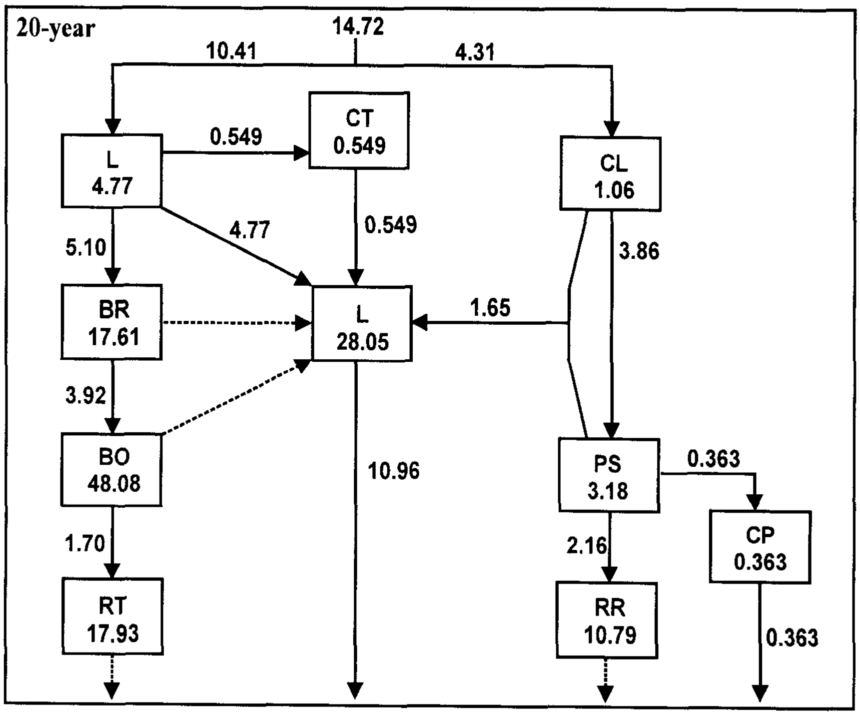
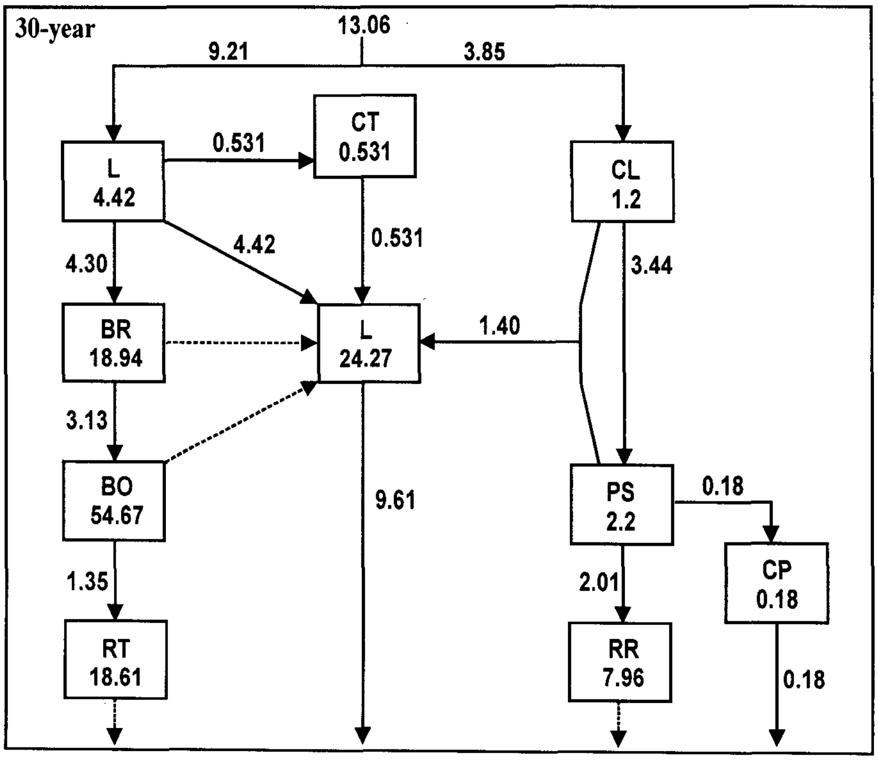

20-year
14.72
10.41
4.31
L
4.77
0.549
CT
0.549
CL
1.06
4.77
0.549
5.10
3.86
BR
17.61
L
28.05
1.65
3.92
BO
48.08
10.96
PS
3.18
0.363
1.70
2.16
CP
0.363
RT
17.93
RR
10.79
0.363

Fig. 4.7c. Compartment model showing distribution of dry matter biomass, net primary production, litter disappearance rate and cardamom capsule harvest in 30- and 40-year stand of *Alnus*-cardamom plantations. Broken lines indicate that values are not estimated. Units are t h^{-1} for compartments and t ha^{-1} $year^{-1}$ for flows. L= leaf, BR= branch, BO= bole, RT= root, CT= catkin, FL= floor litter, CL= cardamom leaf, PS= pseudo-stem, RR= root/rhizome, CP= cardamom capsule.


30-year
13.06
9.21
3.85
L
4.42
0.531
CT
0.531
CL
1.2
4.42
0.531
4.30
3.44
BR
18.94
L
24.27
1.40
3.13
BO
54.67
9.61
PS
2.2
0.18
CP
0.18
1.35
2.01
RT
18.61
RR
7.96
0.18

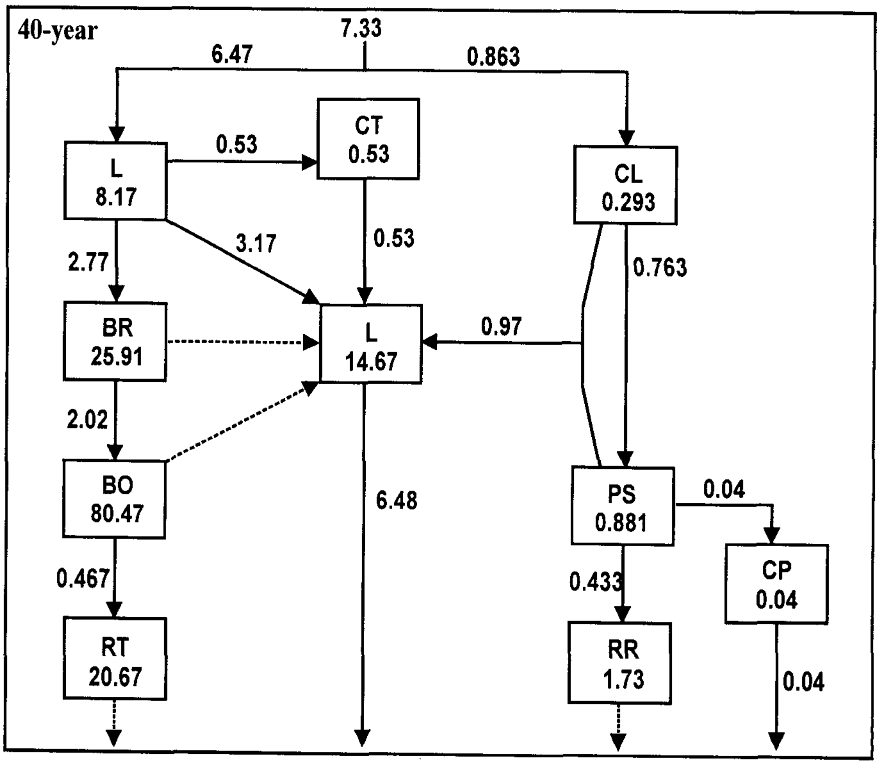
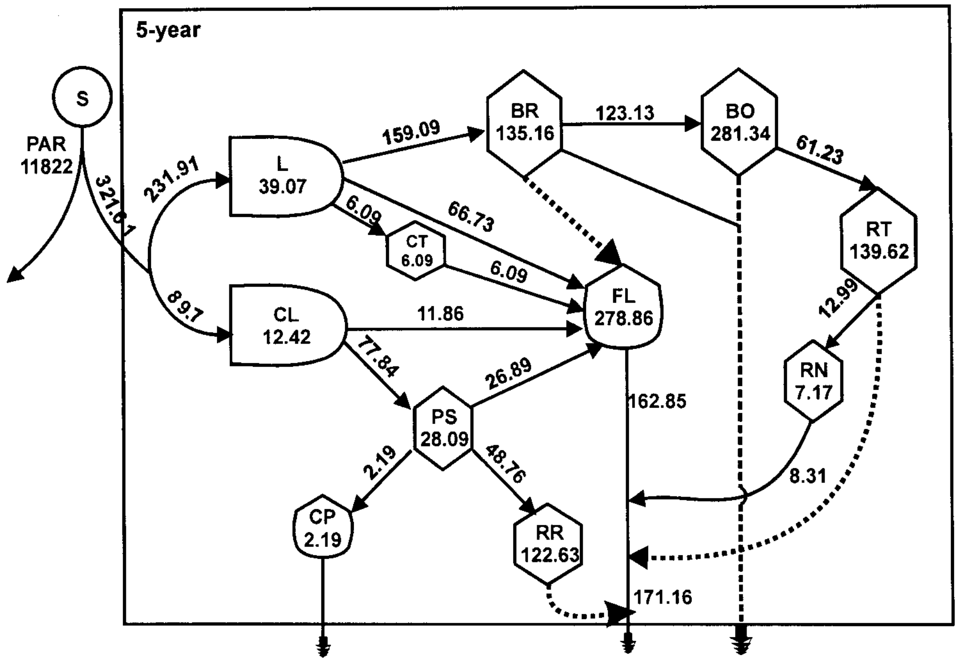

40-year
7.33
6.47
0.863
L
8.17
0.53
CT
0.53
CL
0.293
3.17
0.53
2.77
0.763
BR
25.91
L
14.67
0.97
2.02
BO
80.47
6.48
PS
0.881
0.04
CP
0.04
0.467
0.433
RT
20.67
RR
1.73
0.04

Fig. 4.8a. Distribution of energy storage in components, net energy flow and heat sink from the stand floor in 5- and 10-year-old *Alnus*-cardamom plantation stands. Units are $\times 10^6$ kJ ha^{-1} for compartments and $\times 10^6$ kJ ha^{-1} $year^{-1}$ 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; and CP=cardamom capsule. This figure is drawn using the symbols given by Odum and Odum (1976).


5-year
S
PAR
11822
321.61
231.91
89.7
L
39.07
CL
12.42
CT
6.09
BR
135.16
BO
281.34
RT
139.62
RN
7.17
FL
278.86
PS
28.09
CP
2.19
RR
122.63
159.09
123.13
61.23
66.73
6.09
6.09
11.86
77.84
26.89
12.99
162.85
2.19
48.76
8.31
171.16

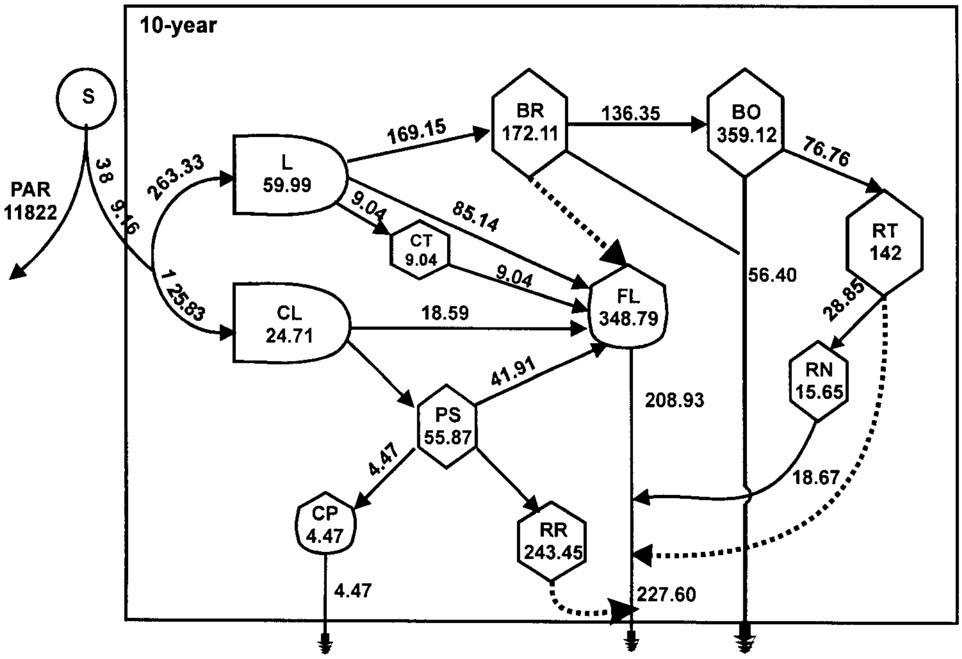
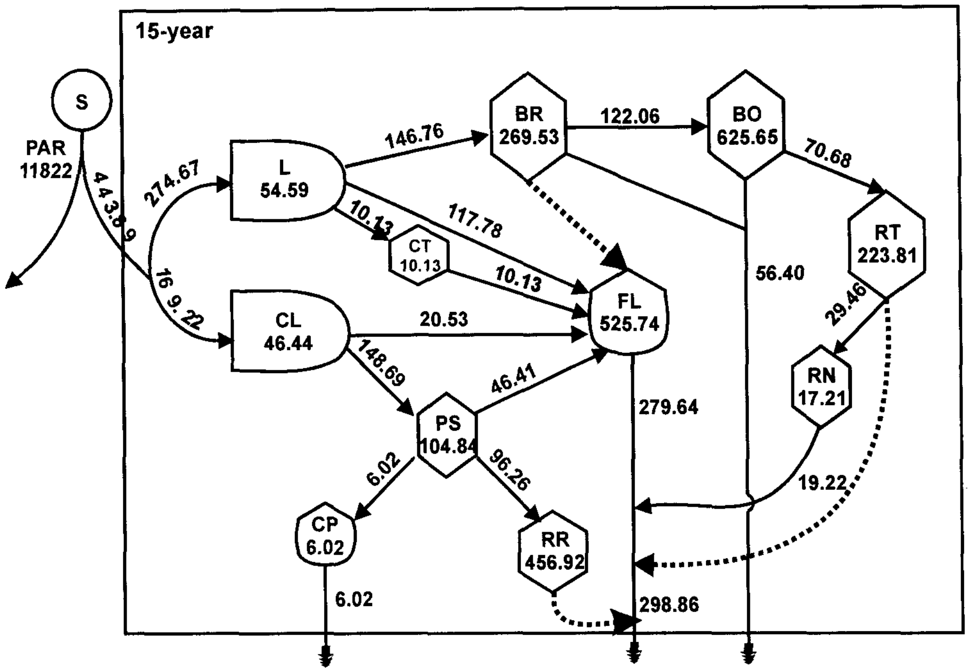

10-year
S
PAR
11822
38 9.16
263.33
1 25.83
L
59.99
CL
24.71
CT
9.04
BR
172.11
BO
359.12
RT
142
RN
15.65
FL
348.79
PS
55.87
CP
4.47
RR
243.45
169.15
136.35
76.76
85.14
9.04
9.04
18.59
56.40
28.85
41.91
208.93
4.47
18.67
4.47
227.60

Fig. 4.8b. Distribution of energy storage in components, net energy flow and heat sink from the stand floor in 15- and 20-year-old *Alnus*-cardamom plantation stands. Units are $\times10^6$ kJ ha^{-1} for compartments and $\times10^6$ kJ ha^{-1} year^{-1} 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; and CP=cardamom capsule. This figure is drawn using the symbols given by Odum and Odum (1976).


15-year
S
PAR
11822
4 4 3.8 9
274.67
16 9. 22
L
54.59
CL
46.44
146.76
117.78
10.13
CT
10.13
10.13
20.53
148.69
BR
269.53
122.06
BO
625.65
70.68
RT
223.81
56.40
FL
525.74
29.46
RN
17.21
PS
104.84
46.41
279.64
6.02
96.26
19.22
CP
6.02
RR
456.92
6.02
298.86

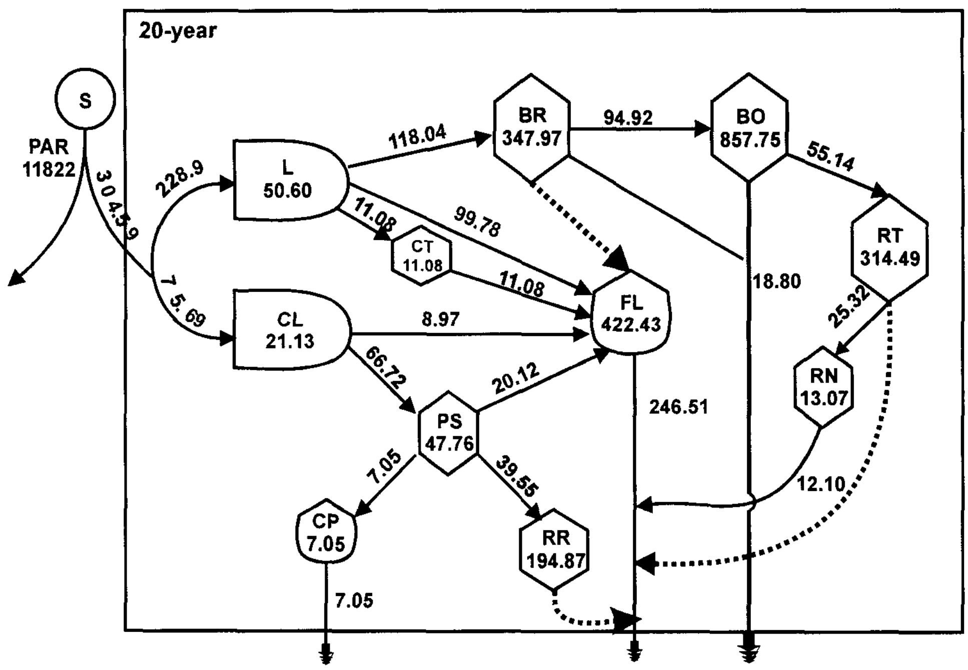
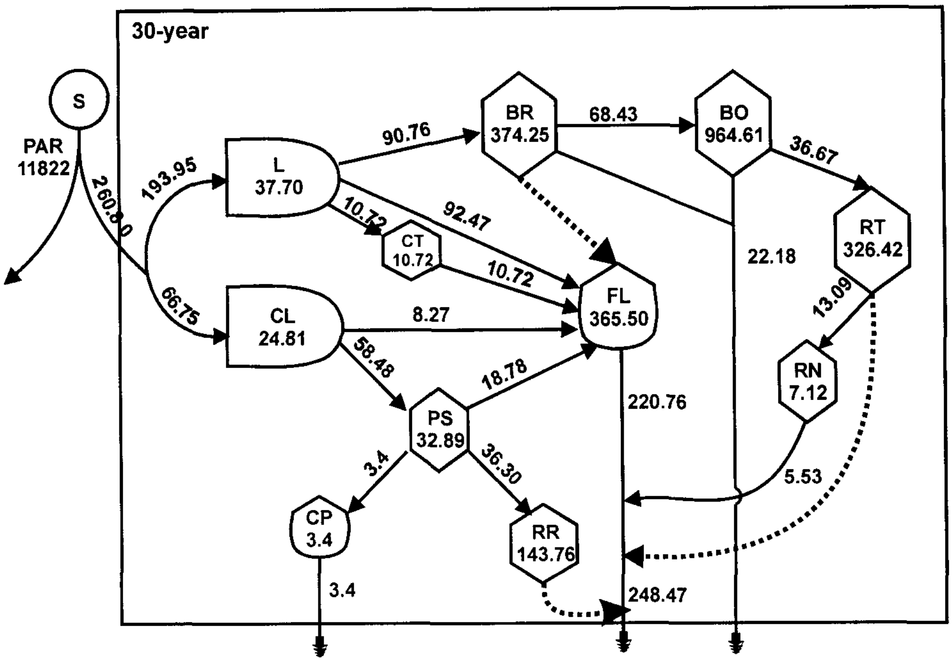
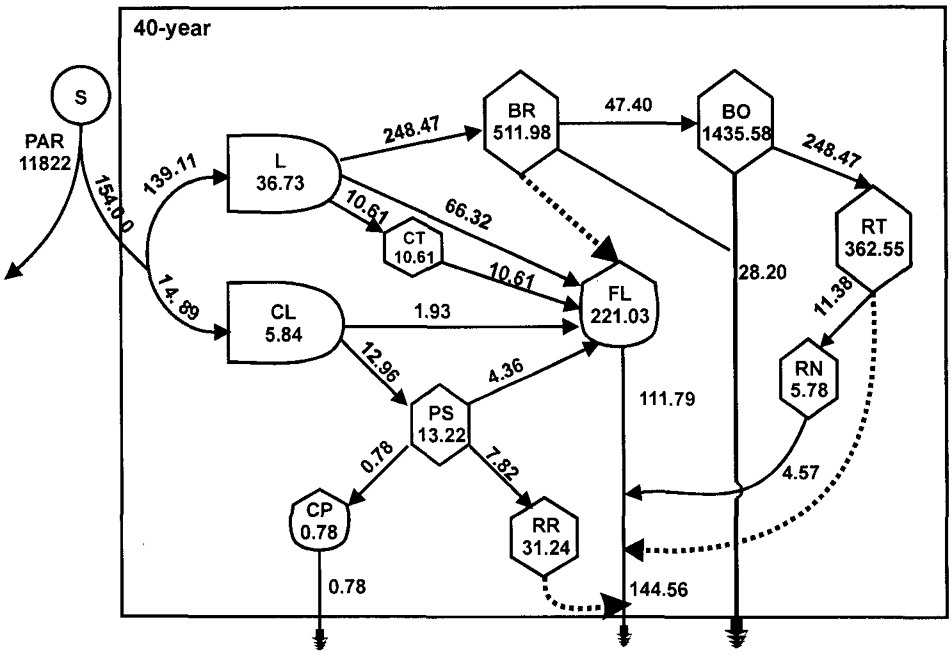

20-year
S
PAR
11822
3 0 4.5 9
228.9
7 5. 69
L
50.60
CL
21.13
118.04
99.78
11.08
CT
11.08
11.08
8.97
66.72
BR
347.97
94.92
BO
857.75
55.14
RT
314.49
18.80
FL
422.43
25.32
RN
13.07
PS
47.76
20.12
246.51
7.05
39.55
12.10
CP
7.05
RR
194.87
7.05

Fig. 4.8c. Distributic n of energy storage in components, net energy flow and heat sink from the stand floor in 30- and 40-year-old *Alnus*-cardamom p antation stands. Units are $\times 10^6$ kJ ha^{-1} for compartments and $\times 10^6$ kJ ha^{-1} $year^{-1}$ for flows. Broken lines indicate that value; are not estimated. PAR=photosynthetically active radiation; S =sun; L=*Alnus* leaf; CT=catkin; BR=branch; BO=bole; RT=root;] N=root nodule; FL=floor litter; CL=cardamom leaf; PS=pseudo-st m; RR=root/rhizome; and CP=cardamom capsule. This figurε is drawn using the symbols given by Odum and Odum (1976).


30-year
S
PAR
11822
260.80
193.95
66.75
L
37.70
CL
24.81
90.76
92.47
10.72
CT
10.72
10.72
8.27
58.48
BR
374.25
68.43
BO
964.61
36.67
RT
326.42
22.18
FL
365.50
13.09
RN
7.12
18.78
PS
32.89
220.76
3.4
36.30
5.53
CP
3.4
RR
143.76
3.4
248.47


40-year
S
PAR
11822
154.00
139.11
14.89
L
36.73
CL
5.84
248.47
66.32
10.61
CT
10.61
10.61
1.93
12.96
BR
511.98
47.40
BO
1435.58
248.47
RT
362.55
28.20
FL
221.03
11.38
RN
5.78
4.36
PS
13.22
111.79
0.78
7.82
4.57
CP
0.78
RR
31.24
0.78
144.56

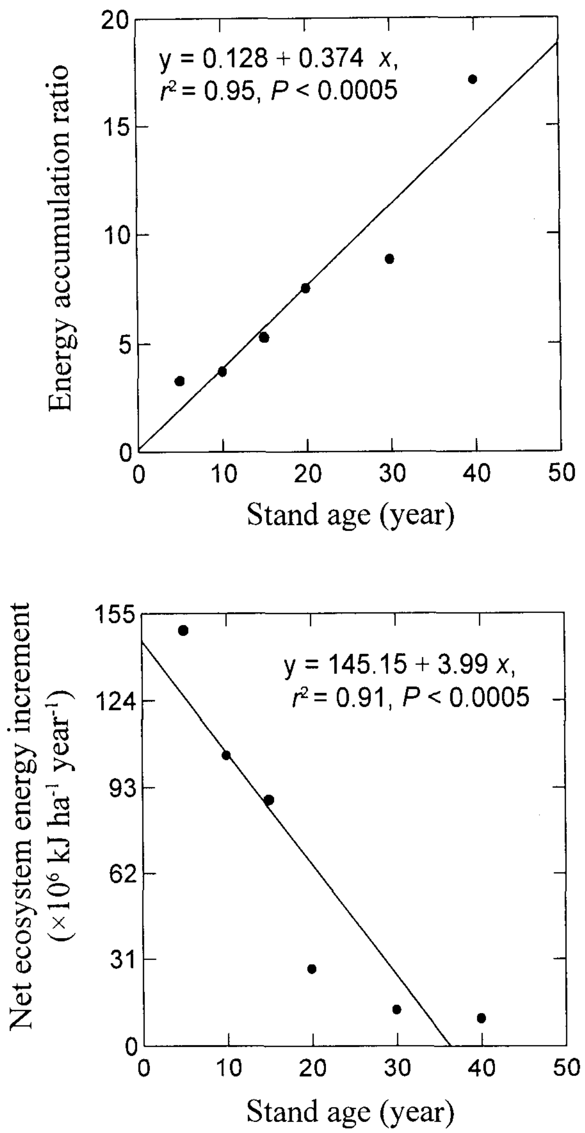


Fig. 4.9. Relationships between energy accumulation ratio and net ecosystem energy increment with stand age in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

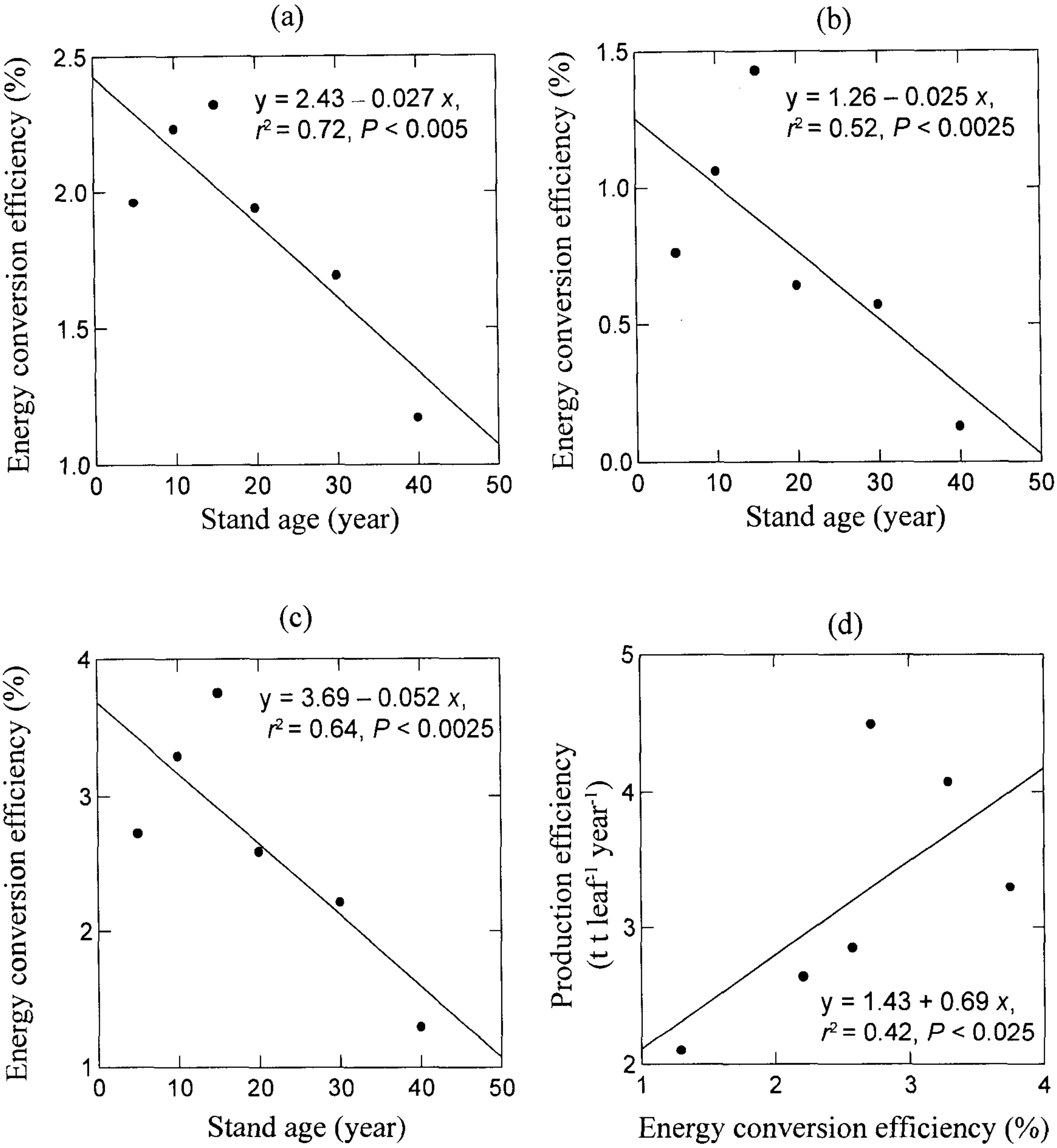


Fig. 4.10. Relationships between energy conversion efficiency (%) of shade tree *Alnus* with stand age (a), understorey cardamom with stand age (b) and plantation stand as a whole with stand age (c), and (d) relationship between production efficiency and energy conversion efficiency in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

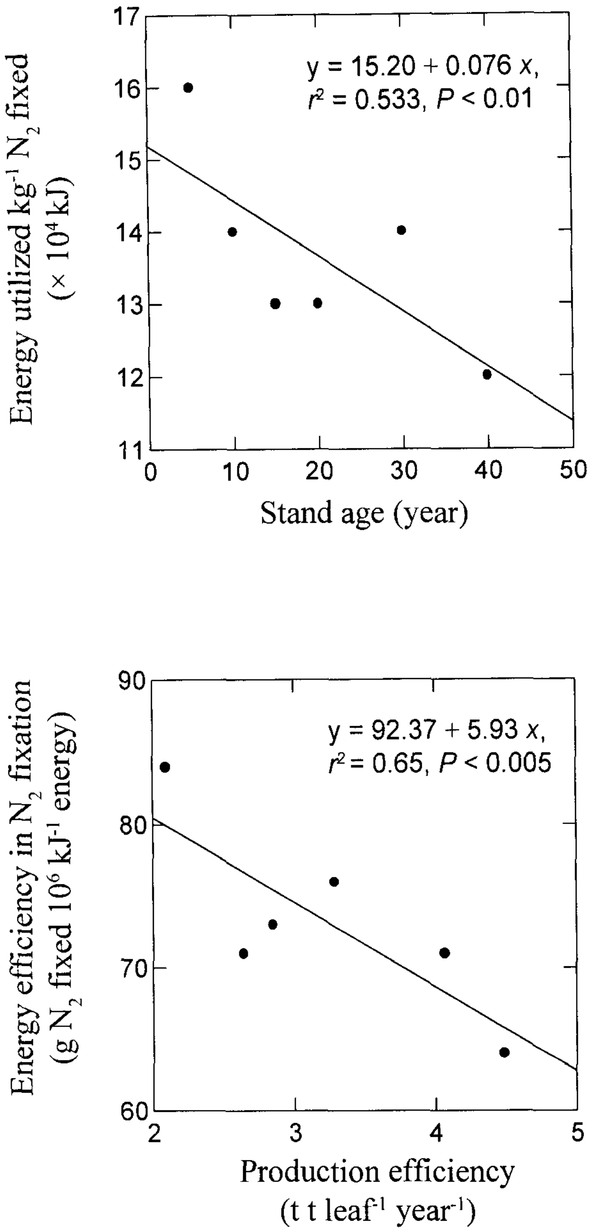


Fig. 4.11. Relationships between energy utilized per kg N_2 fixed with stand age, and energy efficiency in N_2-fixation with production efficiency in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

ROOT NODULE PRODUCTION, NITROGEN FIXATION EFFICIENCY AND ENERGETICS

5.1 Introduction

Nitrogen fixing species used in plantations are expected to offer both high rates of growth and soil enrichment. Environmental conditions that favour tree growth should favour higher rates of N_2-fixation, including adequate water and temperature, high supplies of plant nutrient and favourable soil pH. The effect, of N_2-fixing trees on ecosystem nutrient cycle depends on the amount of N_2-fixed, quantity of N or other nutrients taken up from the soil, and the quality and quantity of litter input.

Roots of *Alnus* spp. are nodulated with *Frankia* as an endophyte, and are efficient in biological nitrogen fixation (Becking 1970; Akkermans and van Dijk 1981; Sharma and Ambasht 1984). Information with emphasis on various aspects of root nodule production and nitrogen accretion are available (Akkermans 1971; Schubert and Evans 1976; Skeffington and Stewart 1976; Binkley 1981; Sharma and Ambasht 1986b, 1988).

The potential increased productivity of plants growing near N_2-fixing species has been recognized for long on the major ecological interactions that occur in mixed stands of N_2-fixing trees (Binkley 1992, 1997). Mixed stand present ecological opportunities for increasing both the stand growth and growth of the non-N_2-fixing associates (Cote and Camire 1987; DeBell *et al.* 1989; Binkley *et al.* 1992a & 1992b). The significance of N_2-fixing species with respect to nitrogen accretion through fixation and energetics in association with the non-N_2-fixing species to plantation age and energy efficiency has always been overlooked given that these are the phenomenal processes that change with stand age maturity. A large amount of energy is consumed during N_2-fixation (Sharma and Ambasht 1988), substantially more than is required for nitrogen assimilation from soil (Salisbury 1977). Nitrogen fixation and accretion by *A. nepalensis* is the most important functional attribute in the mix *Alnus*-cardamom plantations in terms of ecosystem energetics and efficiency. However, information on the mixtures of N_2-fixing and non-N_2-fixing species with regard to energy efficiency in N_2-fixation in relation to energy fixation efficiency and system functioning is lacking. Mix *Alnus*-cardamom plantation in the eastern Himalaya is a good example for understanding the impact of stand age on performance of mixtures of N_2-fixing and non-N_2-fixing plants.

This chapter deals with the stand energy efficiency in N_2-fixation as a function of plantation age. The specific objectives of the study were to determine (a) root nodule biomass and production, (b) seasonal, altitudinal and diurnal variations in nitrogenase activity (d) N_2-fixation efficiency and its energetics, and (e) relationship between energy fixation efficiency and N_2-fixation efficiency in the age series of *Alnus*-cardamom plantation stands.

5.2 Materials and methods

Sample plots of 30×40 m were marked (18 plots; 6 age groups × 3 sites) at each of the plantations in all the sites. All samplings were carried out in these marked plots. Altitudinal and diurnal variation studies were carried out by selection of an altitudinal gradient of 500–2100 m asl from Ranipool to Hanumantok in East Sikkim. Productivity, energetics and efficiencies are given in Chapter IV and used for quantifying the energy efficiency relationship.

5.2.1 Root nodule biomass and production

Root nodules of five average sized *Alnus* trees from all the 18 plots were recovered for estimation of biomass and nutrient contents. Seasonal sampling was done during autumn, winter, spring and rainy in 1998–1999. All the root nodules of each of the trees were recovered. Root nodules in the field were classified into two distinct categories, i.e. active and inactive nodules, on the basis of their colour; they were initially confirmed by nitrogen-fixing potential. The active nodules were further separated into young, medium and old following Sharma and Ambasht (1984, 1986b). Nodule age in the field was determined by colour, young being pale yellow, medium-aged dull yellow and old yellowish brown. The inactive nodules were dark brown. The total root nodule biomass of a single tree was multiplied to the total number of trees to calculate the biomass on per hectare basis. Samples were taken to the laboratory and oven dried (48 h, 80°C). Positive values of the differences of nodule biomass in progressive samplings were added to calculate annual production.

5.2.2 Nitrogenase activity

Nitrogenase activity was estimated by acetylene reduction technique (Stewart *et al.* 1967). Experiments on acetylene reduction assay (5 replicates x 3 nodule age-class x 4 seasons x 18 plots) were carried out during autumn (post monsoon), winter (high litter production, and low temperature and moisture), spring (transition period between winter and pre-monsoon) and rainy (monsoon) season at all the sites and age groups of plantations during 1998 and 1999.

The *Alnus* root nodules were excised along with subtending roots, seasonally. They were gently brushed to free soil particles and categorized into young, medium and old nodules. Samples were weighed (1 g) and transferred to airtight glass vials. Acetylene gas was introduced using gas tight syringe and incubated for 1 h on the plantation floor. Acetylene reduction assay was carried out using Perkin Elmer 8700 Gas Chromatograph. Diurnal variation in nitrogenase activity was conducted in the *Alnus*-cardamom plantations between 1300–1600 m elevations during September 2000. Seven altitudinal gradient sites between 500–2100 m asl were selected and nitrogenase activity was estimated for altitudinal variation in September 2000.

Quantities of nitrogen fixed were estimated by assuming conversion ratio of 3 moles C_2H_2 per mole of N_2 (Hardy *et al.* 1973; Binkley 1981). Nitrogen fixation of each age-class of root nodules for a season was obtained by taking the product of its biomass and N_2-fixation rate. Thus, in a stand the values of all the nodule age-classes were added to give seasonal accretion and total of seasons through the year represented annual accretion from fixation.

5.2.3 Energetics and energy cost analysis

Energy values of root nodules and other plant components were measured by oxygen bomb calorimeter (Lieth 1975). The net energy input in nodulation was calculated as the product of net nodule biomass production and its energy value. The energy required in N_2 reduction at the stand level was computed using energy cost per mole NH_4^+ formed and the total amount of N_2 reduction *in situ*. The biological reduction of N_2 to per mole NH_4^+ requires energy equivalent to 363.66 kJ assuming perfect coupling (Schubert 1982). 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 efficiency in *A. nepalensis* was based on energy cost in N_2 reduction and net energy input in nodulation as a function of plantation age. Net energy input in nodulation when combined with the amounts of energy used in N_2

reduction gives 'energy cost'. The ratio of energy cost per unit weight of nitrogen fixed is the 'nitrogen fixation efficiency'. Energy conversion efficiency (%) is the ratio of energy captured by the vegetation (both *Alnus* and cardamom) to the photosynthetically active radiation reaching an area over a period of time. Net energy fixation was calculated as the total energy contained in the annual biomass production.

All statistical analyses were made using Systat version 6.0 (1996). In case of interactions being significant in analysis of variance the significance between means were compared using Tukey's pairwise mean comparison probabilities.

5.3 Results

5.3.1 Root nodule occurrence

Alnus nodulated profusely in and around cardamom bushes mostly on upper soil horizon of 20 cm depth. The surface soil in the age sequence of plantation stands is invariably loose consisting of humus and soil with low bulk density. In *Alnus*-cardamom plantations, the *Alnus* roots were interestingly dispersed more towards the understorey cardamom bushes showing mutual sharing of soil space. This ecological adaptation could be a commensalism type of relationship.

5.3.2 Root nodule biomass and production

The active root nodule biomass build up within the age series of *Alnus*-cardamom plantation stands increased progressively during the growing season (rainy and autumn) and peaked during July to October. Nodule biomass decreased sharply in winter season (Fig. 5.1). Annual formation and production of new active nodules in the plantation ages was ≈54% of the total nodule production. The contribution of active nodule biomass was 52-69% that of total nodules in the plantation age series. The turnover time of root nodules ranged between 1.70−9.09 years, the lowest being recorded at 5-year stand increased with age to be highest at 40-year stand.

Active and inactive nodules varied significantly between the stand age, season and nodule age-class. Tukey's pairwise mean difference probabilities within the season were significant between 10- with 15- and 20-year (P<0.001); 15- with 30- and 40-year (P<0.0001); 20- with 30- and 40-year (P<0.0001). Pairwise mean differences between the seasons were not significant except spring with autumn (P<0.02). Between active and inactive nodules differences were significant (P<0.0001).

Seasonal variation in active root nodule biomass in an age series is presented in Fig. 5.2. The biomass contribution of young nodules were highest followed by medium and least in old nodules. Active root nodule biomass was highest in the 15-year stand and was 2.4 times that of 5-year and 2.2 times that of the 40-year stand.

Analysis of variance of active root nodule biomass showed significant variation within stand age, nodule age-class and season. Interactions were also significant (Fig. 5.2). Tukey's pair wise mean difference probabilities also showed significant differences between 5- with 10-, 15- and 20-year ($P<0.0001$); 10- with 15-year ($P<0.02$), 20-, 30- and 40-year ($P<0.0001$); 15- with 20-, 30- and 40-year ($P<0.001$); and 20- with 30- and 40-year ($P<0.0001$). Pairwise differences between the stand ages were also significant ($P<0.0001$). Within seasons, difference between rainy with winter was not significant. Variations between the other seasons and nodule age-class were also significant ($P<0.0001$).

The biomass contribution of inactive nodules was highest during spring season nearly 1.9–3.2 times more than the autumn in the age series of *Alnus*-cardamom plantations. Highest inactive nodule biomass was recorded during spring while lowest was recorded during the autumn season (Fig. 5.1). The range of inactive nodule biomass between seasons was lowest (40–75 kg ha^{-1}) in 40-year stand and was highest (110–221 kg ha^{-1}) in the 10-year stand. Inactive nodule biomass between 15- and 20-year stand was almost similar with not much difference while there was a sharp decline in the 30-year and 40-year stand (Fig. 5.1).

Annual root nodule production was highest (165 kg ha^{-1}) in the 10-year stand and lowest in the 30- (18 kg ha^{-1}) and 40-year (14 kg ha^{-1}) stands. Annual production of inactive root (1.40–73.54 kg

ha^{-1}) nodules was lower than the active (12.73–109.94 kg ha^{-1}) nodules.

5.3.3 Nodule moisture and nitrogen concentration

The highest nodule moisture was recorded during the rainy (71–75%) and post-monsoon autumn (66–71%) season and lowest during winter (54–60%) which is the period of low rainfall (Table 5.1).

Nitrogen concentrations were highest (1.87–2.66%) in old nodules followed by medium (1.25–2.07%) and least in young (1.23–1.91%) (Table 5.2). It was highest in the 20-year stand with about 1.4–1.7 times more than the 40-year stand.

The fresh weight: dry weight ratios of nodule age-class were just inverse of the nitrogen concentration, being highest (3.13–3.70) in young nodules, fairly low (3.02–3.44) in the medium and lowest (2.88–3.34) in the old (Table 5.2).

5.3.4 Nitrogenase activity

Seasonal variation in nitrogenase activity was significant between the plantation age, season and nodule age-class (Fig. 5.3). Range of seasonal nitrogenase activity was lowest in the 5-year stand (4–28 C_2H_4 µmoles g^{-1} d. wt. nodules h^{-1}), high in the 15-year stand (5–52 C_2H_4 µmoles g^{-1} d. wt. nodules h^{-1}) and highest in the 40-year stand (3–65 C_2H_4 µmoles g^{-1} d. wt. nodules h^{-1}) (Tables 5.3–5.6). Activity in young nodules ranged from 14–28 C_2H_4 µmoles g^{-1} d. wt. nodules h^{-1} in 5-year, 18–52 C_2H_4 µmoles g^{-1} d. wt.

nodules h^{-1} in 15-year and 19–65 C_2H_4 µmoles g^{-1} d. wt. nodules h^{-1} in 40-year during peak-growing season. But, during the dry winter season, activity was comparatively low and ranged between 4–17 C_2H_4 µmoles g^{-1} d. wt. nodules h^{-1} in 5-year, 5–15 C_2H_4 µmoles g^{-1} d. wt. nodules h^{-1} in 15-year and 3–17 C_2H_4 µmoles g^{-1} d. wt. nodules h^{-1} in the 40-year stand. Activity remained almost similar in all the stand ages during winter season. Analysis of variance showed significant variation between stand age, season and nodule age-class. Interactions were also significant (Fig. 5.3). Tukey's pair wise mean difference probabilities showed significant differences between plantation age – 5- with 10- ($P<0.001$), 15- ($P<0.0001$) and 20- ($P<0.01$); 10- with 30- and 40-year ($P<0.003$); 15- with 30- and 40-year ($P<0.0001$); and 20- with 30-year ($P<0.05$) stand. Pair wise difference between season and nodule age-class was also significant.

Among the nodule age-class, activity was highest in young nodules (8–65 C_2H_4 µmoles g^{-1} d. wt. nodules h^{-1}) followed by medium (5–34 C_2H_4 µmoles g^{-1} d. wt. nodules h^{-1}) and least (3–19 C_2H_4 µmoles g^{-1} d. wt. nodules h^{-1}) in old nodules (Table 5.3–5.6). Difference in nitrogenase activity among nodule age-class in younger plantations was low that appeared distinct with 3–5 and 2–3 times that of old in young and medium aged nodules beyond 15 years age. Nitrogenase activity was higher in autumn season (onset of growing season) than spring (season of higher growth rate) although there was a negligible temperature difference of 1±0.5°C.

Alnus and cardamom plantations between 1100–1700 m asl during rainy season was found most active and thus selected for the diurnal variation study. Experiment was conducted between 05.00–20.00 h in September. Nitrogenase activity showed marked diurnal variability (Table 5.7). Activity increased (23 C_2H_4 μmoles g^{-1} d. wt. nod. h^{-1}) from 5.00 h in the morning to a peak value at 8.00 h (58 C_2H_4 μmoles g^{-1} d. wt. nodules h^{-1}) and lowered in the evening with a least value at 20.00 h (12 C_2H_4 μmoles g^{-1} d. wt. nodules h^{-1}). There was no activity during the predawn hours; the first activity was recorded just at the sunrise. Activity was fairly high in the afternoon and lowered by 4.8 times at 20 h.

Nitrogenase activity was highly dependent on nodule moisture and soil temperature. Relationships between nitrogenase activity with nodule moisture and soil temperature showed significantly positive relationships in the age series of *Alnus*-cardamom plantation stands (Fig. 5.4).

Nitrogenase activity along the altitudinal gradient in *Alnus*-cardamom plantation was lowest at both the extreme high (2100 m) and low (500 m) altitudes (Table 5.8). Activity in the *Alnus*-cardamom plantations was optimum between 700–1900 m elevations. This elevation range represents the major large cardamom growing areas in the eastern Himalaya. At 500 m and

2100 m activity were 1.8 and 2.7 times, respectively, less than at 1500 m (71 C_2H_4 µmoles g^{-1} d. wt. nodules h^{-1}).

5.3.5 Nitrogen fixation and energy cost analysis

Nitrogen fixation in the age series of *Alnus*-cardamom plantation stands showed high and low accretion periods, maximum fixation (64–74%) during the growth period between rainy and autumn seasons, and comparatively low (24–26%) in the dormant growth period of severe winter and spring seasons (Table 5.9). These seasons correspondingly coincide with the cardamom flowering and fruiting stage and a period of dormant growth. During rainy and autumn seasons, fixation was maximum and ranged between 15–18 kg ha^{-1} in 5-year, 47–69 kg ha^{-1} in 15-year and 15–27 kg ha^{-1} in the 40-year stand. Conversely, fixation ranged between 5–14 kg ha^{-1} in 5-year, 14–25 kg ha^{-1} in 15-year and 5–11 kg ha^{-1} in the 40-year stand, during the winter and spring seasons. There was a tremendous variation of nitrogen fixation with 3.69–5.84 times in rainy season as great as that of winter in the age series of *Alnus*-cardamom plantation. Per cent contribution of nitrogen fixation was highest in *Alnus* young nodules (54–60%), fairly low (27–30%) in medium and lowest (10–19%) in old nodules.

Annual nitrogen fixation increased from 5-year (51.96 kg ha^{-1}) to reach highest at the 15-year stand (154.48 kg ha^{-1}) and then decreased to remain stagnant around the 30- and 40-year stand (58 kg ha^{-1}). Plantation age between 10 to 20 years added substantial amount of nitrogen in the stands. Of the total N uptake (90–239 kg ha^{-1} $year^{-1}$) in the plantation age series, addition through biological fixation contributed 39–66%. Nitrogen fixation was consistent with the stand productivity rates (7–22 t ha^{-1}) and energy conversion efficiency (1–4%) in the age series of *Alnus*-cardamom plantations.

Energy utilized in N_2-fixation and net input in nodulation was 2.5 and 2.9 times higher, respectively, in the 15-year stand (2028×10^4 kJ $year^{-1}$) than in the 5-year and 40-year stands (Table 5.10). These stands possess the largest amount of nodule biomass and eventually brought about higher nitrogen fixation. Energy cost in N_2-fixation and nodulation and energy per kg N_2-fixation was comparatively higher in the young nodules followed by medium and low in old nodules. Of the total energy utilized in N_2-fixation and nodulation, young nodules used 43–45%, medium around 30–31% and old nodules 23–26% of energy in the plantation age series. Net energy input in nodulation for unit N_2-fixation in the 5-year stand (13×10^4 kJ kg^{-1} N_2 fixation) was much higher that hovered around $10.5–11.5\times10^4$ kJ kg^{-1} N_2 fixation in 10-, 15-, 20- and 30-year stands, and recorded lowest in the 40-year stand (9×10^4 kJ kg^{-1} N_2 fixation). The younger plantation stand accounted to be the more cost-effective system in terms of energy utilization. Although, the unit energy requirement in nodulation for unit N_2-fixation was proportionately substantial in the 40-year stand. The total energy cost in N_2-fixation and nodulation in the 5-year and

40-year stands was only 40% and 34% of the total energy cost (2028×10^4 kJ $year^{-1}$) utilized in the 15-year stand.

Energy required per kg N_2-fixation was 16×10^4 kJ in the 5-year stand that gradually decreased to a value of 12×10^4 KJ in the 40-year stand. Energy conversion efficiency, energy fixation efficiency and net ecosystem energy increment were greater at the younger stands and reduced to >50% in the older stands. In contrast, the energy efficiency in N_2-fixation was lowest (64 g N_2 fixed 10^4 kJ^{-1} energy) in the 40-year stand. At the stands with low energy conversion efficiency N_2-fixation efficiency increased. Energy utilized per kg N_2 fixed consistently increased with increase in energy conversion efficiency. N_2-fixation efficiency showed a significant negative relationship with energy conversion efficiency and energy fixation efficiency while energy utilized per kg N_2-fixed showed positive relationship with energy conversion efficiency (Fig. 5.5). This is an indication of greater energy demand for efficient functioning although there was low energy conversion efficiency in the older stands. Energy input in nodulation for unit N_2-fixation showed an inverse function with stand age (Fig. 5.5).

5.4 Discussion

Alnus root nodule formation in and around the cardamom bushes and mutual rhizospheric sharing is an interesting ecological adaptation in *Alnus*-cardamom plantations. Many workers have reported estimates on root nodule biomass of *Alnus*.

Zavitkovski and Newton (1968) estimated the nodule biomass of 117 kg ha^{-1} in 7-year and 244 kg ha^{-1} in the 30-year-old pure *Alnus rubra* stands. Akkermans and van Dijk (1976) recorded 454 kg ha^{-1} in a 20-year old *A. glutinosa* stand and Binkley (1981) reported 390 and 110 kg ha^{-1} in *A. rubra* and *A. sinuata* stands. Sharma and Ambasht (1986b) estimated 457 kg ha^{-1} in the 7-year and 149 kg ha^{-1} in the 56-year-old pure *A. nepalensis* stands. In the present study, root nodule biomass of *A. nepalensis* estimated was highest (302–416 kg ha^{-1}) at the 15-year stand and lowest in the 40-year stand (112–145 kg ha^{-1}). Root nodule biomass estimates between 10- to 30-year *Alnus*-cardamom plantations were comparable to estimates cited above.

Of the total root nodule production, 52–69% was contributed by active and 31–48% by inactive nodules. The annual root nodule production was always smaller than the actual nodule biomass at a time per unit area. The increase in inactive nodule was due to the transition of 1-2-year-old active nodule formation, growth and decay are the continual processes with little nodule biomass accumulation (Sharma and Ambasht 1986b). Turnover time of the nodules is the time required to provide a quantity equal to maximum biomass and was longest in the 30-year (8.26 year) and 40-year (9.09 years) stands and shortest between 5- to 15-year stands (1.7–2.65 years). These *Alnus* cardamom plantations had higher standing nodule biomass and lower production rate (i.e.

slower nodule turnover) compared to pure *A. nepalensis* stands (Sharma and Ambasht 1986b).

Reports on the nitrogensase activity based on acetylene reduction assay are available. Although acetylene reduction technique is not accurate as ^{15}N studies but it works well for comparative studies as this one between ages and seasons. Sharma and Ambasht (1984) reported highest activity rate of 35.3 nmole C_2H_4 mg^{-1} nod. min^{-1} during July in a pure *A. nepalensis* stands. Nitrogenase activity in the *Alnus*-cardamom plantations estimated was truely seasonal with highest activity during the growth period. The high nitrogenase activity during the rainy and autumn season correlates with high temperature, adequate moisture and high growth rates. Nitrogenase activity showed a positive relationship with soil temperature and nodule moisture in the age series. Changes in the ambient air and soil temperature, photoperiodicity and light intensity also reinforce each other on the effect of seasonal variation in nitrogenase activity. The optimum temperature for acetylene reduction was between 20-25°C in most actinorhizal plants- *A. glutinosa* (Akkermans 1971; Wheeler 1971) and *A. nepalensis* (Sharma and Ambasht 1984). Nitrogenase activity in the age series remained fairly optimum until plantation age attained 40-year. The highest nodule biomass production and nitrogenase activity during the growing season suggests that there is a greater requirement of warmer photoperiod than cool dark nights, which directly corresponds to nutrient requirement of cardamom for flowering and fruiting.

Nitrogenase activity recorded was highest between 1300-1500 m altitudes, but was fairly high between 700-1900 m the major cardamom growing elevation in the region. Most interestingly, the activity was recorded comparatively low at the high and low altitudinal zone which is on the extremes of ecological amplitude of occurence for both *Alnus* and cardamom. Sharma (1988) recorded highest activity at 1830 m elevations in *Alnus* naturally regenerating on land-slide affected sites.

Diurnal fluctuations in nitrogenase activity have been reported in *A. nepalensis* with highest activity during 13.00–14.00 h (Sharma 1988). Activity in young plants of *A. glutinosa* and *Myrica gale* growing in a glass house under natural illumination was also maximal during mid day (Wheeler 1969). In the present study, activity increased with increase in light and temperature during a day and peaked between 8.00-14.00 h and decreased to low values by evening. Diurnal fluctuations in the field are often due mainly to changes in temperatures and irradiation that lead to photosynthetic allocation to the root nodules resulting into higher activity and inturn falls when carbohydrate levels in nodules are all metabolized in the dark period (Wheeler 1971).

Per cent nitrogen concentrations of root nodules were highest in old nodules, less in medium and comparatively low in young nodules irrespective of the plantations. The fresh weight: dry weight ratios of nodule age-class were proportionately opposite with highest in young and lowest in old. Regression analysis between nodule nitrogen with nitrogenase activity gave significantly negative relationship (Nitrogenase activity=40.87–11.6N concn., r^2=0.30, P<0.005). The relationship predicts the higher nodule activity coupled with lower nitrogen activity (Skeffington 1975; Sharma and Ambasht 1984).

Average annual fixation of nitrogen in *Alnus*-cardamom ecosystems based on acetylene reduction assay was highest (130 kg ha^{-1}) in *A. rubra* stands and fixation value of 20 kg ha^{-1} was recorded in 15- to 20-year *A. sinuata* and *A. crispa* mixed stands (Binkley 1981). Annual fixation was reported to be highest (117 kg ha ha^{-1}) in 7-year and lowest (29 kg ha^{-1}) in 56-year stand of pure *A. nepalensis* plantations (Sharma and Ambasht 1988). In the present mixed stands of *Alnus*-cardamom plantations, annual nitrogen fixation recorded was highest in 15-year stand (155 kg ha^{-1}) and lowest in 5-year stand (52 kg ha^{-1}). Annual nitrogen fixation recorded in this study was higher side of above reports. This is mainly due to management of *Alnus*-cardamom system. Newton *et al.* (1968) reported annual nitrogen fixation as high as 130 kg ha^{-1} between 2- to 15-year-old *A. rubra* stands. Of the total nitrogen uptake in the age series, contribution of nitrogen fixation ranged from 39–66% and the higher percentage was recorded in 10-, 15-, and 20-year plantation stands. In *Alnus*-cardamom plantations, the mechanism of nitrogen accumulation through fixation and stand productivity are counter balanced to the requirement for system equilibrium, irrespective to their stand age and microclimatic regulations.

The energy cost in N_2-fixation and nodulation increased with stand age and decreased sharply in the older plantations. This was due to the increase of nodule biomass production and nitrogen accretion in the younger stands and reduction in older stands. Sharma and Ambasht (1988) reported that N_2-fixation efficiency, and energy cost in N_2-fixation and nodulation decreased from 7-year to 56-year with corresponding decrease in nitrogen accretion and nitrogen demand in a pure *A. nepalensus* plantations. Relationship between energy input in nodulation for unit N_2-fixation with stand age and energy efficiency in N_2-fixation with energy fixation efficiency and energy conversion efficiency showed an inverse function. N_2-fixation efficiency increased in the stands with low energy conversion efficiency while energy utilised per kg N_2-fixed consistently increased with increase in energy conversion. Thus, an energy balance between the stands is maintained. This was attributed to the decrease in energy conversion efficiency, energy fixation efficiency and net ecosystem energy increment beyond 20-year plantation age in *Alnus*-cardamom system. Energy utilized per kg N_2 fixed was dependent on energy conversion efficiency, and showed a positive relationship with energy conversion efficiency. High N_2-fixation efficiency in older stands and low energy input for unit N_2-fixation indicates a greater energy demand for nodulation and N_2-fixation. However, substantial amount of energy is supplemented by the younger stands through their high energy consumption processes of conversion and fixation efficiency. The inverse relationship indicates that the stand energy efficiency in N_2-fixation is subsided over by energy conversion and fixation efficiency and is highly dependent on plantation age. The root nodule production, nitrogen fixation and stand energy efficiencies reduced to almost >50% in the older stands. The inverse relationships between energy efficiency in N_2-fixation against energy fixation efficiency and energy conversion efficiency suggests that the immature plantations until 15 year function as the most efficient system, while the mature plantations beyond 20 years age are least efficient. *A. nepalensis* adds significant amount of nitrogen to the *Alnus*-cardamom plantation stands and proves itself to be an excellent associate for efficient system functioning of cardamom plantations in the eastern Himalaya. Cardamom yield depends largely on the performance of both the associates. Performance of the mixture of cardamom with N_2-fixing *A. nepalensis* in the age series suggests that a rotational cycle of 20 year could be maintained for its sustainability ❖

Table 5.1. Seasonal variation in *Alnus* active root nodule moisture (%) content in an age series of *Alnus*-cardamom plantation stands. Values are mean ±SE, n=3.

Stand age (year)	Seasons			
	Winter	Summer	Rainy	Autumn
5	54.27±2.98	69.69±0.12	71.40±0.39	66.65±1.43
10	58.31±1.82	69.02±0.64	73.18±1.53	71.31±0.51
15	60.84±2.74	68.73±0.53	73.07±0.32	68.79±0.77
20	51.56±1.49	70.88±0.25	75.53±0.99	74.68±0.49
30	50.700±5.33	69.81±0.45	74.65±0.74	73.24±0.46
40	59.113±3.68	64.35±0.98	73.76±1.34	65.97±0.58

ANOVA: Season $F_{3,48}$=115.530, P<0.0001; Stand-age $F_{15,48}$=3.424, P<0.001; Interaction between the stand-ages and seasons not significant.

Table 5.2. Nitrogen concentration and fresh weight: dry weight ratio of the three age-classes of root nodules of *Alnus* in the age series of *Alnus*-cardamom plantation stands. Values are mean ±SE; n=9.

Nodule age	Nitrogen/ weight ratio	Stand age (year)					
		5	10	15	20	30	40
Young	Nitrogen	1.49 ±0.02	1.57 ±0.15	1.63 ±0.19	1.91 ±0.08	1.86 ±0.07	1.23 ±0.03
	Weight ratio*	3.13 ±0.23	3.28 ±0.19	3.36 ±0.15	3.70 ±0.28	3.58 ±0.23	3.37 ±0.29
Medium	Nitrogen	1.79 ±0.38	1.76 ±0.01	1.77 ±0.09	2.07 ±0.04	1.91 ±0.01	1.25 ±0.04
	Weight ratio*	3.02 ±0.24	3.13 ±0.23	3.44 ±0.25	3.44 ±0.25	3.38 ±0.22	3.38 ±0.22
Old	Nitrogen	1.87 ±0.42	1.87 ±0.72	2.02 ±0.17	2.66 ±0.18	2.11 ±0.07	2.01 ±0.07
	Weight ratio*	2.88 ±0.27	2.97 ±0.22	3.34 ±0.23	3.34 ±0.23	3.32 ±0.20	3.32 ±0.20

*Fresh weight: dry weight ratio

Table 5.3. Nitrogenase activity and fresh weight/dry weight ratio of the three age-classes of *Alnus* root nodules in an age series of *Alnus*-cardamom plantation stands in winter season. Values are mean ±SE, n=3.

Stand age (year)	Nodule age	Fr. wt/d. wt. ratio	C_2H_4 μmoles g^{-1} d. wt. nodule h^{-1}	C_2H_4 μmoles g^{-1} nodule N min^{-1}
5	Young	2.36	16.71±0.63	18.69±0.70
	Medium	2.31	7.88±1.61	7.34±1.49
	Old	2.0	3.51±0.32	3.12±0.28
10	Young	2.61	21.26±0.89	22.57±0.94
	Medium	2.37	8.31±1.53	7.87±1.45
	Old	2.23	3.37±0.39	3.00±0.35
15	Young	2.97	14.81±1.12	15.15±1.15
	Medium	2.37	8.19±0.13	7.72±1.06
	Old	2.40	4.56±0.30	3.76±0.25
20	Young	2.91	8.95±0.35	17.81±0.30
	Medium	2.62	4.98±0.43	4.01±0.35
	Old	2.61	3.18±0.11	1.99±0.20
30	Young	2.93	12.58±2.6	11.28±2.32
	Medium	2.70	6.91±1.1	6.03±0.96
	Old	2.62	3.79±0.86	2.30±0.68
40	Young	2.72	17.11±0.73	29.19±0.99
	Medium	2.61	6.02±0.97	8.03±1.29
	Old	2.08	3.14±0.43	2.60±0.35

Table 5.4. Nitrogenase activity and fresh weight/dry weight ratio of the three age-classes of *Alnus* root nodules in an age series of *Alnus*-cardamom plantation stands in spring season. Values are mean ±SE, *n*=3.

Stand age year)	Nodule age	Fr. wt./d. wt.	C_2H_4 µmoles g^{-1} d. wt. nodule h^{-1}	C_2H_2 µmoles g^{-1} nodule N min^{-1}
5	Young	3.33	24.84±0.71	27.78±0.79
	Medium	3.31	14.06±3.28	13.09±3.05
	Old	3.28	9.10±0.22	8.11±0.19
10	Young	3.36	24.67±4.29	26.19±4.55
	Medium	3.16	16.65±1.29	15.77±1.22
	Old	3.05	9.09±2.65	8.11±2.36
15	Young	3.30	21.59±1.11	22.08±1.13
	Medium	3.18	10.42±2.27	9.81±1.94
	Old	3.05	5.36±0.47	4.43±0.39
20	Young	3.52	24.29±3.39	21.19±2.96
	Medium	3.41	9.99±1.21	8.04±0.97
	Old	3.36	5.18±1.04	3.24±0.65
30	Young	3.41	31.05±13.7	27.82±12.2
	Medium	3.33	13.29±1.08	11.59±0.94
	Old	3.24	7.66±1.58	6.05±1.25
40	Young	3.32	27.45±3.98	37.19±5.39
	Medium	3.22	12.15±1.09	16.20±1.46
	Old	3.12	8.99±0.19	7.46±0.16

Table 5.5. Nitrogenase activity and fresh weight/dry weight ratio of the three age-classes of *Alnus* root nodules in an age series of *Alnus*-cardamom plantation stands in rainy season. Values are mean ±SE, *n*=3.

Stand age (year)	Nodule age	Fr.wt./d.wt.	C_2H_4 µmoles g^{-1} d. wt. nodule h^{-1}	C_2H_4 µmoles g^{-1} nodule N min^{-1}
5	Young	3.55	28.21±1.12	31.55±1.26
	Medium	3.51	18.16±0.74	16.91±0.68
	Old	3.40	13.64±1.52	12.16±1.36
10	Young	3.58	31.02±0.87	32.93±0.93
	Medium	3.51	24.41±1.87	23.11±1.78
	Old	3.31	16.83±0.43	14.99±0.38
15	Young	3.79	51.83±8.30	52.60±8.48
	Medium	3.71	28.57±4.90	26.90±4.61
	Old	3.64	17.66±3.19	14.57±2.63
20	Young	4.44	38.93±0.54	33 97±0.47
	Medium	3.91	27.07±2.24	21.80±1.80
	Old	3.81	13.58±2.38	8.51±1.44
30	Young	4.17	48.16±1.27	43.17±1.13
	Medium	3.89	27.42±2.43	23.92±2.12
	Old	3.78	10.81±0.56	8.54±0.45
40	Young	4.24	65.12±8.77	88.23±11.78
	Medium	3.68	34.39±1.23	45.86±1.64
	Old	3.51	19.17±3.56	15.90±2.90

Table 5.6. Nitrogenase activity and fresh weight/dry weight ratio of the three age-classes of *Alnus* root nodules in an age series of *Alnus*-cardamom plantation stands in autumn season. Values are mean ±SE, n=3.

Stand age (year)	Nodule age	Fr.wt./d.wt. Ratio	C_2H_4 µmoles g^{-1} d. wt. nodule h^{-1}	C_2H_4 µmoles g^{-1} nodule N min^{-1}
5	*Young*	3.27	25.52±2.92	28.54±3.3
	Medium	2.93	10.40±1.08	9.68±1.02
	Old	2.82	7.03±0.55	6.26±0.49
10	Young	3.56	26.84±6.92	28.49±7.3
	Medium	3.46	12.28±1.89	11.63±1.8
	Old	3.33	9.88±0.36	8.81±0.32
15	Young	3.36	45.22±11.6	46.64±11.9
	Medium	3.16	15.92±6.21	14.99±5.8
	Old	3.09	6.09±0.28	5.02±0.23
20	Young	3.93	41.04±8.90	35.82±7.8
	Medium	3.83	26.14±3.28	21.04±2.6
	Old	3.60	13.35±0.95	8.37±0.59
30	Young	3.80	24.33±6.53	21.80±5.8
	Medium	3.70	19.01±2.33	16.59±2.1
	Old	3.60	10.88±2.78	8.60±2.20
40	Young	3.14	33.36±4.85	45.20±6.6
	Medium	3.02	19.39±1.76	25.86±2.3
	Old	2.85	10.01±2.6	8.30±2.2

Table 5.7. Diurnal variation in soil temperature, ambient air temperature and nitrogenase activity in the root nodules of *Alnus* in 20-year-old *Alnus*-cardamom plantation stand. Values are mean ±SE, *n*=6.

Time (hours)	Soil temperature (°C)	Ambient air temp. (°C)	Nitrogenase activity (C_2H_4 μmoles g^{-1} d. wt. nodules h^{-1})
5.00	17.91±0.21	18.51±0.33	23.17±5.96
8.00	19.81±0.15	20.01±0.21	57.87±6.13
11.00	21.48±0.18	23.78±0.31	39.57±1.98
14.00	22.05±0.16	25.41±0.34	37.08±1.73
17.00	21.42±0.14	20.97±0.21	35.06±4.11
20.00	16.18±0.31	15.22±0.32	12.05±1.81

Table 5.8. Altitudinal variation in nitrogenase activity of root nodules of *Alnus* and soil temperature in *Alnus*-cardamom plantations. Values are mean ±SE, n=6.

Elevation (m)	Soil temperature (°C)	Nitrogenase activity (C_2H_4 μmoles g^{-1} d. wt. nodules h^{-1})
500	26.31±0.35	33.69±0.92
700	25.34±0.53	38.73±1.69
900	24.32±0.45	44.81±2.14
1100	23.52±0.43	54.13±3.31
1300	22.52±0.52	64.44±0.63
1500	21.25±0.54	70.94 ±2.91
1700	19.51±0.61	50.94±2.81
1900	18.21±0.54	35.94±3.95
2100	17.12±0.13	26.37±1.55

Table 5.9. Seasonal fixation of nitrogen (kg ha^{-1}) by three age-classes of *Alnus* root nodules based on acetylene reduction assay in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

Stand age (year)	Season	Nitrogen fixation (kg ha^{-1})			
		Young	Medium	Old	Stand total
5	Winter	3.25	1.28	0.47	5.00
	Spring	7.27	3.89	2.68	13.84
	Rainy	9.32	5.25	3.87	18.44
	Autumn	8.47	3.81	2.40	14.68
	Total	28.31	14.23	9.42	51.96
10	Winter	8.85	3.54	1.10	13.49
	Spring	13.17	7.78	3.95	24.90
	Rainy	24.67	17.86	11.91	54.44
	Autumn	18.18	9.73	7.25	35.16
	Total	64.87	38.91	24.21	127.99
15	Winter	8.28	4.06	2.05	14.39
	Spring	13.60	6.55	3.13	23.28
	Rainy	37.46	19.80	12.14	69.40
	Autumn	31.98	10.96	4.47	47.41
	Total	91.32	41.37	21.79	154.48
20	Winter	4.17	2.22	1.19	7.58
	Spring	11.92	4.65	2.23	18.80
	Rainy	23.81	14.19	6.25	44.25
	Autumn	21.64	12.69	6.47	40.80
	Total	61.54	33.75	16.14	111.43
30	Winter	3.29	1.79	0.93	6.01
	Spring	8.45	3.24	1.73	13.42
	Rainy	13.81	7.43	2.92	24.16
	Autumn	7.07	5.08	2.49	14.64
	Total	32.64	17.54	8.07	58.25
40	Winter	3.38	1.16	0.62	5.16
	Spring	6.59	2.93	1.52	11.04
	Rainy	16.59	8.59	2.10	27.28
	Autumn	8.18	4.59	2.14	14.91
	Total	34.74	17.27	6.38	58.39

Table 5.10. Energetics of N_2-fixation and nodulation in an age series of *Alnus*-cardamom plantation stands.

Efficiency parameters	Stand age (year)	Nodule age			Stand total
		Young	Medium	Old	
Energy used in N_2 reduction to NH_4^+ ($\times 10^4$ kJ ha^{-1} year^{-1})	5	73.5	36.9	24.5	135
	10	168.4	101.0	62.9	332
	15	237.1	107.4	56.5	401
	20	159.7	87.6	41.9	289
	30	84.6	45.5	20.9	151
	40	90.2	44.8	16.6	152
Net energy input in nodulation ($\times 10^4$ kJ ha^{-1} year^{-1})	5	282.3	214.5	182.5	679
	10	596.7	473.6	409.6	1480
	15	651.4	528.4	447.2	1627
	20	502.2	394.8	346.5	1244
	30	268.2	213.4	190.3	672
	40	226.2	172.2	148.7	547
Energy cost in N_2-fixation and nodulation ($\times 10^4$ kJ ha^{-1} year^{-1})	5	355.8	251.4	207.0	814
	10	765.1	574.6	472.5	1812
	15	888.5	635.8	503.7	2028
	20	661.9	482.4	388.4	1533
	30	352.8	258.9	211.2	823
	40	316.4	217.1	165.3	699
Energy cost (x10^4 kJ) per kg N_2-fixation	5	-	-	-	15.66
	10	-	-	-	14.16
	15	-	-	-	13.13
	20	-	-	-	13.75
	30	-	-	-	14.13
	40	-	-	-	11.96

The biological reduction of N_2 to per mole NH_4^+ requires energy equivalent to 363.66 kJ (Schubert 1982)

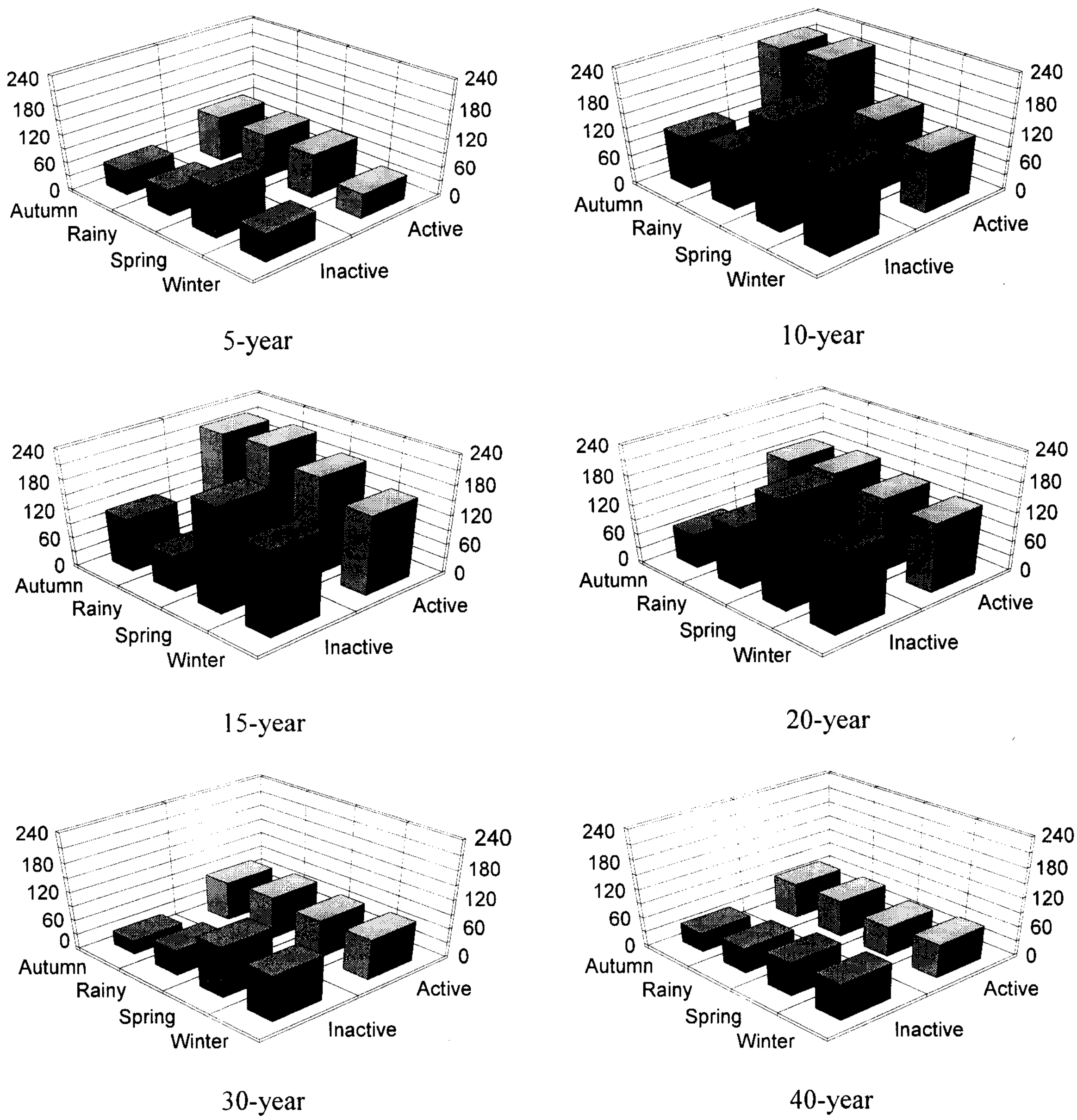


Fig.5.1. Seasonal variation in active and incative root nodule biomass (kg ha^{-1}) of *Alnus* in the age series of *Alnus*-cardamom plantation sands. Values are means of three site replicates. ANOVA showed significant variation between stand age ($F_{5,144}$=45.4; P<0.0001), all interactions were also significant. Tukey's pairwise mean difference probabilities are: between stand age- 5- with 10-, 15- and 20-year (P<0.0001); 10- with 15- and 20-year (P<0.001); 15- with 30- and 40-year (P<0.0.0001); 20- with 30- and 40-year (P<0.0001); Seasons- spring with autumn (P<0.023); Nodule age class-active with inactive (P<0.0001).

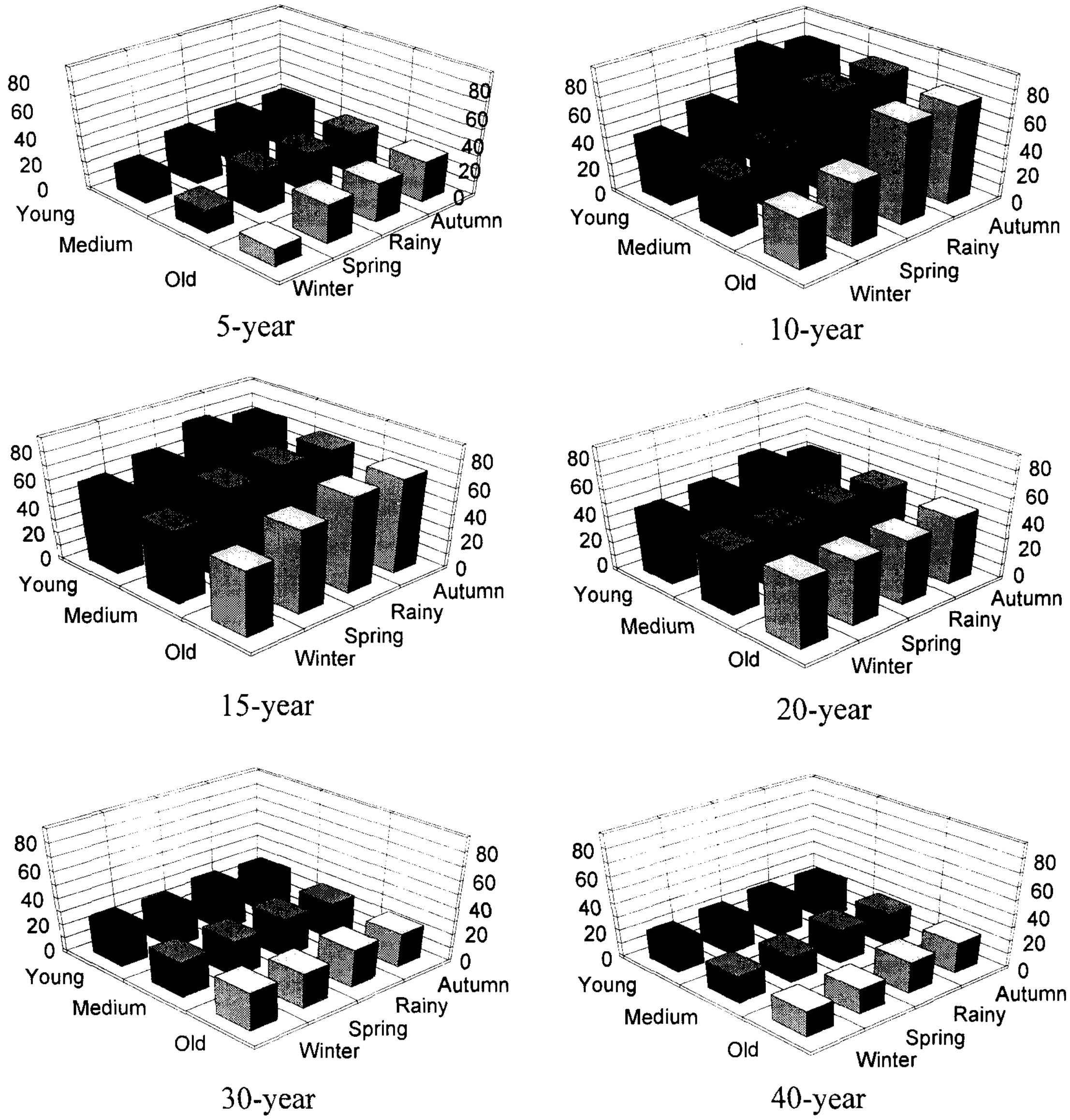


Fig. 5.2. Seasonal variation in active root nodule biomass (kg ha^{-1}) in an age series of *Alnus*-cardamom plantation stands. *ANOVA* : Stand ages $F_{5,144}$ = 6218, P<0.0001; Nodule ages $F_{5,144}$= 220, P<0.0001; Seasons $F_{3,144}$ = 1047, P<0.0001; Stand age x Nodule age, $F_{10,144}$ = 6.7, P<0.0001; Stand age x Season $F_{1,5}$144 = 192, P<0.0001; Nodule age x Season, $F_{6,144}$ = 5.2, P<0.0001; Stand age x Nodule age x Season $F_{30,144}$ = 4.6, P<0.0001; LSD (0.05) = 0.48.Tukey's pairwise mean difference probabilities are: between stand age - 5- with 10-, 15- and 20-year (P<0.0001), 10- with 15-year (P<0.025), 10- with 20- 30- and 40-year (P<0.0001), 15- with 20-, 30- and 40-year (P<0.0001), 20- with 30- and 40-year (P<0.0001); between season - winter with spring and autumn (P<0.0001), spring with rainy and autumn (P<0.0001), and rainy with autumn (P<0.014); and between nodule age-class differences were not significant.

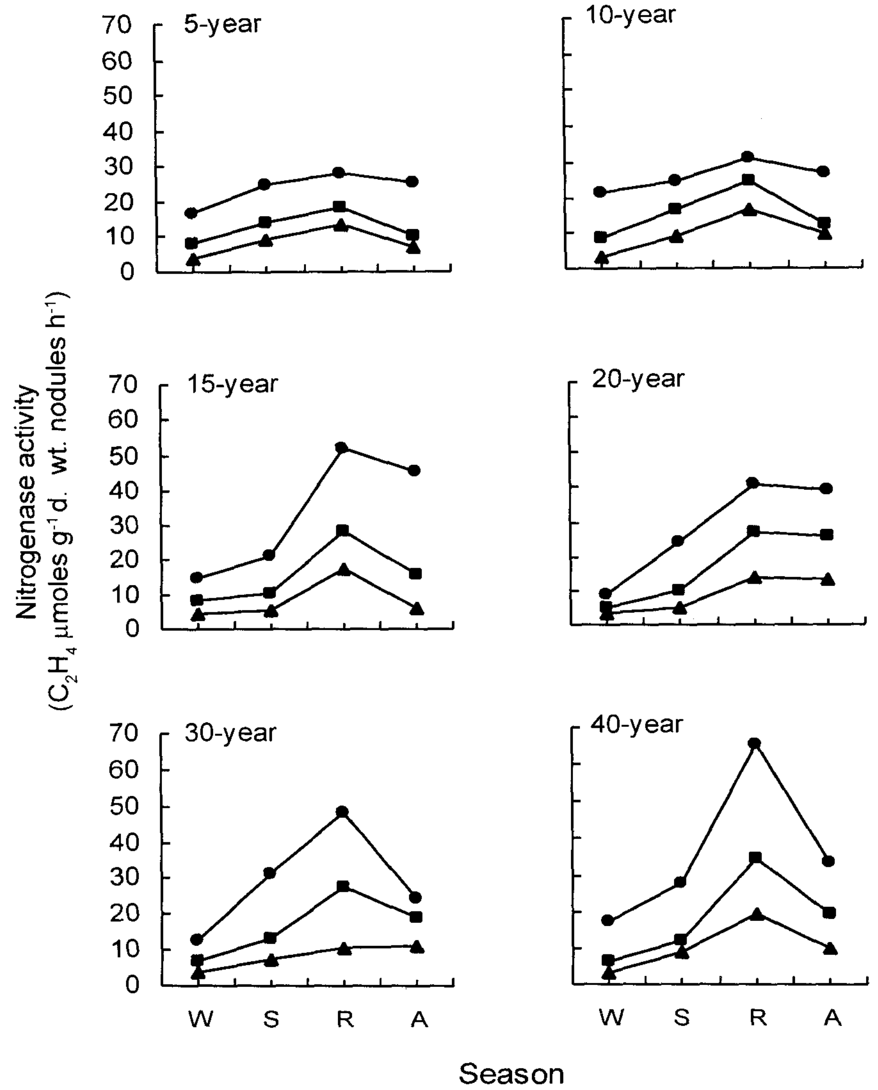


Fig. 5.3. Seasonal variation in nitrogenase activity in the young (●), medium (■) and old (▲) root nodules of *Alnus* in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates. ANOVA showed significant variation between stand age ($F_{5,144}$=1102; P<0.0001), season ($F_{3,144}$=2521, P<0.0001) and nodule age-class ($F_{2,144}$=3917; P<0.0001), all interactions were also singificant. Tukey's pairwise mean difference probabilities are: between stand age- 5- with 10- (P<0.001), 15- (P<0.0001), and 20-year (P<0.01); 10- with 30- and 40-year (P<0.003); 15- with 30 and 40-year (P<0.0001); and 20- with 30-year (P<0.05); between season- winter with rainy and autumn (P<0.0001), spring with rainy (P<0.0001 and autumn (P<0.023); and rainy with autumn (P<0.007); between nodule age-class- young with medium and old (P<0.0001), medium with old (P<0.006). W=winter, S=spring, R=rainy, A=autumn

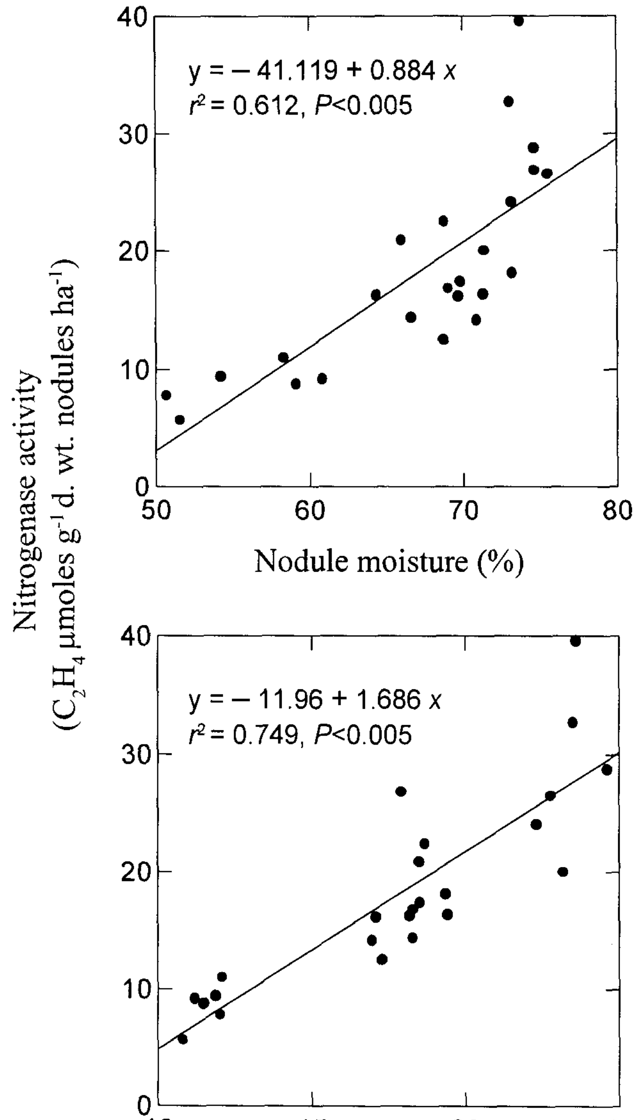


Fig. 5.4. Relationships between nitrogenase activity of root nodules of *Alnus* with its moisture and soil temperature in the age series of *Alnus*-cardamom plantation stands.

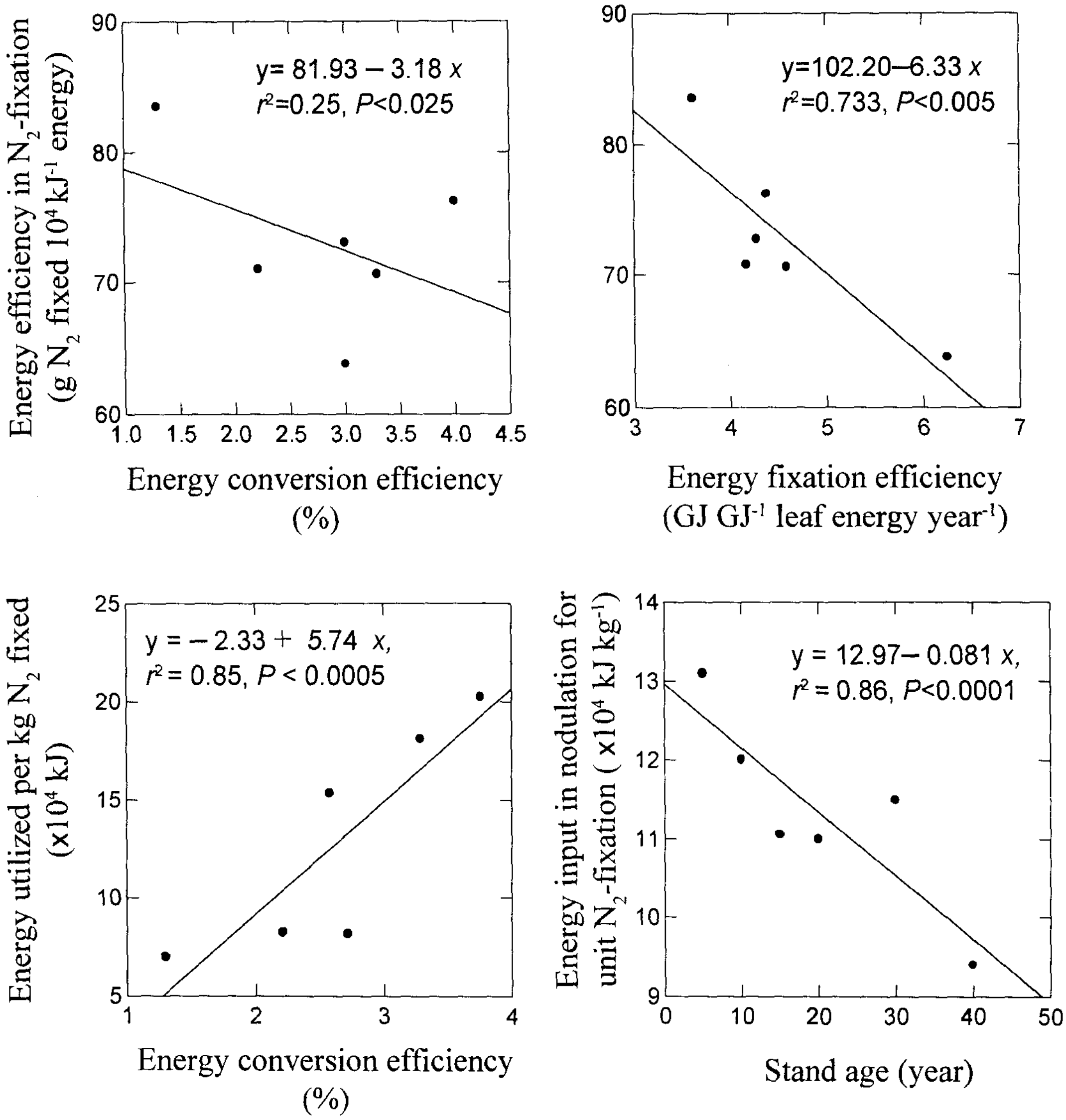


Fig. 5.5. Relationships between energy efficiency in N_2-fixation with energy conversion efficiency and energy fixation efficiency, and energy utilized per kg N_2 fixed with energy conversion efficiency; and net energy input in nodulation for unit N_2-fixation with stand age in the age series of *Alnus*-cardamom plantation stands.

Chapter VI

LITTER DECOMPOSITION

6.1 Introduction

In both natural and plantation agroforestry nutrient cycling is dominated by litter production and decomposition. During litter breakdown, release of plant nutrients occurs through microbially mediated bio-chemical reactions. Mineralized nutrients are available for the uptake by the plant community.

Intensive studies have been carried out in many parts of the world (Bray and Gorham 1964; Hopkins 1966; Fogel and Cromack 1977; Meentemeyer 1978; Birk and Simpson 1980; Sharma and Ambasht 1987; Sharma *et al.* 1997a) but most of the studies involve comparisons between litter decomposition of a single species at different sites or between different species within sites (Vogt *et al.* 1980; Melillo *et al.* 1982).

Studies on litter production and decomposition dynamics of managed agroforestry systems are limited. There has been a growing effort of inclusion of N_2-fixing species in plantation agroforestry systems in tropics and temperate regions, which in regard is a new intervention for influencing the soil fertility and quick nutrient dynamics. There are reports of much greater litter production in mixed stands of tree plantations with N_2-fixing associate than in stands containing only non-N_2-fixing trees (Tarrant *et al.* 1969; Binkley *et al.* 1992b). The litter of N_2-fixing species generally decomposes faster and the addition of N_2-fixing tree litter may accelerate the decomposition of non-N_2-fixing litter types (Taylor *et al.* 1989). The ratio of lignin: N and C:N ratio predicts litter decomposition well in temperate forests (Berg and McClaugherty 1987). The decomposition of N-fixing litter is typically much higher than those of other species, although decomposition rates can vary substantially among N_2-fixing trees (Sankaran *et al.* 1993; Mwiinga *et al.* 1994).

Inclusion of N_2-fixing *Alnus* in the cardamom based agroforestry systems in the eastern Himalaya is a good example for understanding the impact of stand age in the performance of mixtures of N_2-fixing and non-N_2-fixing plants. Reports on accelerated cycling of N and P in the mixed stands of N_2-fixing *Alnus* and *Albizia* in North America and Hawaii are available (Binkley *et al.* 1992b; Cote and Camire 1987; Tarrant *et al.* 1969). The greater N content of the litter in the N_2-fixing stands is attributable to N_2-fixation while greater P cycling in mixed cropping with N_2-fixing species hence been explained as: greater rooting depth (Malcolm *et al.* 1985), rhizospheric acidification (Gillespie and Pope 1990), production of low molecular weight acid and chelates (Ae *et al.* 1990), and increased phosphatase activity (Ho 1979). The N_2-fixing species conserves less nutrient compared to non-N_2-fixing species and hence, contributed more of these nutrients in their litter which results in greater cycling (Sharma *et al.* 1994, 1995). However, information of the mixtures of N_2-fixing and non-N_2-fixing stands on litter decomposition, its dynamics and nutrient and energy release with respect to their stand age and maturity is lacking.

This chapter examines the litter production, decomposition and pattern of nutrient and energy release in an age series of *Alnus*-cardamom plantation stands. The main objectives of the study were to determine (i) seasonal patterns of litter decomposition rates in the different stands, (ii) nutrients release and energy loss, (iii) relationships between decomposition rates, litter quality and environmental factors, and (iv) relationship between decomposition constant as a function of initial lignin: N ratio in the age series of *Alnus*-cardamom plantation stands.

6.2 Materials and methods

6.2.1 Litter decomposition

Sample plots of 30×40 m were marked at each of the six *Alnus*-cardamom plantation stands (5-, 10-, 15-, 20-, 30- and 40-year stand) of all the three sites. Litter decomposition studies were carried out by using litterbag technique (Witkamp and Olson 1963; Edmonds 1980; Bocock *et al.* 1960; Wieder *et al.* 1983; Sharma and Ambasht 1987). The rate of decomposition of fallen litter was measured by deploying nylon litterbags (20×20 cm) with a mesh size of 1 mm. Freshly fallen litter and slashed off cardamom pseudo-stem and leaves were collected during late December 1997. Monthly litter production estimations were carried out for a two year period (1998–1999) using five litter traps of 1 m^2 collecting area in each sample plots and pooled to annual values (see Chapter IV). Litter samples were air-dried. The equivalent of 10 g dry weight litter from air dried stock was placed in each litterbag. This litter weight per unit area of litterbags falls within the range of annual litter production weights per unit area on the floor. Four major litter fractions viz. *Alnus* leaf, *Alnus* twig, cardamom leaf and cardamom pseudo-stem was considered for decomposition. A total of 864 litterbags were placed within an area of 4×4 m in 18 plots (288 m^2) in January 1998. Litterbags containing litter fractions were retrieved in replicates of three at each collection time of 3, 6, 12 and 24 months from the date of placement for analysis. The collected litter samples were taken to the laboratory and dried immediately at 80°C to constant weight and kept for analysis.

6.2.2 Rainfall, moisture and temperature determinations

Rainfall data was recorded using automatic weather station (Campbell Scientific Inc. USA). Temperature measurements were made using a soil thermometer which was placed within the litter-soil interface at every stand. The litter temperature reading were noted at 30 minute intervals for 3 h (08.00–09.00; 12.00–13.00 and 16.00–17.00 h) for at least 3 times in alternate days during each sampling times, and the mean litter temperature was calculated. Litter moisture of the bagged litter fractions and freshly fallen litter was determined and expressed on a dry weight basis after drying at 80°C for 48 h during every retrieval time.

6.2.3 Analytical methods

The soil particles adhering to the bagged litter samples were removed with gentle brushing. Cleaned litter fractions were oven-dried at 80°C for 48 h, weighed and ground to pass through a 2-mm sieve. Ground samples were analyzed for total nitrogen by modified Kjeldahl method and phosphorus following ascorbic acid method (Anderson an Ingram 1993). Lignin of the decomposing litter fraction was estimated by using Tecator Fibertec system. Carbon contents of the plant samples were estimated by assuming 48% carbon at different stages of decomposition (Edmonds 1980, Sharma and Ambasht 1987). Energy value on ash-free mass basis was estimated by using oxygen bomb calorimeter (Lieth 1975). The sum of the heat release values from different stages of decomposing litter samples per year represented the total heat release from the floor-litter.

6.2.4 Statistical analysis and decomposition constant

All statistical analysis were made using Systat version 6.0, (1996). Per cent nutrient and energy release of each litter fraction was determined and annual release calculated. Observed losses of ash-free mass, N, P and energy contents from decomposing litter fractions were described by a single exponential decay function. The half life ($T_{1/2}$) was calculated using the decomposition constant (*k*) as 0.693/k (Olson 1963).

6.3 Results

6.3.1 Loss of ash free mass

Per cent ash content ranged between 3.05–16.30 in the litter fraction with highest value in *Alnus* leaf and lowest in pseudo-stem at different stages of decomposition (Table 6.1–6.6). Ash content was low in the freshly fallen litter. As the decomposition progressed, per cent ash increased consistently with time and showed highest concentration at 24 months of decomposition. The per cent ash content in *Alnus* leaf was much higher than other litter fractions until final stages of decomposition in all the plantation ages.

Ash free mass remaining in decomposing litter fraction at each sampling date decreased significantly ($P<0.0001$) (Table 6.7–6.12). Analysis of variance showed significant variation between stand age, retrieval date and litter fraction. Interactions between all these dependent variables were also significant. Tukey's pariwise mean difference probabilities between the plantation stands were not significant (Table 6.13). Pairwise differences between the different retrieval dates were highly significant ($P<0.0001$). Differences between the litter fractions were significant between cardamom pseudo-stem with *Alnus* leaf ($P<0.0001$) and *Alnus* twig ($P<0.004$) with cardamom pseudo-stem ($P<0.0001$). Differences between other litter fractions were not significant. The ash-free mass remaining in the *Alnus* leaf ranged within 15−32%, *Alnus* twig 28−47%, cardamom leaf 17−38% and pseudo-stem 18−41%, during the 24 months of decomposition in the age series of plantations (Table 6.7−6.12).

Decomposition and ash-free mass loss were not conspicuous during first three month period of decomposition and showed 15−20% of the initial mass loss. In the first six month more than 30−40% of initial mass (>50% of the 24 months of decomposition) was lost in the all the stands (Fig. 6.2a, b & c). After six month period of decomposition in 5- to 40-year of plantation age the stand to stand differences were relatively high and significant. During the first six month of decomposition the environmental factors relating to decomposition (warm rainy season) were favourable. The loss rate was extremely slow during moist winter conditions and was lowest in the subsequent dry winter and dry summer seasons. Patterns of ash-free mass loss in different litter fractions during 24 months of decomposition period was *Alnus* leaf>cardamom leaf>cardamom pseudo-stem>*Alnus* twig while within the stand ages it was in the order 15>10>5>20>30>40-year stand. The absolute loss of ash-free mass in 5-, 15- and 40-year stand are presented in Figure 6.2a, b & c. The $T_{1/2}$ values of ash-free mass among the litter fractions was lowest in *Alnus* leaf (8.84−14.85 months) and highest in *Alnus* twig (13.41−17.69 months) indicating that the mass loss was much more rapid in leaf liter in N_2-fixing *Alnus* than other plant components litter (Table 6.14−6.19). The half life and turnover time of ash-free mass was lowest (8.84–13.41; 12.76–19.35) in the 15-year stand with high decomposition constant (0.62–0.94) (Table 6.16). Decomposition constant was lowest (0.43–0.57) in the 40-year stand with corresponding high value of half life and turnover time of the litter fractions. In the age series of plantation stands *k* value was in the order 15>20>10>5>30>40-year stand.

In the litter fractions, the loss of ash-free mass during a year was highest in *Alnus* leaf followed by cardamom leaf and pseudo-stem and lowest in *Alnus* twig in the entire plantation stands. The single exponential decay functions show that the *k* values decreased with plantation stand maturity, indicating that loss was faster in younger stands.

6.3.2 Nutrient loss and release

Nitrogen and P concentrations in the decomposing litter fractions increased throughout to be highest at the final sampling (Table 6.1–6.6) while per cent weight remaining decreased with advancing decomposition period (Table 6.7–6.12). The concentrations of N and P in *Alnus* leaf were higher than cardamom leaf in all the plantation ages. At each sampling date, nutrients (N and P) remaining in decomposing litter fractions decreased significantly. An inverse relationship was obtained between the per cent weight remaining and N concentration in the residual litter fraction in the age series of plantations (Fig. 6.1).

Nitrogen concentration of litter fractions increased from the initial along the decomposition period. Analysis of variance between the stand ages, retrieval dates and litter fractions were significant (Table 6.13). All other interactions were also significant. Tukey's pairwise mean differences probabilities showed significant ($P<0.0001$) differences between the retrieval dates. Within the litter fractions, pairwise comparison was significant between cardamom pseudo-stem and *Alnus* leaf. The 15-year stand consistently lost more N from the litter bags than in the other stands (Fig. 6.2a, b & c) while 40-year showed the least. The N turnover time and half life in decomposition at all the stands were in the order 15>20>10>5>30>40-year stand (Table 6.14-6.19). Within litter fractions, the half life and turnover time of N in *Alnus* leaf was lowest followed by cardamom leaf and pseudo-stem and highest in *Alnus* twig.

The quantities of N released per unit area were highest in 15-year stand (36.56 g m^{-2}) which was 1.6 times that of 5- and 2.5 times that of 40-year stand (Fig. 6.2a, b & c).

Phosphorus remaining in the decomposing litter fraction showed significant ($P<0.0001$) variation between stand age, retrieval date and litter fraction in the analysis of variance. All interactions were also significant. Tukey's pair wise mean difference probabilities between the plantation stands and litter fractions were not significant but was significant between the retrieval dates (P<0.0001). Phosphorus loss from the bagged litter was highest in the 15-year stand and lowest in the 40-year stand (Table 6.7–6.12). Within the litter fractions, P loss was comparatively more in *Alnus* leaf followed by cardamom leaf in all the plantation stands. The initial percentage of labile fraction of N was more than the P. The decomposition constant and turnover time of P ranged between 0.64–0.88 (highest) in *Alnus* leaf and 0.40–0.83 (lowest) in *Alnus* twig. The turnover time of P in the *Alnus* leaf and twig, cardamom leaf and pseudo-stem differ much within the plantation age in the order 15>20>10>5>30>40-year stand.

Phosphorus release per unit area in 24 months was highest (3.92 g m^{-2}) in the 15-year stand and lowest (1.12 g m^{-2}) in the 40-year stand (Fig. 6.2a, b & c). The absolute release of nutrients in the age sequence was 15>20>10>5>30>40-year stand. The release of nutrient (6.02–10.84 g m^{-2} N and 0.48–1.59 g m^{-2} P) was highest in the first 6 months and declined gradually with time. The nutrient loss and release pattern were same for all plantation ages and relative mobility of nutrients was P>N, the absolute release of N in comparison to P was 10–15 times higher in different stands.

The k value was comparatively higher for P than N in the litter fractions with consequence that $T_{1/2}$ values were short for P. The $T_{1/2}$ values for both N and P leaf litter were lower indicating a faster decomposition.

6.3.3 Energy loss

Energy content of the litter fraction decreased significantly at every retrieval dates from the initial values throughout the 24 months study period in all the plantation stands (Table 6.1−6.6). Mean caloric content of *Alnus* leaf was highest followed by cardamom leaf, *Alnus* twig and cardamom pseudo-stem. At each retrieval date the absolute energy content in decomposing litter fractions decreased significantly (Table 6.7−6.12). Analysis of variance indicated that the stand age effect, date effect, litter fractions and multiple interactions were significant ($P<0.0001$) (Table 6.13). Tukey's pairwise comparison probabilities showed highly significant ($P<0.0001$) differences between different retrieval dates but was not significant between the stand ages. Pairwise comparison probabilities between *Alnus* leaf with cardamom leaf and cardamom pseudo-stem ($P<0.02$), *Alnus* twig with cardamom leaf and cardamom pseudo-stem and cardamom leaf with pseudo-stem were significant ($P<0.0001$).

The energy loss was highest in the 15-year stand and pairwise comparisons at each sampling date showed significant variations. The $T_{1/2}$ values (7.09−9.45 months) and turnover time (11.43−13.64 months) for energy was lowest in decomposing litter at the 15-year stand (Table 6.16). The half life and turnover time of energy in *Alnus* leaf was lowest (7.09−9.56; 11.43−13.39 months) among the litter fractions in the entire plantation stands (Table

6.14–6.19). The mean litter energy content loss per unit area was highest (55024 kJ m^{-2}) in the 15-year stand. The pattern of energy content loss was similar in all the plantation ages while the sequence of decrease in absolute energy loss was 15>20>10>5>30>40-year stand (Fig. 6.2a, b & c). The sampling interval and cumulative loss from the decomposing litter fraction showed that a considerable amount of energy was lost during 24 months, with highest loss (30–40%) during first 6 month period in all the stands. The loss of energy from the litter fraction was more in *Alnus* leaf and less in *Alnus* twig in the plantation ages. Loss of energy contents from the litter fractions in the plantation stands after 6 month period were relatively uniform and closely resembled ash-free mass losses.

6.3.4 Lignin

The percent initial lignin and initial lignin: N content in litter fractions are given in Table 6.20. Per cent lignin was highest in *Alnus* leaf that was 1.2, 1.53 and 1.46 times that of *Alnus* twig, cardamom leaf and pseudo-stem, respectively. Lignin: N ratio was highest in cardamom pseudo-stem followed by *Alnus* twig, cardamom leaf and *Alnus* leaf. Inverse curvilinear relationships exist between *k* values of ash-free mass and N expressed as a function of initial lignin: initial N concentration in the regression analysis (Fig. 6.3).

6.3.5 Relationships between decomposition rates, litter quality and environmental factors

Mean litter temperature (soil litter interface) and mean per cent moisture of decomposing litter for 24 month period are presented in Figure 6.4. The first three to six month period (April-June) had the highest average litter temperature and per cent litter moisture while minimum average temperature and per cent moisture was recorded during 12 and 24 month (Fig. 6.4).

Multiple regression analysis was carried out to understand the relationships of ash-free mass with the C:N, C:P and N:P ratios remaining in litter on all the retrieval dates for each plantation stand, but the ash-free mass appeared to be strongly related to the C:N ratio only. Thus, relationships between the ash-free mass and C:N ratio was observed in the simple linear regression analysis. It showed that the reduction in the ash-free mass remaining for all the litter fractions in the bags was associated with narrowing of the C:N ratio in the plantation stands. Analysis of covariance indicated that the relationships between ash-free mass remaining as a function of C:N ratio of litter fractions was highly significant (Fig. 6.5).

The relative loss rate of ash-free mass, nutrient and energy content was strongly related to C:N ratio, litter temperature and litter moisture (Table 6.21). Relative loss rate of ash-free mass and nutrients of the litter fractions depended more strongly on litter quality followed by litter temperature and then litter moisture, whereas in the case of energy, litter temperature had greater effect than C:N ratio and litter moisture.

6.4 Discussion

The maximum litter decomposition was reported at the time of canopy closure (20- to 30-years age) using the production to accumulation ratio in Douglas fir stands (Turner and Long 1975). It was supported by *k*-values based on litter bag technique after 12 month decomposition in the same stands (Edmonds 1979). Sharma and Ambasht (1987) reported the maximum decomposition at the time of canopy closure in a 30-year *Alnus nepalensis* stands. In the present study, using both the above methods maximum decomposition and heat release was recorded in the younger stands (10- to 15-year stand) with full canopy closure which declined with decrease in tree density and crown cover. Decomposition constant (*k*) in these stands was highest (0.59–1.05) with lowest half life (7.09–14.09 month) and turnover time (11.43–20.34 month). The *k* value, half life and turnover time was lowest at the 40-year stand which is attributed to the low canopy closure and low tree density factor. The loss of initial ash-free mass after one year of decomposition was 46–67%. This rate is comparable to 46–61% loss of ash-free mass per year in *A. nepalensis* (Sharma and Ambasht 1987) and 55% decomposition per year in *A. rubra* (Edmonds 1980) and *A. crispa* (Van Cleve 1971).

Decomposition rates of all the litter fractions are predicted from the lignin or nutrient (N and P) content, the C:N ratio and lignin: N ratio. In the present study, inverse curvilinear relationship between the decomposition constants of ash-free mass and N expressed as a function of ratio of initial lignin: N content was observed in the regression analysis indicating that high levels of lignin may slow decomposition rates (Aber and Melillo 1982). A significant non-linear relationship was reported between relative initial proportions of labile to recalcitrant fraction of both initial lignin content and initial C:N ratio (Wieder and Lang 1982). Initial lignin content or initial C:N ratio of litter determines the decomposition rate to a considerable extent (Meentemeyer 1978; Melillo *et al.* 1982). In the present study, decomposition was slow at high initial lignin: initial N and C:N ratio. The relationship suggests that higher the lignin content of the litter fraction, larger the change in the N concentration of the material per unit carbon respired during decomposition (Aber and Melillo 1982).

At all the plantation stands, litter exhibited an increase in N concentration during decomposition but the absolute N content decreased from the beginning. This was also reported in *A. glutinosa* and *A. nepalensis* litter decomposition (Bocock 1964; Sharma and Ambasht 1987). The reason would be due to the microbial invasion in litter fractions, mineralization of nutrients in soils and microbial immobilization during the process of decomposition. Sharma *et al.* (1994) reported N and P immobilization in litter fractions in 8-year-old *Alnus*-cardamom stands.

In *A. rubra* (Edmonds 1980) and *A. nepalensis* (Sharma and Ambahst 1987) stands P was found to be rapidly lost in the first three months and absolute weights never exceeded initial weights. Phosphorus loss in this study was relatively high during the first six month of decomposition in all the plantation stands. Phosphorus release per unit area was highest at the 15-year stand (3.92 g m^{-2}) and lowest (1.25 g m^{-2}) in the 40-year stand. The initial C:P ratio of the (300–686) litter fractions in all the plantation stands was comparable to *A. rubra* (574) and *A. nepalensis* (637) stands (Edmonds 1980; Sharma and Ambasht 1987). High rainfall during 3–6 month of decomposition may be the reason for rapid P loss. The pattern of release of P from a unit area of floor was similar in all the plantation stands.

The proportion of ash-free mass and energy content in the decomposition bags within 24 month period of study declined at different absolute and relative rates in all the plantation stands. The loss of nutrients indicated approximately uniform absolute and relative rates in the entire stands across the sampling dates. Energy release in the form of heat was substantial in 15-year stand. The energy value per unit weight of the residual ash-free mass of decomposing litter decreased across the entire decomposition period. Absolute energy content also decreased considerably with 81–88% loss during the 24 month period.

Relative decomposition rate of ash-free mass, N and P were significantly related to C:N ratio, litter temperature and moisture in the multiple regression analysis. Linear regression of ash-free mass remaining as a function of the C:N ratio of retrieved litter from decomposition litter bags in the age series of *Alnus*-cardamom plantations showed a strong positive relationship. The ash-free mass release and nutrient mineralization were also related to C:N ratio, with high partial regression coefficients of C:N ratio for nutrient mineralization.

The ash-free mass, nutrient and energy release during the first 6 month of decomposition was highest which is attributable by a high rate of loss of labile fractions and by the most favourable environmental conditions for decomposition. Each fraction of litter decomposes at a specific rate and is variably dependent on resource quality (C:N ratio, lignin: N ratio) and largely contributed by environmental factors (Sandhu *et al.* 1990; Sharma and Ambasht 1987). The lignin: N and C:N ratio of the litter fractions played a more important role in determining the rate of litter decomposition than litter moisture and temperature although the role of moisture and temperature was quite significant. The relative loss rate of 60–90% of the ash-free mass, nutrients and energy were determined to be related to litter quality and environmental factors.

The release of nutrients due to rapid decomposition from nutrient rich litter of *Alnus* make nutrients more available for uptake by associates, and with time, nutrient cycle is expected to be accelerated, even in the non-N_2-fixing associate. This provides better production potential for associate crops in the stands with nitrogen fixers (Sharma *et al.* 1997a). The magnitude of release of nutrients and energy in the younger plantations were rapid indicating accelerated nutrient cycling through litter production, decomposition and heat sink than the older stands beyond 20 years age. This is explained by high tree density, crown cover, litter production, resource quality, cardamom crop management and environmental factors in these stands. The N_2-fixing *Alnus* in the cardamom based agroforestry systems have influenced the accelerated nutrient cycling and energy dynamics through litter production and greater release of nutrients and energy to the soil. The intensity of these processes was highly phenomenal and observed considerably high in younger plantations up to 20 years of age ❖

Table 6.1. Ash-free mass, per cent ash, nutrient concentration and caloric value of decomposing litter in different retrieval dates in 5-year *Alnus*-cardamom plantation stand. Values are mean ±SE, *n*=9

Retrieval date	Litter fraction	Ash-free mass (g)	Ash (%)	Moisture (%)	Nitrogen (%)	Phosphorus (%)	Caloric value (cal g^{-1})
Jan. 1998 (0 time)	*Alnus* leaf	9.69±0.98	3.05±0.06	49.61±2.81	2.73±0.21	0.17±0.012	5304±311
	Alnus twig	9.62±1.02	3.81±0.13	31.93±2.74	0.95±0.01	0.10±0.001	4497±425
	Cardamom leaf	9.56±0.87	4.37±0.07	57.48±4.61	1.59±0.12	0.15±0.011	4706±132
	Cardamom pseudo-stem	9.55±0.89	4.54±0.09	39.09±2.41	0.56±0.02	0.13±0.023	3571±464
April 1998 (3 month)	*Alnus* leaf	8.62±0.17	4.65±0.07	48.38±4.26	2.83±0.08	0.18±0.011	4841±435
	Alnus twig	8.70±0.24	4.06±0.07	40.60±2.24	0.96±0.01	0.10±0.001	4273±325
	Cardamom leaf	7.99±0.12	4.71±0.28	40.30±1.56	1.69±0.01	0.13±0.002	4593±265
	Cardamom pseudo-stem	8.09±0.15	5.07±0.21	46.04±2.82	0.68±0.01	0.09±0.003	3079±214
July 1998 (6 month)	*Alnus* leaf	5.71±0.14	6.49±0.09	82.28±4.46	2.95±0.05	0.21±0.051	4870±421
	Alnus twig	8.09±0.25	4.13±0.06	66.77±3.41	0.94±0.02	0.13±0.020	4396±325
	Cardamom leaf	7.63±0.26	5.53±0.19	84.41±4.92	1.73±0.11	0.15±0.020	4270±315
	Cardamom pseudo-stem	7.05±0.15	4.83±0.11	83.71±6.79	0.69±0.02	0.14±0.011	4281±326
Jan 1999 (12 month)	*Alnus* leaf	3.32±0.16	6.75±0.44	43.42±2.81	3.12±0.04	0.14±0.012	3705±325
	Alnus twig	5.74±0.14	4.27±0.08	44.71±4.38	0.98±0.04	0.10±0.001	3684±215
	Cardamom leaf	4.27±0.13	6.45±0.26	38.21±5.21	1.86±0.01	0.13±0.001	3840±265
	Cardamom pseudo-stem	4.18±0.15	7.61±0.14	47.29±3.59	0.89±0.01	0.11±0.004	2973±254
Jan 2000 (24 month)	*Alnus* leaf	2.10±0.06	13.36±0.7	50.93±2.51	3.29±0.04	0.14±0.004	3641±451
	Alnus twig	3.25±0.05	7.15±0.42	45.82±3.51	1.01±0.03	0.18±0.005	2783±512
	Cardamom leaf	1.81±0.16	9.26±0.29	51.56±2.14	2.19±0.01	0.14±0.041	2041±126
	Cardamom pseudo-stem	2.59±0.13	8.31±0.41	46.42±1.98	0.92±0.03	0.07±0.003	2182±215

Table 6.2. Ash-free mass, percent ash, nutrient concentration and caloric value of decomposing litter in different retrieval dates in 10-year *Alnus*-cardamom plantation stand. Values are mean ±SE, *n*=9

Retrieval date	Litter fraotion	Ash-free mass (g)	Ash (%)	Moisture (%)	Nitrogen (%)	Phosphorus (%)	Caloric value (cal g^{-1})
Jan. 1998 (0 time)	*Alnus* leaf	9.69±1.20	3.09±0.15	52.68±4.61	2.14±0.01	0.13±0.002	4718±513
	Alnus twig	9.61±0.99	3.87±0.14	31.32±4.21	1.17±0.06	0.16±0.002	4309±345
	Cardamom leaf	9.64±1.03	3.64±0.22	58.41±2.78	1.76±0.01	0.13±0.006	3546±234
	Cardamom pseudo-stem	9.58±1.03	4.25±0.13	57.25±4.23	0.68±0.01	0.12±0.001	4487±654
April 1998 (3 month)	*Alnus* leaf	8.15±0.45	4.48±0.18	62.55±2.77	2.62±0.24	0.15±0.006	4886±354
	Alnus twig	8.77±0.48	4.27±0.07	50.80±2.36	1.19±0.02	0.13±0.011	4087±321
	Cardamom leaf	8.28±0.19	4.96±0.18	63.39±3.53	1.87±0.06	0.13±0.002	3098±231
	Cardamom pseudo-stem	8.88±0.27	5.41±0.11	65.86±1.53	0.69±0.17	0.12±0.002	4267±341
July 1998 (6 month)	*Alnus* leaf	6.25±0.13	5.86±0.22	79.42±4.61	2.69±0.05	0.18±0.012	4889±453
	Alnus twig	7.95±0.34	4.35±0.91	69.80±5.20	1.20±0.05	0.16±0.003	4298±241
	Cardamom leaf	7.55±0.82	5.68±0.17	73.21±4.92	1.78±0.05	0.13±0.013	3178±231
	Cardamom pseudo-stem	7.37±0.58	5.45±0.31	74.44±5.21	0.68±0.19	0.13±0.025	4386±233
Jan 1999 (12 month)	*Alnus* leaf	3.99±0.35	6.79±0.11	47.27±8.21	3.07±0.01	0.13±0.001	3767±211
	Alnus twig	5.74±0.70	4.75±0.18	42.39±8.61	1.25±0.04	0.10±0.001	2565±215
	Cardamom leaf	5.33±0.39	6.45±0.02	53.51±2.41	1.99±0.01	0.11±0.009	2978±435
	Cardamom pseudo-stem	4.28±0.55	7.64±0.14	53.42±4.72	0.66±0.16	0.11±0.009	3887±432
Jan 2000 (24 month)	*Alnus* leaf	1.66±0.06	13.12±0.6	46.76±2.31	3.11±0.13	0.15±0.006	3467±432
	Alnus twig	2.95±0.12	8.02±0.21	40.12±1.23	1.26±0.03	0.15±0.002	2034±423
	Cardamom leaf	1.36±0.13	9.14±0.19	53.23±3.43	2.07±0.07	0.14±0.001	2487±342
	Cardamom pseudo-stem	2.50±0.07	9.56±0.44	54.23±34	0.72±0.07	0.11±0.002	2768±231

Table 6.3. Ash-free mass, percent ash, nutrient concentration and caloric value of decomposing litter in different retrieval dates in 15-year *Alnus*-cardamom plantation stand. Values are mean ±SE, n=9

Retrieval date	Litter fraction	Ash-free mass (g)	Ash (%)	Moisture (%)	Nitrogen (%)	Phosphorus (%)	Caloric value (cal g^{-1})
Jan. 1998 (0 time)	*Alnus* leaf	9.78±1.12	3.36±0.11	46.43±4.23	2.44±0.14	0.16±0.003	5354±242
	Alnus twig	9.60±1.32	3.99±0.10	31.78±3.41	1.03±0.08	0.11±0.005	4756±354
	Cardamom leaf	9.62±1.13	3.83±0.05	58.61±4.21	1.37±0.03	0.16±0.021	44.54±343
	Cardamom pseudo-stem	9.54±1.03	4.64±0.09	36.80±4.21	0.57±0.06	0.10±0.002	3576±343
April 1998 (3 month)	*Alnus* leaf	8.13±0.10	4.68±0.15	59.87±1.08	2.58±0.03	0.16±0.004	4876±231
	Alnus twig	8.61±0.12	4.20±0.06	51.08±1.32	1.83±0.05	0.09±0.001	4076±342
	Cardamom leaf	8.26±0.01	4.79±0.06	64.26±1.01	1.45±0.02	0.16±0.023	4278±234
	Cardamom pseudo-stem	8.54±0.19	5.18±0.19	70.67±1.96	0.59±0.05	0.10±0.003	3276±324
July 1998 (6 month)	*Alnus* leaf	6.15±0.61	5.91±0.16	78.86±3.41	2.82±0.06	0.14±0.005	4679±231
	Alnus twig	7.51±0.34	5.49±0.16	69.07±5.21	1.09±0.01	0.10±0.008	4287±243
	Cardamom leaf	7.13±0.78	5.88±0.15	79.57±6.71	1.69±0.04	0.12±0.012	4196±265
	Cardamom pseudo-stem	7.56±0.26	5.66±0.12	78.26±6.87	0.66±0.43	0.10±0.004	3169±221
Jan 1999 (12month)	*Alnus* leaf	3.82±0.21	7.92±0.21	43.27±5.28	2.91±0.03	0.13±0.003	4764±276
	Alnus twig	4.99±0.31	6.11±0.31	38.41±4.21	1.16±0.07	0.11±0.003	2967±234
	Cardamom leaf	5.25±0.11	7.49±0.22	52.38±3.21	1.76±0.01	0.12±0.005	3967±352
	Cardamom pseudo-stem	4.49±0.21	8.31±0.13	41.43±2.43	0.71±0.05	0.13±0.004	3067±334
Jan 2000 (24 month)	*Alnus* leaf	1.50±0.23	16.3±0.13	42.58±3.54	3.45±0.10	0.17±0.001	4264±265
	Alnus twig	2.79±0.13	9.48±0.05	42.21±2.13	1.46±0.06	0.08±0.002	3787±323
	Cardamom leaf	1.70±0.36	10.6±0.62	50.12±1.23	2.16±0.15	0.09±0.003	2198±154
	Cardamom pseudo-stem	1.95±0.12	9.55±0.29	45.13±3.56	1.08±0.03	0.05±0.004	2998±276

Table 6.4. Ash-free mass, per cent ash, nutrient concentration and caloric value of decomposing litter in different retrieval dates in 20-year *Alnus*-cardamom plantation stand. Values are mean ±SE, n=9

Retrieval date	Litter fraction	Ash-free mass (g)	Ash (%)	Moisture (%)	Nitrogen (%)	Phosphorus (%)	Caloric value (cal g^{-1})
Jan. 1998 (0 time)	*Alnus* leaf	9.68±1.02	3.15±0.23	52.01±3.81	2.42±0.003	0.14±0.005	5367±255
	Alnus twig	9.61±1.23	3.89±0.81	52.18±2.35	0.70±0.023	0.12±0.005	4712±234
	Cardamom leaf	9.64±1.03	3.58±0.81	49.76±1.94	1.63±0.127	0.17±0.006	4069±215
	Cardamom pseudo-stem	9.58±1.32	4.14±0.78	57.87±3.31	0.62±0.015	0.11±0.001	3545±235
April 1998 (3 month)	*Alnus* leaf	7.98±0.12	4.51±0.87	47.65±2.83	2.61±0.038	0.16±0.009	4856±465
	Alnus twig	8.59±1.11	4.38±0.98	38.54±4.21	0.75±0.018	0.15±0.015	4098±235
	Cardamom leaf	8.39±0.87	4.93±0.78	60.51±4.21	1.68±0.019	0.11±0.006	4289±256
	Cardamom pseudo-stem	7.99±0.54	5.02±0.72	47.06±2.81	0.85±0.156	0.11±0.004	3859±246
July 1998 (6 month)	*Alnus* leaf	5.82±0.12	5.22±0.12	75.97±4.21	2.77±0.016	0.25±0.003	4896±256
	Alnus twig	7.20±0.25	4.44±0.54	62.45±6.78	0.82±0.052	0.15±0.008	4256±356
	Cardamom leaf	7.45±0.11	5.51±0.87	83.41±7.21	1.72±0.042	0.23±0.004	4158±245
	Cardamom pseudo-stem	7.47±0.23	5.56±0.81	79.61±5.59	0.91±0.021	0.11±00.01	2878±267
Jan 1999 (12 month)	*Alnus* leaf	3.72±0.12	6.61±0.87	45.57±3.59	3.15±0.014	0.18±0.004	4378±164
	Alnus twig	6.35±0.65	4.79±0.69	41.53±4.31	0.89±0.03	0.11±0.003	2939±278
	Cardamom leaf	5.06±0.34	6.48±1.81	54.53±2.89	1.80±0.28	0.11±0.002	3759±267
	Cardamom pseudo-stem	3.79±0.54	7.69±0.81	51.54±4.51	1.61±0.087	0.09±0.002	3670±256
Jan 2000 (24 month)	*Alnus* leaf	1.56±0.54	10.90±1.83	48.97±4.32	3.41±0.047	0.18±0.008	4171±356
	Alnus twig	3.31±0.76	9.01±2.81	46.29±2.68	0.71±0.051	0.13±0.008	2654±223
	Cardamom leaf	2.10±0.76	9.89±1.11	50.21±3.61	2.15±0.311	0.18±0.007	3168±165
	Cardamom pseudo-stem	2.00±0.18	9.68±1.21	56.38±4.81	1.72±0.451	0.14±0.007	3158±268

Table 6.5. Ash-free mass, per cent ash, nutrient concentration and caloric value of decomposing litter in different retrieval dates in 30-year *Alnus*-cardamom plantation stand. Values are mean ±SE, *n*=9

Retrieval date	Litter fraction	Ash-free mass (g)	Ash (%)	Moisture (%)	Nitrogen (%)	Phosphorus (%)	Caloric value (cal g^{-1})
Jan. 1998 (0 time)	*Alnus* leaf	9.68±1.34	3.18±0.98	42.67±2.41	2.86±0.012	0.11±0.003	5314±211
	Alnus twig	9.60±0.54	3.98±0.91	29.73±1.21	0.94±0.021	0.09±0.001	4706±325
	Cardamom leaf	9.63±0.18	3.71±0.88	33.694.21	1.43±0.007	0.12±0.005	4571±132
	Cardamom pseudo-stem	9.57±0.67	4.33±0.11	36.34±2.41	0.52±0.003	0.10±0.002	4497±464
April 1998 (3 month)	*Alnus* leaf	8.64±1.21	4.56±0.98	40.67±4.98	2.95±0.54	0.15±0.08	4941±455
	Alnus twig	8.76±1.23	4.47±0.87	30.71±1.44	0.95±0.026	0.10±0.008	4394±235
	Cardamom leaf	8.72±2.16	5.11±0.79	48.72±3.57	1.51±0.011	0.14±0.02	4273±265
	Cardamom pseudo-stem	8.68±2.11	5.62±0.91	39.71±1.44	0.67±0.031	0.10±0.001	3079±214
July 1998 (6 month)	*Alnus* leaf	5.98±0.19	5.78±0.99	81.80±6.21	3.07±0.140	0.14±0.01	4870±421
	Alnus twig	7.29±0.87	4.46±0.88	69.08±4.37	0.96±0.023	0.07±0.005	4281±325
	Cardamom leaf	7.44±0.37	5.79±0.69	86.54±7.81	1.75±0.032	0.12±0.004	4396±315
	Cardamom pseudo-stem	7.52±0.07	5.91±0.69	80.74±6.86	0.80±0.042	0.10±0.003	3179±326
Jan 1999 (12 month)	*Alnus* leaf	4.26±0.38	6.88±1.30	45.51±5.23	3.49±0.052	0.14±0.003	4075±325
	Alnus twig	5.41±0.58	5.01±1.01	41.45±4.21	1.43±0.034	0.09±0.001	3973±215
	Cardamom leaf	4.54±0.65	6.59±0.86	39.41±3.29	1.96±0.021	0.17±0.002	3884±265
	Cardamom pseudo-stem	4.55±0.46	8.01±1.02	39.98±2.91	0.98±0.034	0.09±0.006	2540±243
Jan 2000 (24 month)	*Alnus* leaf	1.89±0.19	14.2±2.11	46.49±2.33	3.46±0.018	0.13±0.0.01	3658±351
	Alnus twig	2.73±0.46	7.80±2.32	45.62±3.16	1.19±0.129	0.12±0.005	3182±512
	Cardamom leaf	2.55±0.27	9.81±1.78	42.36±3.61	1.97±0.120	0.14±0.004	2783±126
	Cardamom pseudo-stem	3.25±0.03	9.67±.093	43.42±2.51	0.56±0.003	0.12±0.009	2241±215

Table 6.6. Ash-free mass, per cent ash, nutrient concentration and caloric value of decomposing litter in different retrieval dates in 40-year *Alnus*-cardamom plantation stand. Values are mean ±SE, n=9

Retrieval date	Litter fraction	Ash-free mass (g)	Ash (%)	Moisture (%)	Nitrogen (%)	Phosphorus (%)	Caloric value (cal g^{-1})
Jan. 1998 (0 time)	*Alnus* leaf	9.68±1.21	3.16±0.91	33.96±2.41	2.43±0.01	0.13±0.003	5304±311
	Alnus twig	9.62±2.12	3.81±0.81	44.14±3.14	0.86±0.29	0.07±0.011	4706±525
	Cardamom leaf	9.64±1.34	3.61±0.61	42.42±2.41	1.45±0.17	0.15±0.004	4497±132
	Cardamom pseudo-stem	9.58±1.43	4.11±0.19	36.46±3.21	0.66±0.11	0.08±0.004	3571±564
April 1998 (3 month)	*Alnus* leaf	8.36±0.11	4.01±0.81	50.25±2.11	2.69±0.34	0.13±0.002	4891±435
	Alnus twig	8.47±0.17	4.12±0.91	48.97±2.54	0.89±0.01	0.07±0.011	4094±325
	Cardamom leaf	7.86±0.87	4.91±0.89	45.16±2.33	1.48±0.36	0.14±0.006	4073±265
	Cardamom pseudo-stem	8.56±0.95	5.51±0.76	46.67±3.54	0.78±0.05	0.08±0.002	3079±214
July 1998 (6 month)	*Alnus* leaf	5.84±0.89	5.52±0.76	36.89±2.01	2.87±0.07	0.14±0.009	4670±421
	Alnus twig	7.37±0.87	4.38±0.92	49.81±8.21	0.92±0.02	0.08±0.006	4281±325
	Cardamom leaf	7.08±0.76	5.82±0.78	47.82±2.34	1.69±0.24	0.14±0.006	4396±412
	Cardamom pseudo-stem	7.51±0.78	5.36±0.81	41.43±3.81	0.96±0.02	0.08±0.007	3179±426
Jan 1999 (12 month)	*Alnus* leaf	4.49±0.87	6.82±0.78	38.39±1.89	2.91±0.06	0.12±0.002	3705±325
	Alnus twig	5.33±0.23	4.88±0.88	50.19±2.51	1.11±0.03	0.07±0.008	2973±215
	Cardamom leaf	5.28±0.29	6.51±0.81	37.97±1.23	1.72±0.17	0.13±0.002	3884±276
	Cardamom pseudo-stem	4.83±0.94	7.62±0.96	46.87±2.89	0.94±0.04	0.08±0.003	2540±254
Jan 2000 (24 month)	*Alnus* leaf	3.18±0.54	12.1±1.23	43.23±1.43	3.31±0.12	0.11±0.005	2801±551
	Alnus twig	3.77±0.54	9.08±1.12	45.15±2.54	1.62±0.06	0.09±0.005	2783±512
	Cardamom leaf	3.09±0.14	9.89±0.98	46.25±1.89	1.63±0.08	0.13±0.003	2882±126
	Cardamom pseudo-stem	4.06±0.49	9.55±0.98	46.87±2.87	1.47±0.02	0.09±0.001	2041±215

Table 6.7. Variation in percentages of initial amount of ash-free mass, nitrogen, phosphorus and energy remaining in decomposing litter fractions at different retrieval dates in 5-year *Alnus*-cardamom stand. Values are mean ±SE, *n*=9

Months elapsed	Litter fraction	Ash-free mass	Nitrogen	Phosphorus	Energy
03	*Alnus* leaf	83.62±1.73	74.93±4.71	85.88±5.23	75.06±1.05
	Alnus twig	87.06±2.42	87.21±5.81	86.43±3.41	82.73±2.38
	Cardamom leaf	79.92±1.23	72.85±2.89	87.05±1.77	69.52±1.05
	Cardamom pseudo-stem	80.90±1.51	64.35±1.64	82.94±1.55	69.75±1.43
06	*Alnus* leaf	57.18±1.46	62.42±1.96	71.30±2.62	52.39±1.39
	Alnus twig	80.97±2.58	77.62±1.37	80.63±4.55	75.54±2.62
	Cardamom leaf	71.63±2.67	68.29±2.63	77.51±2.19	65.18±1.60
	Cardamom pseudo-stem	70.59±1.52	68.35±2.84	72.22±1.15	63.79±1.58
12	*Alnus* leaf	33.21±1.62	53.53±1.44	47.72±0.97	33.38±1.40
	Alnus twig	57.44±1.42	52.17±1.25	55.38±1.33	38.75±0.48
	Cardamom leaf	42.71±1.31	52.51±3.76	39.92±1.65	23.54±1.27
	Cardamom pseudo-stem	41.84±1.56	47.30±1.16	43.57±3.58	35.55±0.55
24	*Alnus* leaf	21.10±0.56	26.11±0.65	17.84±0.75	14.38±1.29
	Alnus twig	32.54±0.54	35.91±1.96	19.27±0.92	20.19±1.33
	Cardamom leaf	18.13±1.58	26.86±1.25	17.67±1.01	14.48±0.49
	Cardamom pseudo-stem	25.94±1.30	26.10±1.72	20.83±1.07	16.57±1.37

Table 6.8. Variation in percentages of initial amount of ash-free mass, nitrogen, phosphorus and energy remaining in decomposing litter fractions at different retrieval dates in 10-year *Alnus*-cardamom stand. Values are mean ±SE, n=9

Months elapsed	Litter fraction	Ash-free mass	Nitrogen	Phosphorus	Energy
03	*Alnus* leaf	81.46±4.46	87.51±2.69	78.71±1.95	74.16±1.95
	Alnus twig	87.68±4.75	82.46±3.27	71.76±4.45	82.82±2.76
	Cardamom leaf	82.82±1.89	77.24±3.98	82.03±2.91	72.47±3.86
	Cardamom pseudo-stem	88.84±2.73	82.80±1.89	82.78±1.91	76.52±2.86
06	*Alnus* leaf	62.46±1.33	69.16±1.12	64.92±2.78	57.11±3.57
	Alnus twig	79.48±3.41	76.46±2.44	67.55±1.43	72.49±1.31
	Cardamom leaf	75.46±8.22	73.29±1.85	78.66±2.92	69.35±1.54
	Cardamom pseudo-stem	73.71±5.78	74.62±2.51	71.11±2.35	66.49±3.88
12	*Alnus* leaf	39.86±3.46	35.52±1.38	42.69±2.44	27.90±2.29
	Alnus twig	47.36±7.03	53.81±1.96	36.21±0.91	49.75±2.66
	Cardamom leaf	53.32±3.92	58.82±1.12	46.54±1.96	35.74±6.75
	Cardamom pseudo-stem	42.81±5.51	51.09±1.42	36.62±1.39	35.59±3.51
24	*Alnus* leaf	16.60±0.63	24.48±1.85	17.13±0.69	12.59±1.36
	Alnus twig	29.53±1.21	33.05±1.29	19.19±0.64	14.49±0.48
	Cardamom leaf	16.60±1.32	20.25±0.72	18.54±4.83	12.08±0.55
	Cardamom pseudo-stem	25.00±0.71	27.63±2.09	17.83±1.35	15.99±0.74

Table 6.9. Variation in percentages of initial amount of ash-free mass, nitrogen, phosphorus and energy remaining in decomposing litter fractions at different retrieval dates in 15-year *Alnus*-cardamom stand. Values are mean ±SE, n=9

Months elapsed	Litter fraction	Ash-free mass	Nitrogen	Phosphorus	Energy
03	*Alnus* leaf	81.31±01.03	85.65±1.42	82.39±2.79	74.14±1.34
	Alnus twig	86.13±1.24	72.09±1.11	67.26±2.09	81.83±0.41
	Cardamom leaf	82.62±1.04	81.23±1.32	80.43±1.15	71.89±2.67
	Cardamom pseudo-stem	85.43±1.03	80.72±2.51	61.98±1.71	73.65±2.23
06	*Alnus* leaf	61.45±6.14	70.25±1.44	54.98±1.61	56.34±0.33
	Alnus twig	75.05±3.03	68.65±3.11	65.86±1.97	73.21±3.32
	Cardamom leaf	71.32±1.03	78.41±1.61	60.37±1.78	65.44±4.49
	Cardamom pseudo-stem	75.56±2.03	61.82±4.05	55.41±1.45	67.47±2.36
12	*Alnus* leaf	38.15±2.08	44.35±0.74	31.94±1.85	26.66±1.55
	Alnus twig	49.72±2.07	54.58±1.81	49.80±2.04	42.92±2.58
	Cardamom leaf	53.46±1.08	59.43±1.55	40.88±3.14	28.74±2.48
	Cardamom pseudo-stem	44.86±2.09	48.19±1.43	40.14±1.89	37.30±2.78
24	*Alnus* leaf	15.00±2.28	22.00±1.99	16.29±1.69	12.21±1.30
	Alnus twig	27.96±1.25	22.15±1.92	21.14±0.82	17.03±1.41
	Cardamom leaf	17.04±1.04	27.85±1.09	18.78±1.89	14.94±1.19
	Cardamom pseudo-stem	19.52±1.24	29.05±1.66	22.46±1.06	17.13±2.37

Table 6.10. Variation in percentages of initial amount of ash-free mass, nitrogen, phosphorus and energy remaining in decomposing litter fractions at different retrieval dates in 20-year *Alnus*-cardamom stand. Values are mean ±SE, *n*=9

Months elapsed	Litter fraction	Ash-free mass	Nitrogen	Phosphorus	Energy
03	*Alnus* leaf	79.81±1.20	82.33±2.83	72.58±2.85	72.96±1.62
	Alnus twig	85.92±1.12	80.36±1.04	84.33±3.91	76.02±2.63
	Cardamom leaf	83.92±1.13	81.69±3.53	61.62±2.61	69.64±1.30
	Cardamom pseudo-stem	79.93±1.15	84.05±1.70	83.50±1.34	71.44±1.73
06	*Alnus* leaf	58.23±1.20	64.71±6.73	61.62±2.61	60.86±1.29
	Alnus twig	72.01±2.51	64.68±1.58	76.60±1.80	71.59±1.54
	Cardamom leaf	74.52±1.09	67.38±3.53	60.52±1.20	50.33±1.31
	Cardamom pseudo-stem	74.71±1.06	78.71±1.40	75.38±1.71	66.75±1.49
12	*Alnus* leaf	37.23±1.04	42.04±2.43	58.71±2.95	35.91±1.29
	Alnus twig	53.52±1.08	43.83±1.65	46.71±1.33	46.76±1.47
	Cardamom leaf	50.62±2.18	51.78±4.21	45.61±1.32	27.73±0.95
	Cardamom pseudo-stem	37.93±1.05	48.68±0.83	45.95±1.44	31.55±0.45
24	*Alnus* leaf	15.60±1.22	22.70±1.56	20.72±1.19	12.52±0.25
	Alnus twig	33.08±0.81	34.93±1.14	28.70±0.87	19.40±1.35
	Cardamom leaf	20.00±0.13	28.73±1.92	23.06±0.66	15.44±1.17
	Cardamom pseudo-stem	17.61±1.42	17.39±2.19	26.57±0.81	16.91±0.40

Table 6.11. Variation in percentages of initial amount of ash-free mass, nitrogen, phosphorus and energy remaining in decomposing litter fractions at different retrieval dates in 30-year *Alnus*-cardamom stand. Values are mean ±SE, *n*=9

Months elapsed	Litter fraction	Ash-free mass	Nitrogen	Phosphorus	Energy
03	*Alnus* leaf	82.64±2.04	81.75±1.96	72.16±1.72	75.47±1.40
	Alnus twig	87.65±2.03	76.15±1.47	78.03±2.36	83.45±1.31
	Cardamom leaf	87.18±1.30	73.93±3.40	85.88±2.53	75.49±1.35
	Cardamom pseudo-stem	86.83±2.40	76.46±1.08	83.53±1.95	74.71±1.31
06	*Alnus* leaf	59.86±1.51	74.68±2.15	64.59±1.64	54.91±2.47
	Alnus twig	72.95±5.44	72.17±1.77	69.39±2.73	71.59±2.54
	Cardamom leaf	74.39±3.75	72.72±1.44	72.51±2.08	67.70±1.33
	Cardamom pseudo-stem	75.28±7.01	66.80±1.06	73.09±2.84	68.00±2.37
12	*Alnus* leaf	42.63±3.82	49.45±0.68	41.36±1.43	29.36±0.39
	Alnus twig	54.07±5.80	53.34±0.91	57.67±1.49	46.66±2.44
	Cardamom leaf	45.37±6.49	57.06±1.86	59.14±1.53	24.61±1.37
	Cardamom pseudo-stem	45.54±4.60	53.11±2.08	59.31±1.27	37.87±0.35
24	*Alnus* leaf	18.86±1.87	23.62±0.59	23.07±1.63	13.44±1.47
	Alnus twig	37.28±0.61	36.00±0.81	37.91±1.58	19.23±1.34
	Cardamom leaf	25.46±1.56	35.27±1.59	30.89±1.28	16.12±0.84
	Cardamom pseudo-stem	32.52±2.84	29.73±0.87	33.75±1.61	16.92±0.17

Table 6.12. Variation in percentages of initial amount of ash-free mass, nitrogen, phosphorus and energy remaining in decomposing litter fractions at different retrieval dates in 40-year *Alnus*-cardamom stand. Values are mean ±SE, *n*=9

Months elapsed	Litter fraction	Ash-free mass	Nitrogen	Phosphorus	Energy
03	*Alnus* leaf	83.61±1.07	85.92±4.75	83.67±0.91	76.31±1.61
	Alnus twig	84.71±1.70	82.06±1.59	82.72±1.41	80.54±1.59
	Cardamom leaf	78.62±1.12	74.72±1.22	70.81±2.58	60.64±1.83
	Cardamom pseudo-stem	85.61±1.03	74.09±3.49	82.34±1.34	72.99±1.60
06	*Alnus* leaf	58.41±1.07	75.23±1.89	62.23±1.93	53.53±2.61
	Alnus twig	73.73±2.28	70.61±1.96	64.52±7.79	71.86±1.54
	Cardamom leaf	70.82±2.17	67.85±2.11	57.49±2.29	57.16±1.37
	Cardamom pseudo-stem	75.14±1.03	63.89±1.09	69.79±1.71	66.90±1.28
12	*Alnus* leaf	44.96±1.04	64.75±0.89	44.48±1.06	31.36±1.29
	Alnus twig	53.26±1.03	60.16±2.29	56.37±2.63	45.86±1.37
	Cardamom leaf	52.82±1.05	57.25±2.55	46.26±1.45	35.29±1.23
	Cardamom pseudo-stem	48.26±01.09	57.19±0.94	57.61±0.84	40.08±1.76
24	*Alnus* leaf	31.86±1.22	44.74±2.48	27.79±2.42	17.34±2.16
	Alnus twig	47.74±1.24	39.64±2.24	23.09±2.35	23.17±1.74
	Cardamom leaf	37.92±1.41	36.03±1.12	34.19±3.99	20.54±0.31
	Cardamom pseudo-stem	40.56±2.16	28.81±1.71	37.08±3.01	24.22±0.96

Table 6.14. Single exponential decay function parameters describing decomposition in 5-year *Alnus*-cardamom plantation stand.

Parameters	Litter fraction	*k* (per year)	$T_{1/2}$ (months)	Turnover time (months)
Ash-free mass	*Alnus* leaf	0.76	10.94	15.78
	Alnus twig	0.54	15.40	22.22
	Cardamom leaf	0.83	10.01	14.45
	Cardamom pseudo-stem	0.60	12.79	18.46
Nitrogen	*Alnus* leaf	0.67	12.41	17.91
	Alnus twig	0.51	16.31	23.52
	Cardamom leaf	0.67	12.41	17.91
	Cardamom pseudo-stem	0.40	20.79	30.00
Phosphorus	*Alnus* leaf	0.86	9.67	13.95
	Alnus twig	0.81	10.27	14.81
	Cardamom leaf	0.83	10.01	14.46
	Cardamom pseudo-stem	0.78	10.66	15.38
Energy	*Alnus* leaf	0.96	8.66	12.50
	Alnus twig	0.78	10.66	15.38
	Cardamom leaf	0.96	8.66	12.50
	Cardamom pseudo-stem	0.89	9.34	13.48

Table 6.15. Single exponential decay function parameters describing decomposition in 10-year *Alnus*-cardamom plantation stand.

Parameters	Litter fraction	*k* (per year)	$T_{1/2}$ (months)	Turnover time (months)
Ash-free mass	*Alnus* leaf	0.88	9.45	13.63
	Alnus twig	0.59	14.09	20.34
	Cardamom leaf	0.84	9.90	14.28
	Cardamom pseudo-stem	0.67	12.41	17.91
Nitrogen	*Alnus* leaf	0.70	11.88	17.14
	Alnus twig	0.60	13.86	20.00
	Cardamom leaf	0.80	10.39	15.00
	Cardamom pseudo-stem	0.64	12.99	18.75
Phosphorus	*Alnus* leaf	0.88	9.45	13.64
	Alnus twig	0.83	10.02	14.46
	Cardamom leaf	0.85	9.78	14.12
	Cardamom pseudo-stem	0.86	9.67	13.96
Energy	*Alnus* leaf	1.04	7.99	11.54
	Alnus twig	0.97	8.57	12.37
	Cardamom leaf	1.05	7.92	11.43
	Cardamom pseudo-stem	0.91	9.04	13.04

Table 6.16. Single exponential decay function parameters describing decomposition in 15-year *Alnus*-cardamom plantation stand.

Parameters	Litter fraction	*k* (per year)	$T_{1/2}$ (months)	Turnover time (months)
Ash-free mass	*Alnus* leaf	0.94	8.84	12.76
	Alnus twig	0.62	13.41	19.35
	Cardamom leaf	0.87	9.55	13.79
	Cardamom pseudo-stem	0.80	10.39	15.00
Nitrogen	*Alnus* leaf	0.76	10.94	15.79
	Alnus twig	0.75	11.09	16.00
	Cardamom leaf	0.64	12.99	18.75
	Cardamom pseudo-stem	0.61	13.63	19.67
Phosphorus	*Alnus* leaf	0.79	10.55	15.19
	Alnus twig	0.78	10.66	15.38
	Cardamom leaf	0.83	10.02	14.46
	Cardamom pseudo-stem	0.75	11.09	16.00
Energy	*Alnus* leaf	1.05	7.09	11.43
	Alnus twig	0.88	9.45	13.64
	Cardamom leaf	0.95	8.75	12.63
	Cardamom pseudo-stem	0.95	8.75	12.63

Table 6.17. Single exponential decay function parameters describing decomposition in 20-year *Alnus*-cardamom plantation stand.

Parameters	Litter fraction	k (per year)	$T_{1/2}$ (months)	Turnover time (months)
Ash-free mass	*Alnus* leaf	0.91	9.14	13.18
	Alnus twig	0.53	15.69	22.64
	Cardamom leaf	0.76	10.94	15.78
	Cardamom pseudo-stem	0.78	10.66	15.38
Nitrogen	*Alnus* leaf	0.74	11.24	16.21
	Alnus twig	0.53	15.69	22.64
	Cardamom leaf	0.62	13.41	19.35
	Cardamom pseudo-stem	0.68	12.23	17.64
Phosphorus	*Alnus* leaf	0.78	10.16	15.38
	Alnus twig	0.62	13.41	19.35
	Cardamom leaf	0.73	11.39	16.44
	Cardamom pseudo-stem	0.69	12.05	19.35
Energy	*Alnus* leaf	1.03	8.07	11.65
	Alnus twig	0.82	10.14	14.63
	Cardamom leaf	0.93	8.94	12.90
	Cardamom pseudo-stem	0.91	9.14	13.19

Table 6.18. Single exponential decay function parameters describing decomposition in 30-year *Alnus*-cardamom plantation stand.

Parameters	Litter fraction	k (per year)	$T_{1/2}$ (months)	Turnover time (months)
Ash-free mass	*Alnus* leaf	0.82	10.14	14.63
	Alnus twig	0.47	17.69	25.53
	Cardamom leaf	0.66	12.60	18.18
	Cardamom pseudo-stem	0.54	15.40	22.22
Nitrogen	*Alnus* leaf	0.72	11.55	16.66
	Alnus twig	0.51	16.30	23.53
	Cardamom leaf	0.50	16.63	24.00
	Cardamom pseudo-stem	0.52	15.99	26.09
Phosphorus	*Alnus* leaf	0.73	11.39	16.44
	Alnus twig	0.48	17.35	25.00
	Cardamom leaf	0.59	14.09	20.34
	Cardamom pseudo-stem	0.53	15.69	22.64
Energy	*Alnus* leaf	1.00	8.36	12.00
	Alnus twig	0.82	10.14	14.63
	Cardamom leaf	0.91	9.14	13.19
	Cardamom pseudo-stem	0.88	9.45	13.64

Table 6.19. Single exponential decay function parameters describing decomposition in 40-year *Alnus*-cardamom plantation stand.

Parameters	Litter fraction	k (per year)	$T_{1/2}$ (months)	Turnover time (months)
Ash-free mass	*Alnus* leaf	0.56	14.85	21.42
	Alnus twig	0.47	17.69	25.53
	Cardamom leaf	0.57	14.58	21.05
	Cardamom pseudo-stem	0.43	19.33	27.90
Nitrogen	*Alnus* leaf	0.40	20.79	30.00
	Alnus twig	0.46	18.08	26.08
	Cardamom leaf	0.51	16.31	23.52
	Cardamom pseudo-stem	0.42	19.80	28.57
Phosphorus	*Alnus* leaf	0.64	12.99	18.75
	Alnus twig	0.41	20.28	29.27
	Cardamom leaf	0.54	15.40	22.22
	Cardamom pseudo-stem	0.49	16.97	24.49
Energy	*Alnus* leaf	0.87	9.56	13.79
	Alnus twig	0.73	11.39	16.44
	Cardamom leaf	0.79	10.53	15.19
	Cardamom pseudo-stem	0.70	11.88	17.14

Table 6.20. Per cent lignin concentration and initial lignin: initial nitrogen ratio of the decomposing litter fractions. Values are mean ±SE, n=9

Litter fractions	Lignin (%)	Initial lignin (%): initial nitrogen (%) ratio
Alnus leaf	32.63±2.31	13.15±1.48
Alnus twig	26.45±1.32	25.21±1.78
Cardamom leaf	21.31±1.89	15.66±2.41
Cardamom pseudo-stem	22.37±1.17	34.54±1.62

Table 6.21. Multiple regression equation relating the relative loss rate, litter quality and environmental factors in the age series of *Alnus*-cardamom plantation stands together, and the squared multiple correlation coefficient (R^2) and F statistics are also given.

Litter	Regression equation					R^2	F
Ash-free mass	RLR =	− 0.086 +	0.005CNR +	0.002MLT	− 0.001LM	0.89	58
Nitrogen	RLR =	− 0.066 +	0.005CNR +	0.002MLT	− 0.001LM	0.84	36
Phosphorus	RLR =	− 0.024 +	0.003CNR +	0.002MLT	− 0.001LM	0.75	16
Energy	RLR =	− 0.077 +	0.002MLT +	0.005CNR	− 0.002LM	0.85	38

RLR = relative loss rate (calculated by dx/dtx, where dx = change in mass/ nutrient content/energy content, dt = change in time and x is the fraction of mass/ nutrient content/energy content remaining); CNR=C/N ratio; MLT=mean maximum litter temperature; and LM=litter moisture (%). All partial regression coefficients are significant P<0.005. R^2 values are significant (P<0.0001) with d.f. 20. F values are significant (P<0.001) with 3 and 20 d.f.

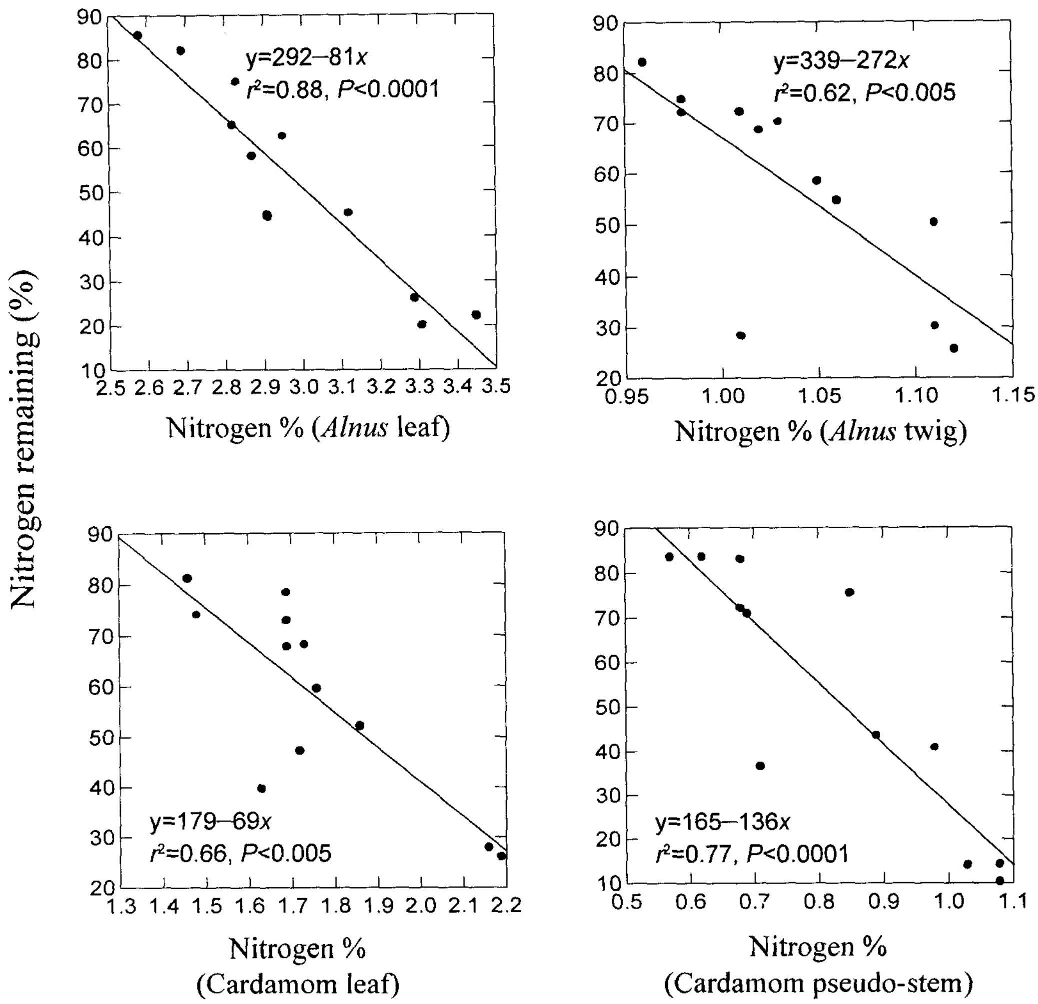


Fig. 6.1. Per cent weight remaining of the residual material as a function of N concentration during different retrieval dates in the age series of *Alnus*-cardamom plantation stands. Values are means of the six plantation stands.

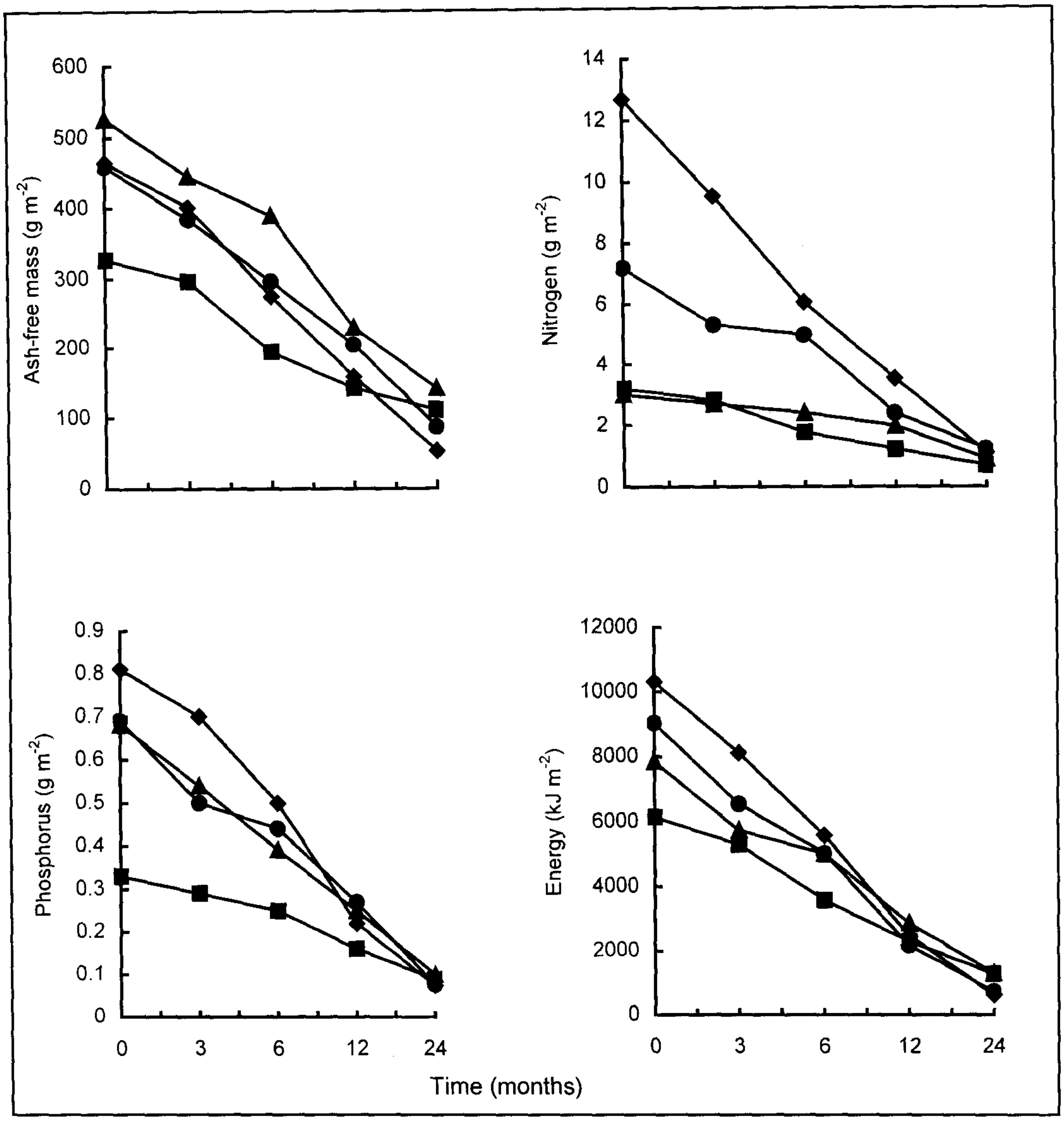


Fig. 6.2a. Ash-free mass, nitrogen, phosphorus and energy contents of decomposing litter (♦*Alnus* leaf, ■ *Alnus* twig, ● cardamom leaf, ▲cardamom pseudo-stem) per unit area on different retrieval dates in the 5-year *Alnus*-cardamom plantation stand.

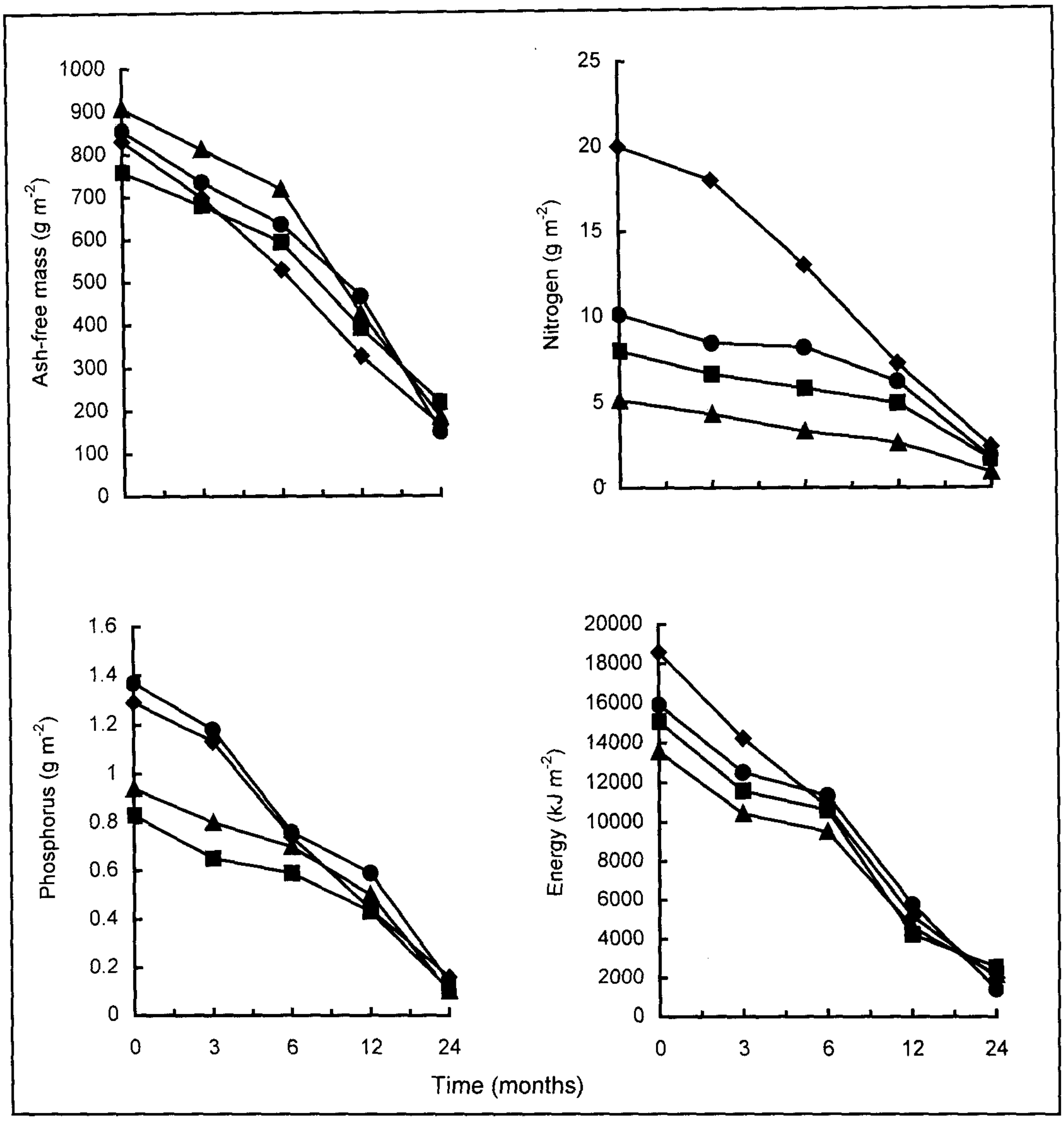


Fig. 6.2b. Ash-free mass, nitrogen, phosphorus and energy contents of decomposing litter (♦ *Alnus* leaf, ■ *Alnus* twig, ● cardamom leaf, ▲cardamom pseudo-stem) per unit area on different retrieval dates in the 15-year *Alnus*-cardamom plantation stand.

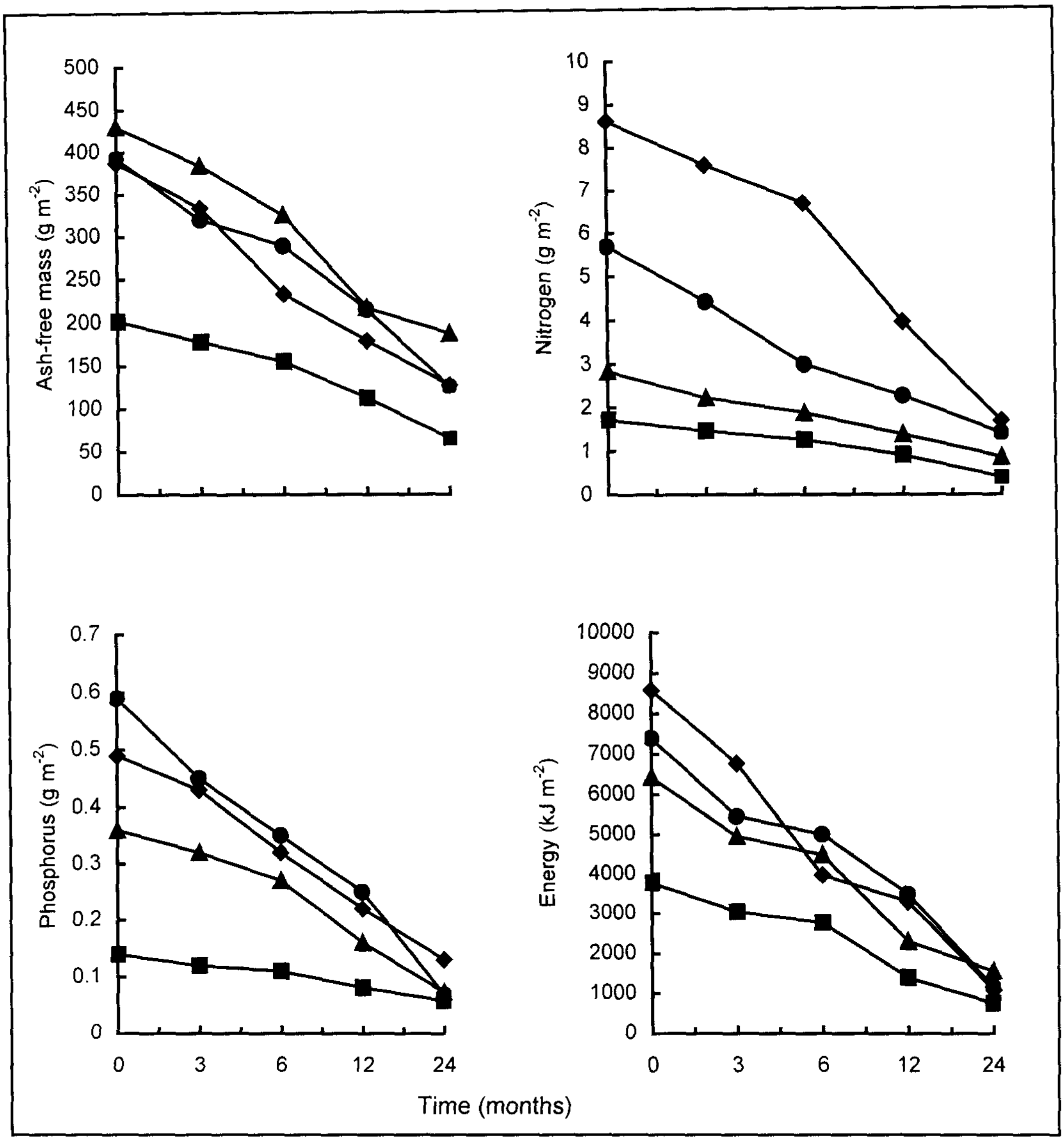
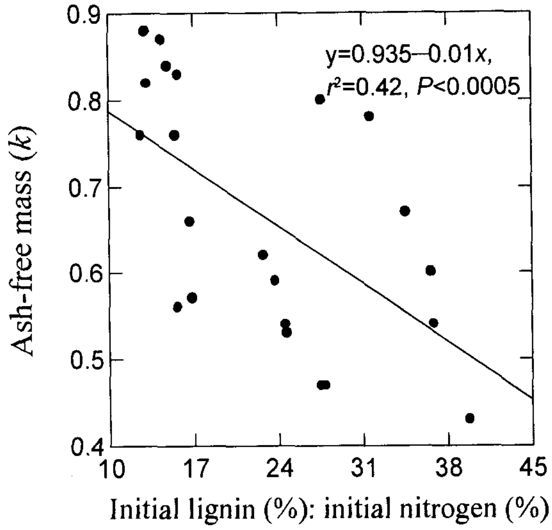


Fig. 6.2c. Ash-free mass, nitrogen, phosphorus and energy contents of decomposing litter (♦ *Alnus* leaf, ■ *Alnus* twig, ● cardamom leaf, ▲ cardamom pseudo-stem) per unit area on different retrieval dates in the 40-year *Alnus*-cardamom plantation stand.



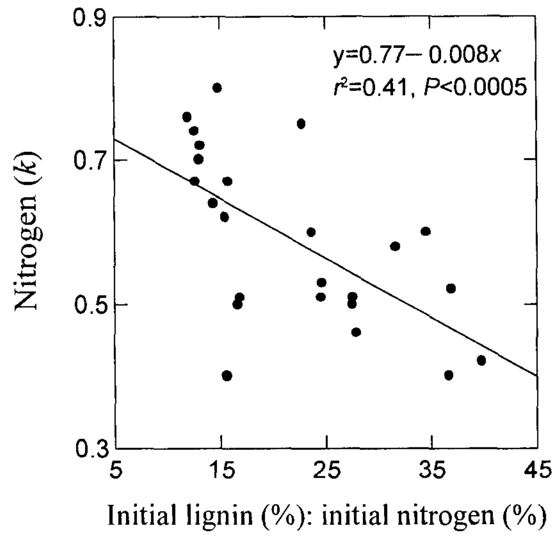


Fig. 6.3. Decomposition constant (*k*) per year of the initial ash-free mass and nitrogen expressed as a function of the ratio of the initial lignin concentration to initial nitrogen concentration.

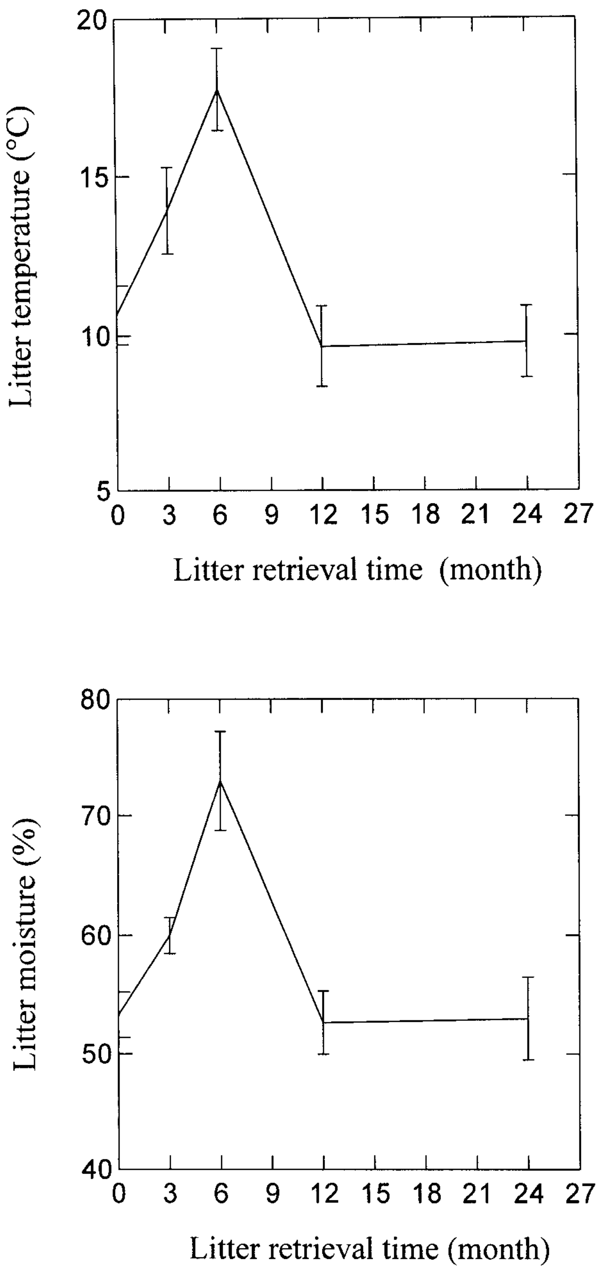


Fig. 6.4. Mean litter temperature and moisture variation during different retrieval dates (0 time is January 1998) in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates. Vertical bars represent standard errors.

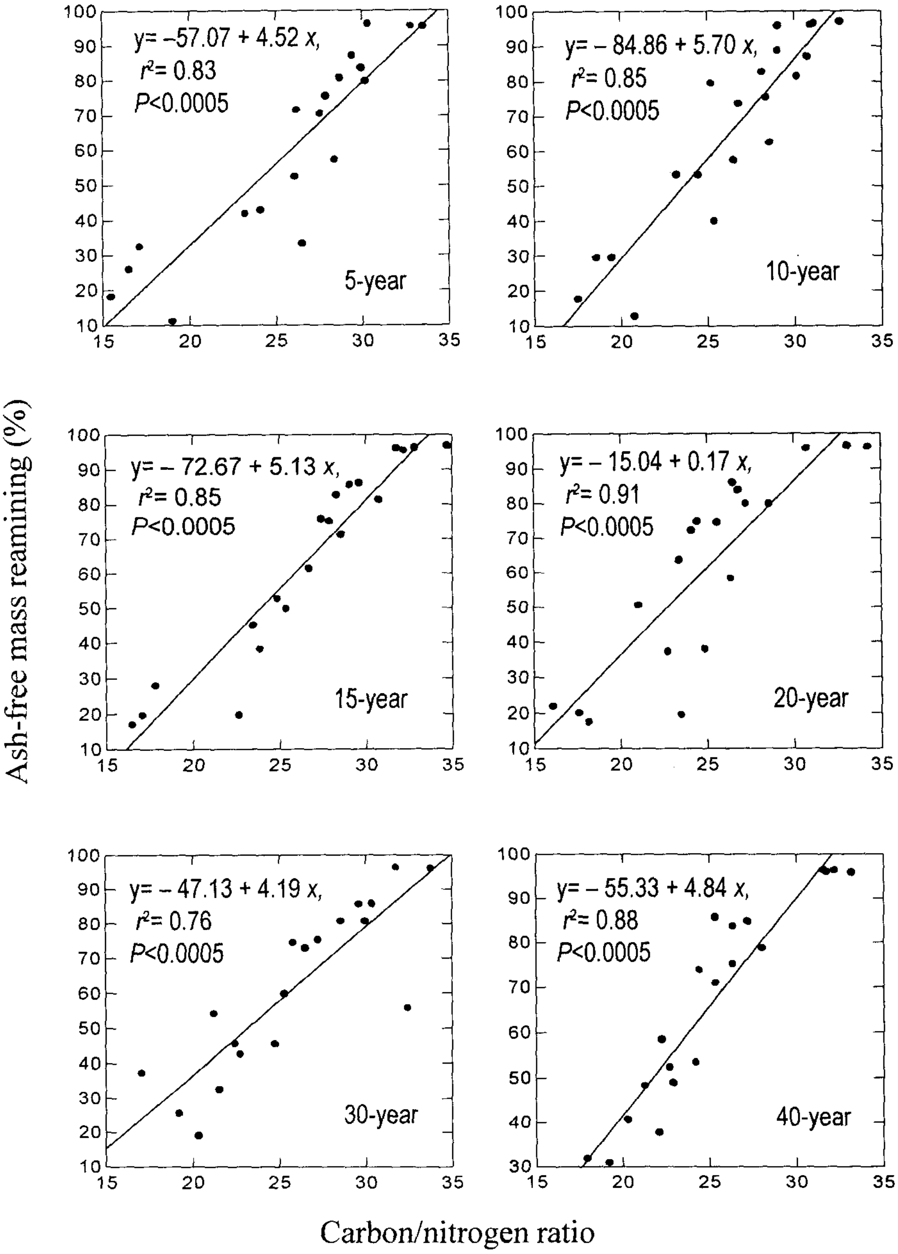


Fig. 6.5. Simple linear regression relating ash-free mass as a function of C:N ratio in the age series of *Alnus*-cardamom plantation stands.

Chapter VII

SOIL NUTRIENT DYNAMICS

7.1 Introduction

The influence of species on ecological processes is fundamental to the understanding of ecosystem functioning. Nutrient budget which compare the balance between input and output fluxes with amount of nutrients in the soil, provide useful information for making decision on the long term supply of nutrients.

In the recent years, incorporation of N_2-fixing *Alnus nepalensis* on cardamom based plantation systems has gained a new impetus in terms of their potential productivity increase and accelerated nutrient dynamics in the eastern Himalaya (Sharma *et al.* 1994, 1995, 1997a & 1997b). But the impacts on the dynamics of nutrient cycling under the influence of *Alnus* in cardamom based plantations are not known. The inclusion of N_2-fixing species with non-N_2-fixing species has 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 (Giardina *et al.* 1995; Binkley 1997; Binkley and Ryan 1998; Binkley *et al.* 1999). The presence of N_2-fixing trees increase 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 typically show increased rates of cycling of nutrients such as N and P (DeBell *et al.* 1989; Binkley *et al.* 1992a & 1992b; Binkley 1983; Cote and Camire 1987).

N_2-fixing trees may increase supply of available-N in the soil benefiting both the N_2-fixing and non-N_2-fixing associates. N_2-fixing tree species can have variable feedback effects on soil P supplies; increases in P supply could enhance long term growth of the N_2-fixer (Binkley *et al.* 1999).

In *Alnus*-cardamom plantations the understanding of soil nutrient enhancement in terms of N, C and P accretion and availability as an effect of plantation age is lacking. Sharma *et al.* (1997b) reported greater soil nutrient dynamics in *Alnus*-cardamom agroforestry compared to non-N_2-fixing forest-cardamom stand of similar age. However, there is no information of soil chemical properties on nutrient supply, availability and soil fertility of such managed ecosystems after the land transformation process and plantation aging.

This Chapter quantifies the performance on the mixtures of N_2-fixing *Alnus* with non-N_2-fixing cardamom crop on nutrient flux and availability as a function of stand age. The main objectives of the study were to examine (a) the characteristic change in soil pH and moisture, (b) soil organic carbon and SOM, (c) forms of N, N-transformation through N-mineralization and net nitrification, and (d) different forms of soil P and pool fractions of fractionated forms in the age series of *Alnus*-cardamom plantation stands.

7.2 Materials and methods

Seasonal soil sampling (winter, spring and rainy) was carried out in the marked sample plots (30×40 m) at each of the six age (5-, 10-, 15-, 20-, 30- and 40-year) series of plantation stands in all the three sites, numbering 18 plots altogether during 1998–1999. Soil samples (5 replicates x 2 soil depths x 3 seasons x 18 plots) collected in fresh were immediately taken to the laboratory.

Per cent soil moisture was determined by drying the soil samples in hot air oven at 80°C till constant weight. Soil pH was measured by mixing 20 g of fresh soil in 50 ml water and by shaking the soil solution for 30 minutes. It was measured using digital pH meter.

Soil samples were air dried, ground and passed through a 2-mm sieve and used for nutrient analysis. Organic carbon of soil samples was measured after the partial oxidation with an acidified dichromate solution which is a modified Walkley-Black method (Anderson and Ingram 1993). Soil organic matter (SOM) was calculated following Anderson and Ingram (1993). Total-N was estimated by a modified Kjeldahl method (Anderson and Ingram 1993). Total-P was estimated using hydrogen peroxide oxidized acidified ammonium fluoride extract by chlorostannous reduced molybdophosphoric blue colour method (Jackson 1967); inorganic-P using dilute HCl ammonium fluoride extract by chlostannous reduced molybdophosphoric blue colour method

(Jackson 1967); available-P using sodium bicarbonate extract by colorimetric method (Anderson and Ingram 1993); Al-, Fe-, Ca- and occluded Fe-phosphate by P-fractionation method of Jackson (1967).

For estimation of N-mineralization and nitrification, *in situ* field aerobic incubation (14 days) of soil samples was performed seasonally in all the stand ages. Soil samples taken afresh were used to estimate the inorganic-N concentrations as NH_4^+ and NO_3^- following methods given by Anderson and Ingram (1993). Net rates of mineralization were determined as the difference in mineral nitrogen (NH_4^++NO_3^-) between the pre- and post-incubated soil samples. Net rates of nitrification were calculated as the difference of nitrate-N between pre- and post-incubated soil samples.

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

7.2.1 Statistical analysis

Execution of statistical analysis was based on Systat 6, SPSS Inc. (1996). Statistical analyses between stand ages, seasons, depths, and their interactions were based on analysis of variance. In case of significant variations between various factors, Tukey's pairwise mean difference probabilities were used. Simple regression analysis were employed to compare the strength of relationships between pH, moisture, SOM and other soil variables as a function of stand age.

7.3 Results

7.3.1 Moisture

Soil moisture in the age series of *Alnus*-cardamom plantations varied significantly between the stands, seasons and depths (Table 7.1). It was highest in the rainy season and lowest during winter. Spring being a pre-monsoon season showed slightly higher level than winter. Moisture level remained higher at 0-15 cm soil horizon than at 15-30 cm depth.

7.3.2 pH

Pooled data showed a decline in soil pH along the age sequence. Soil pH of 0-15 cm depth was 0.35, 0.43, 0.49, 0.65 and 0.85 units lower in 10-, 15-, 20-, 30- and 40-year than 5-year plantation stands, respectively. Similarly, soil pH of 15-30 cm depth also consistently declined from 5-year plantation stand by

0.10, 0.21, 0.26, 0.30 and 0.56 units along the 10-, 15-, 20-, 30-, and 40-year stands, respectively. Analysis of variance showed a significant variation between the stand ages, seasons, and depths (Table 7.2). Interactions between the stand age and season, season and soil depth were not significant. Tukey's pairwise mean difference probabilities showed significant difference between 5- with 40-year ($P<0.0001$), 10- with 40-year ($P<0.01$), 15- with 40-year ($P<0.05$), 20- with 40-year ($P<0.001$ and 30- with 40-year ($P<0.001$) stand. Pairwise variations between other stands were not significant. Differences within the seasons were significant between winter with rainy ($P<0.01$) and spring with rainy ($P<0.001$). Between the soil depth the differences were highly significant ($P<0.0001$).

Mean soil pH of the upper soil horizon was smaller than the lower. Seasonal variation in the soil pH showed highest value during the winter season and lowest during rainy. The range of pH in the entire plantation stands was 3.81−5.60 at different soil depths and seasons.

Relationship between soil pH with stand age showed an inverse function indicating a consistent decline with the advancement of plantation age (Fig. 7.1). The influence of *Alnus* on acidity in the *Alnus*-cardamom plantation stands showed less chances of soil neutralization capacity and accumulation of base cations as the plantation age increased.

7.3.3 Organic carbon

Organic carbon concentrations of both the soil depths varied significantly between the stand ages, seasons and depths. Interactions between stand age and season, and stand age and depth were not significant (Table 7.3). Tukey's pairwise mean difference probabilities showed no significant differences between the stand ages. Pairwise difference within seasons was significant between winter and rainy ($P<0.001$) only. Between the soil depths, mean pariwise differences were highly significant ($P<0.0001$). Pooled data showed an increase in concentrations along the seasons from winter (3.5%) to rainy (4.2%). At lower soil depth percentage of organic carbon was smaller than upper soil layer.

Soil organic carbon content up to 30 cm depth in the age sequence of *Alnus*-cardamom plantations was 85 Mg ha^{-1} in the 5-year (lowest) to 116 Mg ha^{-1} in the 15-year (highest) and 90 Mg ha^{-1} in the 40-year plantation stand. There was a decrease of soil organic carbon content after 15 years of plantation age (Table 7.13).

7.3.4 Soil Organic Matter (SOM)

The accumulation of SOM at the upper soil horizon (0-15 cm) was greater than the lower soil horizon (15-30 cm). The pooled values of SOM of both the depths appeared almost highest until the age of 15 year and decreased with age. Analysis of variance showed significant variation between the stand ages, seasons and depths. Other interactions were not significant (Table 7.4). Tukey's pairwise mean difference probabilities showed no significant difference between stand ages. Between the seasons pairwise differences were significant between winter and rainy season ($P<0.0001$), and between the soil depths ($P<0.0001$).

SOM was highly dependent on pH. Relationship between SOM and pH was significantly negative but was positively related to moisture retention in the age series of plantations (Fig. 7.2).

SOM up to 30 cm soil depth increased from (145 Mg ha^{-1}) in the 5-year stand to 15-year (200 Mg ha^{-1}) and decreased with increase in age to lowest value in the 40-year stand (143 Mg ha^{-1}) in different seasons (Table 7.13). The proportion was less down the soil depth in the entire stand ages. SOM reduced by 1.4 times less in 40-year than the 15-year stand.

7.3.5 Nitrogen

7.3.5.1 Total nitrogen

Soil total-N varied significantly between stands, seasons and depths. Interaction between stands and depths was also significant (Table 7.5). Tukey's pairwise mean difference probabilities were not significant between the stand ages. Between the seasons, differences were significant for winter with rainy ($P<0.01$) and spring with rainy ($P<0.0001$). Mean pairwise differences between the depths were significant ($P<0.0001$). Soil toal-N was always higher in 0-15 cm depth compared to 15-30 cm depth in all the seasons and stands. Pooled values of total-N concentrations at 0-15 cm ranged between 0.30–0.79% and 15-30 cm between 0.20–0.39%. Mean values of per cent total-N was lowest in spring season and highest in rainy season.

Total-N content up to 30 cm depth increased from 8.4 Mg ha^{-1} in the 5-year to 11.7 Mg ha^{-1} in the 15-year and decreased to about 8.8–8.9 Mg ha^{-1} in the 30- and 40-year stand (Table 7.13). Soil total-N accumulation increased form the 5-year stand up to 15-year stand and decreased thereafter with stand maturity.

In the age series, C:N ratio ranged from 9.30–14.83 at different soil depths and seasons (Table 7.6). C:N ratio in all the stands was higher at 15-30 cm depth compared to 0-15 cm depth in all the seasons. The ratio was comparatively higher in the spring and lower in rainy season. Mean C:N ratio was lowest in the 15-year stand and highest in the 40-year stand.

Analysis of variance of C:N ratio showed significant variations between stand ages, seasons and depths. Interactions between season and depth were also significant. Tukey's pairwise mean difference probabilities showed significant variation between winter with rainy ($P<0.001$) and spring with rainy ($P<0.005$), and between depths ($P<0.001$). Differences were not significant between the stands.

Total-N concentrations showed an inverse relationship with pH while it showed a positive relationship with SOM in the linear regression analysis indicating that total-N decreased towards neutrality and increased when SOM is accumulated in the plantation stands (Fig. 7.3).

7.3.5.2 Inorganic-N

7.3.5.2..1 Ammonium-N

The concentrations of NH_4^+-N in the *Alnus*-cardamom plantation stands ranged between 9.59–65.20 μg g^{-1} soil in different depths and seasons. The accumulation of NH_4^+-N was maximum (11.13–65.2 μg g^{-1} soil) in 10-year stand and minimum (9.63–19.68 μg g^{-1} soil) in the 40-year stand. NH_4^+-N was lowest in rainy season and highest in winter. Analysis of variance showed highly significant variation between the stand age and season and the interactions were also significant (Fig. 7.4). At high moisture concentration, the NH_4^+-N levels in the soil decreased considerably. Relationship between NH_4^+-N with soil moisture showed an inverse function in the regression analysis (Fig. 7.5).

NH_4^+-N content up to 30 cm soil depth in the age series showed a maximum range (19.04–98.0 kg ha^{-1}) during winter season, comparatively low in spring (20.06–33.09 kg ha^{-1}) and lowest in rainy season (14.29–16.73 kg ha^{-1}) in different plantation stands.

7.3.5.2.2 Nitrate-N

Soil nitrate-N between different stands and seasons was lowest (13.17–15.20 μg g^{-1} soil) during rainy and highest

(17.26–25.90 μg g^{-1} soil) in spring season in all the plantation stands. Lowest range (13.7--17.3 μg g^{-1} soil) was recorded in 5-year and highest (14.7–25.9 μg g^{-1} soil) in the 40 year stand. Analysis of variance between the stand age and season was highly significant. Interactions between stand and season were also significant. Seasonal variation showed highest concentration during spring and lowest during winter (Fig. 7.4).

Relationship between nitrate-N with soil moisture showed an inverse function (Fig. 7.5). Nitrate-N levels were very low at >50% moisture level but were high within 30–50%.

NO_3^-–N content (up to 30 cm) in the mineral soil varied with highest range in spring (26.24–38.62 kg ha^{-1}) followed with medium range (21.09–31.95 kg ha^{-1}) in rainy season in different plantation stands. The NO_3^-–N content increased in the age series to be highest at the 40-year stand.

Inorganic-N content's up to 30 cm soil depth increased from 90 kg ha^{-1} in the 5-year stand to a highest value of 101 kg ha^{-1} in the 20-year stand and decreased by 1.3 times in the 40-year stand, respectively (Table 7.13).

7.3.5.2.3 Nitrification

A marked seasonality in the rate of nitrification was observed in *Alnus*-cardamom plantation stands. Net nitrification was highest in winter season with a substantial decrease in rainy and spring season after 14 days *in situ* field incubation (Fig. 7.4).

Net nitrification varied significantly between the seasons and along the stand ages. Interactions between stand ages and seasons were not significant. In the plantation stands, net nitrification ranged between 7.10−22.23 μg g^{-1}, 4.20−9.93 μg g^{-1} and 1.80−3.95 μg g^{-1} soil in winter, spring and rainy, respectively. Increase in SOM and high moisture levels along the stand ages showed decrease in nitrification.

Inverse relationships were observed between net nitrification with soil moisture and SOM in the regression analyses (Fig. 7.6 & 7.7). At low soil pH the rate of mineralization was also low and showed a positive relationship (Fig. 7.8).

7.3.5.2.4 Mineralization

Nitrogen mineralization rates at *in situ* moisture and temperature levels in the field were highest (11.72−24.56 μg g^{-1} soil) during the winter season followed by spring (7.91−13.79 μg g^{-1} soil) and the lowest (3.73−9.72 μg g^{-1} soil) in rainy. The rates increased from 5-year to peak at the 15-year stand and thereafter consistently declined with increase in plantation age. Analysis of variance showed significant variation between seasons but was not significant between the stand ages. Interaction between the stand age and season was not significant (Fig. 7.4).

Soil N-mineralization was highly dependent on soil moisture, pH and SOM. Relationships between N-mineralization with soil moisture and SOM showed negative functions (Fig. 7.6 &

7.7). N-mineralization increased with increase in pH. At low pH (below 4.3) mineralization was very low. A positive relationship was obtained between N-mineralization and pH (Fig. 7.8).

Nitrogen availability index based on *in situ* field incubation methods were proportional to total nitrogen. It was highly seasonal showing greatest values during winter (26.21−60.83 kg ha^{-1}), the period of low rainfall. Rainy season showed lowest nitrogen availability index (8.51−24.08 kg ha^{-1}) in all the plantation ages (Table 7.13). The availability of N increased from 5-year (22 kg ha^{-1}) to be highest in the 15-year (38 kg ha^{-1}) stand and thereafter decreased with stand maturity.

7.3.6 Phosphorus

7.3.6.1 Total phosphorus

The range of total-P concentration was 84.58−113.26 mg $100g^{-1}$ soil in the 0-15 cm and 75.46−98.63 mg $100g^{-1}$ soil in 15-30 cm soil depths in different seasons and stands (Table 7.7). Highest values of total-P were recorded in the spring (93−113 mg $100g^{-1}$ soil) season followed by winter (78−111 mg $100g^{-1}$ soil) and lowest in the rainy (75−96 mg $100g^{-1}$ soil) season. Significant variation was obtained between seasons and depths. Tukey's pairwise mean difference probabilities showed significant variation between winter with rainy ($P<0.05$) and spring with rainy ($P<0.001$). Pairwise difference between the depths was also significant ($P<0.0001$).

Total-P contents up to 30 cm depth increased from the 5-year stand (2285 kg ha^{-1}) and peaked at the 15-year stand (2554 kg ha^{-1}) and declined in the 40-year stand (2192 kg ha^{-1}) (Table 7.14).

7.3.6.2 Inorganic phosphorus

Soil inorganic-P in all the stands varied significantly between the seasons and depths. Generally, a decrease of inorganic-P was recorded at the lower than the upper soil depth (Table 7.8). A marked seasonality of inorganic-P with highest (4.53−9.02 mg $100g^{-1}$ soil) in rainy, fairly low in winter (3.37−5.99 mg $100g^{-1}$ soil) and lowest in spring (1.6−6.63 mg $100g^{-1}$ soil) was recorded in different depths and stands.

Inorganic-P content up to 30 cm soil depth increased from the 5-year (110 kg ha^{-1}) to be highest in the 15-year stand (162 kg ha^{-1}) and then decreased to a minimum (107 kg ha^{-1}) value in the 40-year plantation stand (Table 7.14).

The ratio of inorganic-P: total-P varied significantly between the soil depths and seasons. Variations between stand ages were not significant. Other interactions were also not significant. Ratio of inorganic-P: total-P showed a seasonal variation, being highest during rainy season (0.07−0.10) and lowest during spring (0.02−0.06) (Table 7.9). In the younger plantations the ratio was fairly high at the 0-15 cm soil depth, while it was lower in the 30- and 40-year stands. Variation between the stand age and other interactions were not significant.

7.3.6.3 Organic phosphorus

Soil organic-P ranged between 69.22–87.98, 83.06–105.44 and 86.44–109.06 mg $100g^{-1}$ soil in rainy, winter and spring seasons, respectively (Table 7.10). Highest values were recorded during spring and lowest during rainy season. Analysis of variance showed a significant variation between the seasons and depths but not between the stand ages. Interactions were not significant.

The accumulation of soil organic-P content up to 30 cm depth increased as the plantation age progressed with highest value (2392 kg ha^{-1}) in the 15-year stand and decreased with increase in age to a lowest (2085 kg ha^{-1}) value in the 40-year stand. Organic-P forms were highest than inorganic-P forms in the *Alnus*-cardamom plantation stands.

7.3.6.4 Available phosphorus

Soil available-P varied significantly between the stand ages, seasons and depths. No significant variations in the interactions between stand age, season and depth were observed. Concentrations of available-P in the 0-15 cm soil depth were higher than the 15-30 cm in the entire plantation stands. Available-P was highest (4.78–9.21 mg $100g^{-1}$ soil) in spring and slightly lower in winter (2.59–7.87 mg $100g^{-1}$ soil) and rainy (4.27–8.09 mg $100g^{-1}$ soil) seasons (Table 7.11). Available-P showed a positive relationship with pH across the plantation stands and sites indicating smaller concentrations at lower pH (Fig. 7.9). The concentrations were comparatively higher at younger plantations and lower at the older plantations.

Available-P was higher at 0-15 cm and lower at 15-30 cm soil depth. Available-P contents up to 30 cm increased from the 5-year stand (135 kg ha^{-1}) to be highest in the 15-year stand (182 kg ha^{-1}) and decreased thereafter in older plantations (Table 7.14).

7.3.6.5 Fractionated forms of phosphorus

Soil aluminium phosphate (Al-P), iron phosphate (Fe-P), calcium phosphate (Ca-P), and occluded iron phosphate (Occlu. Fe-P) was analyzed, seasonally. Soil Al-P ranged between 29−174 $\mu g\ g^{-1}$ soil in the age series of plantation stands. Al-P was considerably higher in spring season followed by rainy and lower in winter in all the plantation stands. No significant variations between the stand ages were observed. Analysis of variance showed significant variation between seasons (Table 7.12).

Fe-P varied significantly between the stand age and season. Maximum values were recorded during the winter season (101−264 $\mu g\ g^{-1}$ soil) followed by spring (85−150 $\mu g\ g^{-1}$ soil) and lowest (42−135 $\mu g\ g^{-1}$ soil) in the rainy season (Table 7.12).

Ca-P varied significantly between seasons but did not show variation between stands. Ca-P was recorded highest during winter (100−148 $\mu g\ g^{-1}$ soil), followed by spring (83−115 $\mu g\ g^{-1}$) and lowest during rainy (49 −86 $\mu g\ g^{-1}$ soil) season (Table 7.12).

Occluded Fe-P recorded was comparatively highest among all other fractionated forms of phosphorus. Analysis of variance showed significant variation between stand age and season. It was lowest in rainy season (285–412 mg $100g^{-1}$), and increased in the spring (571–1056 mg $100g^{-1}$) and recorded highest (919–1145 mg $100g^{-1}$) during the winter seasons (Table 7.12). The range of difference in the fractionated forms of phosphorus was in order: occluded Fe-P>Ca-P>Fe-P>Al-P in the age series of *Alnus*-cardamom plantation stands.

7.4 Discussion

The nutrient availability in the soil and uptake by trees, regardless of the soil fertility levels are strongly affected by soil moisture regime. Soil moisture levels (between 24–55%) in all the *Alnus*-cardamom plantation age series varied significantly between the seasons proportionately higher in rainy and lower in winter. This saturated moisture level was mainly attributed to perennial water source, less solar radiation incident on the ground by canopy interference and north-west facing plantation stands with corresponding high moisture retention capacity through adsorption and absorption by organic matter.

Soil pH declined from the 5-year stand with increase in stand age until 40-years. The decrease in soil pH with age parallels previous findings on red alder (Bormann and DeBell 1981; Van Cleve and Viereck 1972; DeBell *et al.* 1983). Such increase in acidity with increasing stand age may be related to the accumulation of highly acidic SOM, water percolation due to high rainfall leading to accelerated leaching losses of large quantities of base cations and nitrates from the soil profile.

Soil organic carbon/matter levels are good indicators of soil fertility status (Tiessen *et al.* 1994). Soil organic carbon level was highest in the 15-year old plantation stand. There was a decrease of SOM and organic carbon content with consistent decrease in litter accumulation and productivity in 20-, 30- and 40-year plantation stands. Low rates of annual litter production and floor-litter stores with decrease in tree number due to thinning as a traditional management practice and reduction of cardamom bushes/tillers due to aging could be the indications of less SOM and organic carbon turnover after 15 to 20 year plantation stands.

SOM values increased until 15-year and decreased in the increasing age series of plantations. It was negatively related to pH but was positively related to moisture retention in soil. A similar trend of SOM and pH was reported by Bormann and DeBell (1981) and suggested that soil pH is strongly related to organic matter and moderately related to nitrogen weight. The increased SOM should improve soil tilth and stabilizes soil N. 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 range of pH between 4.3–5.3 has provided better opportunities for both nitrification and mineralization process leading to an increased nitrogen availability in the younger plantation system.

Total-N was invariably higher at pH range between 4.3–5.3. This is indicative of low nitrogen content in the older plantation stands with low pH range. Simple regression between total nitrogen and pH showed a negative relationship. Debell *et al.* (1983) reported a negative correlation between total-N and pH in an age series of red alder plantation stands in west Washington. A similar trend was also reported by Bormann and Debell (1981) which supports the reports made in the present investigation. A significant positive relationship was obtained when total-N was treated with SOM.

The N-availability and supply for short time scale is regulated by the current pool sizes of inorganic, ammonium and nitrate-N and the mobility of these ions. For larger time scale, pools are small relative to the fluxes. Fluxes in the inorganic pools results through the difference in N-mineralization and nitrification of labile pools or from the differences in the rate of immobilization of released organic-N.

Nitrification rates were markedly higher in the 5-year stand and decreased in the advancement of age with significant variation. Further, nitrification was higher in winter than the rainy season. These seasonal differences may be related to heterotrophic activity which is likely to become active during wet season and immobilize ammonium ions due to rapid uptake and thus reduce nitrifier activity (Ramakrishnan and Saxena 1984). High rates of both N-mineralization and nitrification would be due to rapid immobilization during winter season. Low rates in the older plantation 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 variation in N accretion or phosphorus accumulation either through biological fixation or in the soil through microbial immobilization limits both N and P after 20 years plantation age.

Soils with very high C:N ratio have low net rate of mineralization. The ratio most favourable for mineralization lies between 10:1 and 20:1 (Larcher 1975). N-mineralization rates were highest in the 15-year stand which was lowest in both the 5- and 40-year stand. The 15-year stand had the lowest C:N ratio and correspondingly high in 5- and 40-year stand quite comparable to the reports made by Sharma *et al.* (1985) in *Alnus nepalensis* plantations. The C:N ratio between 10–15 appeared most favourable for high N-mineralization in the *Alnus*-cardamom plantations.

Soil total-N content in *Alnus*-cardamom stands increased from 5-year stand to be highest in the 15-year stand and declined with age. The lower range in old stands is attributed to N exit through thinning of *Alnus* and consequently less litter input and low fixation rates after 15 year of plantation. Total-N content of the soil increased with accretion of nitrogen through N_2-fixation in the root nodules of *Alnus* followed by the process of decomposition of plant components release of nutrients (see Chapter V & VI).

The potential net rate of N-transformation through N-mineralization and nitrification were more than twice in the younger plantations than the oldest and consequently more is available for plant uptake in the younger plantations. This study clearly showed that the presence of *Alnus* increased the total-N pools and supply to the agroforestry system. Similar results were reported in mixed stands of *Eucalyptus saligna* and *Albizia falacataria* in Hawaii (Garcia-Montiel and Binkley 1998).

Both inorganic and organic forms of P are important to plant. Of the total-P in the *Alnus*-cardamom plantation stand, most of the phosphorus was in the organic forms. Ratio of inorganic-P: total-P was higher in the upper soil horizon than lower, indicating relatively greater inorganic-P availability for plant uptake on the upper horizon. The ratio was comparatively lower during spring and high in rainy season indicating relatively greater inorganic-P availability during rainy season. The P availability was highly dependent on pH and showed a positive relationship with pH in the age series of plantations. Lower values of available-P with increasing plantation age would have resulted from the lower pH values (Sharma 1993; Sharma *et al.* 1997b). The increasing acidity in these stands would cause transition of phosphate into less soluble compounds with Fe and Al (Brozek 1990; Sharma *et al.* 1997b). A considerable amount of phosphates are not available to plants as they are fixed in the form of occluded Fe-P and certain amounts are fixed 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 lower available-P compared to the younger stands. The amount of organic-P exceeds inorganic-P in all the plantation stands, and turnover of organic-P pools provides a large portion of P taken up by the plants. A heavy accumulation of organic matter in soil would have shifted P from a plant available pool to an organically bound pool (Sharma 1993). Thus, in cardamom based plantations, P budget and availability is considerably controlled by N_2-fixing *Alnus* which proves to be a successful associate.

Phosphorus is secondarily fixed in acidic soils. The *Alnus* rhizosphere releases low molecular weight acids that chelates the inorganic forms of P unavailable to plants and forms oxalates releasing phosphates suitable for plant uptake (Ae *et al.* 1990; Sharma *et al.* 2001). In spite of seasonal fluctuation, considerable amounts of phosphates are not available to plants as they are fixed in the occluded Fe-P form in the stands quite characteristics to soil of the Himalayan region (Sharma 1995). In contrast, among all the fractionated forms, occluded Fe-P was 14–47 times greater than other forms which would be a potential source of available-P in the *Alnus*-cardamom plantations. Therefore, the availability of P appears to have been increased by N_2-fixing tree in mixed *Alnus* and cardamom plantations benefiting both *Alnus* and cardamom in the agroforestry system.

In conclusion, the inclusion of N_2-fixing *Alnus* in the cardamom based plantations has helped in maintaining the soil organic levels, relatively higher N-transformation rates and greater P cycling through the processes of phosphatase activity, rhizospheric acidification and microbial immobilization as reported by Sharma *et al.* (2001). But over the course of stand aging after 20 years, these processes declined with time and consequently showed nutrient limitation and availability. Such variation is due to the plantation age, density, litter production, microbial activity and thinning of *Alnus* as well as reduction of cardamom bushes due to aging. Beyond 20 years of plantation age, given the high rainfall (>3000 mm $year^{-1}$) in the region and low stabilization of SOM, litter and other nutrient status by the soil, soil fertility is unlikely to be an option for cash crop like cardamom. This results into the reduction of sustainability and economic viability of older *Alnus*-cardamom stands. Therefore, dynamics of soil nutrients and availability suggests that the system could be sustainable up to 20 years, and adoption of replantation after 20 years for both *Alnus* and cardamom would be highly beneficial ❖

Table 7.1. Seasonal variation in soil moisture (%) at two soil depths in the age series of *Alnus*–cardamom plantation stands. Values are mean ±SE, n=9

Stand age (year)	Depth (cm)	Season		
		Winter	Spring	Rainy
5	0-15	28.08±2.45	34.11±0.70	47.42±4.50
	15-30	23.89±2.39	28.46±1.28	41.03±3.93
10	0-15	34.11±1.83	36.71±1.66	48.86±3.64
	15-30	24.19±1.68	28.11±1.85	40.68±3.21
15	0-15	29.34±1.45	34.62±1.44	47.94±2.58
	15-30	24.40±2.07	27.65±1.36	41.69±3.42
20	0-15	34.94±2.36	34.58±1.57	48.06±2.05
	15-30	30.17±2.21	27.20±1.55	42.55±1.70
30	0-15	31.32±2.50	36.12±1.86	47.56±2.32
	15-30	23.99±1.44	28.74±0.98	38.12±2.24
40	0-15	30.30±2.95	36.10±0.85	55.21±3.32
	15-30	23.55±2.16	32.26±1.25	49.42±3.23

ANOVA: Stand age $F_{5,288}$ = 2.50, $P<0.031$; Season $F_{2,288}$ = 186.12, $P<0.0001$; Depth $F_{1,288}$ = 72.31, $P<0.0001$; Stand age x Season $F_{10,288}$ = 2.12, $P<0.023$. Other interactions not significant.

Table 7.2. Seasonal variation in soil pH at two soil depths in the age series of *Alnus*–cardamom plantation stands. Values are mean ±SE, n=9

Stand age (year)	Depth (cm)	Season		
		Winter	Spring	Rainy
5	0-15	5.06±0.10	5.27±0.08	4.96±0.10
	15-30	5.25±0.11	5.31±0.07	5.12±0.07
10	0-15	4.86±0.18	4.58±0.14	4.74±0.21
	15-30	5.15±0.21	5.14±0.22	5.12±0.14
15	0-15	4.80±0.17	4.56±0.31	4.64±0.19
	15-30	5.10±0.14	5.11±0.25	4.86±0.16
20	0-15	4.73±0.18	4.54±0.23	4.55±0.27
	15-30	5.10±0.17	5.07±0.19	4.76±0.21
30	0-15	4.30±0.15	4.53±0.27	4.51±0.28
	15-30	5.08±0.16	5.07±0.27	4.66±0.23
40	0-15	3.81±0.16	4.52±0.14	4.41±0.18
	15-30	4.78±0.26	4.77±0.10	4.46±0.11

ANOVA: Stand age $F_{5,288}$ = 6.90, P<0.0001; Season $F_{2,288}$ = 6.71, P<0.001; Depth $F_{1,288}$ = 16.40, P<0.0001. Interactions not significant.

Table 7.3. Seasonal variation in soil organic carbon (%) at two soil depths in the age series of *Alnus*–cardamom plantation stands. Values are mean ±SE, n=9

Stand age (year)	Depth (cm)	Season		
		Winter	Spring	Rainy
5	0-15	3.78±0.38	4.59±0.14	5.10±0.52
	15-30	2.14±0.39	2.81±0.09	2.64±0.31
10	0-15	4.41±0.37	4.57±0.13	5.06±0.66
	15-30	2.56±0.29	2.88±0.10	2.95±0.31
15	0-15	4.62±0.55	5.03±0.29	5.03±0.72
	15-30	3.30±0.58	3.04±0.14	4.29±0.33
20	0-15	3.82±0.60	4.11±0.41	5.50±0.55
	15-30	2.69±0.35	2.56±0.23	2.62±0.37
30	0-15	3.90±0.44	4.83±0.15	5.19±0.60
	15-30	3.46±0.28	4.15±0.22	3.70±0.35
40	0-15	4.16±0.31	4.19±0.27	4.84±0.29
	15-30	2.51±0.19	3.11±0.17	2.84±0.31

ANOVA: Stand age $F_{5,288}$ = 3.33, P<0.006; Season $F_{2,288}$ = 10.00, P<0.0001; Depth $F_{1,288}$ = 172.72, P<0.0001. Interactions not significant.

Table 7.4. Seasonal variation in per cent soil organic matter (SOM) at two soil depths in the age series of *Alnus*–cardamom plantation stands. Values are mean ±SE, n=9

Stand age (year)	Depth (cm)	Season		
		Winter	Spring	Rainy
5	0-15	6.52±0.65	7.91±0.28	8.79±0.89
	15-30	3.70±0.68	4.84±0.16	4.55±0.53
10	0-15	7.60±0.64	7.87±0.23	8.71±1.13
	15-30	4.42±0.51	4.96±0.18	5.08±0.54
15	0-15	7.96±0.95	8.68±0.49	8.67±1.24
	15-30	5.69±1.00	5.24±0.24	7.74±0.58
20	0-15	6.59±1.03	7.08±0.71	9.48±0.95
	15-30	4.63±0.61	4.42±0.40	4.51±0.63
30	0-15	6.73±0.75	8.32±0.26	8.77±1.03
	15-30	4.24±0.49	7.15±0.39	6.39±0.61
40	0-15	8.89±0.54	7.23±0.47	8.35±0.49
	15-30	4.33±0.33	5.37±0.24	4.81±0.05

ANOVA: Stand age $F_{5,288}$ = 3.32, P<0.0001; Season $F_{2,288}$ = 10.00, P<0.0001; Depth $F_{1,288}$ = 172.72, P<0.0001. Interactions not significant.

Table 7.5. Seasonal variation in total nitrogen (%) at two soil depths in the age series of *Alnus*–cardamom plantation stands. Values are mean ±SE, n=9

Stand age (year)	Depth (cm)	Season		
		Winter	Spring	Rainy
5	0-15	0.30±0.05	0.34±0.01	0.48±0.28
	15-30	0.23±0.04	0.20±0.02	0.24±0.02
10	0-15	0.41±0.05	0.40±0.03	0.47±0.03
	15-30	0.21±0.02	0.25±0.02	0.29±0.02
15	0-15	0.49±0.08	0.43±0.03	0.55±0.03
	15-30	0.28±0.03	0.29±0.03	0.39±0.04
20	0-15	0.51±0.05	0.56±0.44	0.79±0.59
	15-30	0.38±0.03	0.39±0.01	0.31±0.02
30	0-15	0.40±0.05	0.41±0.03	0.44±0.05
	15-30	0.29±0.04	0.27±0.04	0.32±0.04
40	0-15	0.38±0.05	0.41±0.06	0.44±0.06
	15-30	0.21±0.02	0.22±0.02	0.24±0.05

ANOVA: Stand age $F_{5,288}$ = 3.74, P<0.003; Season $F_{2,288}$ =14.82, P<0.001; Depth $F_{1,288}$ =2.38, P<0.0001; Stand x depth $F_{5,288}$ =2.8, P<0.01. Other interactions not significant.

Table 7.6. Seasonal variation in C/N ratio at two soil depths in the age series of *Alnus*–cardamom plantation stands. Values are mean ±SE, n=9

Stand age (year)	Depth (cm)	Season		
		Winter	Spring	Rainy
5	0-15	12.71±1.92	13.53±0.89	10.66±1.61
	15-30	9.30±2.95	14.10±1.56	11.18±1.24
10	0-15	10.53±1.08	11.46±0.79	10.66±1.08
	15-30	12.21±1.01	11.12±0.85	10.19±1.21
15	0-15	9.46±1.31	11.66±0.82	9.06±1.17
	15-30	11.30±1.77	10.48±2.65	11.21±3.81
20	0-15	12.22±0.87	12.46±1.26	11.99±0.69
	15-30	12.19±0.61	11.29±0.96	11.21±1.34
30	0-15	9.95±0.32	13.09±1.00	11.83±1.12
	15-30	11.94±0.61	12.49±3.58	12.30±1.50
40	0-15	12.57±0.81	10.23±1.82	11.14±1.75
	15-30	13.97±0.28	14.83±1.63	12.36±1.84

ANOVA: Stand age $F_{5,288}$ = 4.97, P<0.0001; Season $F_{2,288}$ = 8.22, P<0.0001; Depth $F_{1,288}$ = 12.69, P<0.0001; Stand age x Depth $F_{5,288}$ =2.96, P<0.01; Season x Depth $F_{2,288}$ = 3.53, P<0.01. Other interactions not significant.

Table 7.7. Seasonal variation in soil total phosphorus (mg $100g^{-1}$soil) at two soil depths in the age series of *Alnus*–cardamom plantation stands. Values are mean ±SE, n=9

Stand age (year)	Depth (cm)	Season		
		Winter	Spring	Rainy
5	0-15	101.79±7.13	105.33±6.91	90.04±4.91
	15-30	87.07±6.58	97.46±7.34	86.39±5.00
10	0-15	110.98±4.57	113.20±8.05	95.94±5.99
	15-30	91.04±4.63	93.30±7.30	83.81±6.31
15	0-15	101.52±8.57	101.91±9.78	90.17±6.66
	15-30	92.62±8.55	98.63±11.20	80.86±6.37
20	0-15	94.64±8.04	98.31±15.10	95.84±8.74
	15-30	89.94±6.16	95.57±12.42	86.41±8.82
30	0-15	96.48±6.54	108.28±7.30	86.26±3.87
	15-30	86.40±7.23	96.10±8.60	75.46±1.91
40	0-15	84.58±8.35	113.26±7.35	86.66±5.44
	15-30	77.77±7.10	101.08±8.90	78.27±3.92

ANOVA: Stand age $F_{5,288}$ = 0.43, not significant; Season $F_{2,288}$ = 8.29, P<0.0001; Depth $F_{1,288}$ = 13.30, P<0.0001. Interactions not significant.

Table 7.8. Seasonal variation in soil inorganic phosphorus (mg $100g^{-1}$soil) at two soil depths in the age series of *Alnus*–cardamom plantation stands. Values are mean ±SE, n=9

Stand age (year)	Depth (cm)	Season		
		Winter	Spring	Rainy
5	0-15	5.40±1.29	5.57±0.86	6.23±0.56
	15-30	4.02±1.16	1.90±0.11	5.70±0.90
10	0-15	5.54±1.85	2.75±0.33	7.96±2.10
	15-30	4.09±1.09	2.87±0.51	4.53±1.25
15	0-15	5.99±1.86	4.05±0,85	9.02±2.10
	15-30	4.58±1.23	2.20±0.27	6.40±1.44
20	0-15	4.85±1.00	2.68±0.46	8.39±1.18
	15-30	3.62±0.88	1.60±0.31	5.20±1.07
30	0-15	4.72±0.76	6.63±1.75	7.26±1.29
	15-30	5.52±1.80	4.29±0.94	6.24±1.26
40	0-15	5.49±1.34	4.19±0.95	7.93±0.87
	15-30	3.37±0.78	2.83±0.57	5.30±0.63

ANOVA: Stand age $F_{5,288}$ = 1.21, not significant; Season $F_{2,288}$ = 23.42, P<0.0001; Depth $F_{1,288}$ = 19.56, P<0.0001. Interactions not significant.

Table 7.9. Seasonal variation in inorganic-P: total-P at two soil depths in the age series of *Alnus*–cardamom plantation stands. Values are mean ±SE, n=9

Stand age (year)	Depth (cm)	Season		
		Winter	Spring	Rainy
5	0-15	0.06±0.02	0.06±0.01	0.07±0.01
	15-30	0.05±0.02	0.02±0.00	0.07±0.02
10	0-15	0.05±0.02	0.03±0.01	0.10±0.03
	15-30	0.04±0.01	0.03±0.00	0.07±0.02
15	0-15	0.05±0.01	0.04±0.01	0.11±0.03
	15-30	0.05±0.01	0.03±0.01	0.09±0.03
20	0-15	0.05±0.01	0.03±0.01	0.10±0.02
	15-30	0.04±0.01	0.02±0.00	0.07±0.02
30	0-15	0.05±0.01	0.06±0.01	0.09±0.02
	15-30	0.06±0.02	0.04±0.01	0.08±0.02
40	0-15	0.07±0.02	0.04±0.01	0.10±0.02
	15-30	0.05±0.01	0.03±0.01	0.07±0.01

ANOVA: Stand age $F_{5,288}$ = 0.71, not significant; Season $F_{2,288}$ = 33.07, P<0.0001; Depth $F_{1,288}$ = 7.02, P<0.009. Interactions not significant.

Table 7.10. Seasonal variation in soil organic phosphorus (mg $100g^{-1}$soil) at two soil depths in the age series of *Alnus*–cardamom plantation stands. Values are mean ±SE, n=9

Stand age (year)	Depth (cm)	Season		
		Winter	Spring	Rainy
5	0-15	96.39±7.84	89.76±6.15	83.81±5.27
	15-30	83.06±7.15	95.55±7.33	80.69±5.47
10	0-15	105.44±5.01	100.45±8.27	87.98±7.86
	15-30	86.95±3.75	90.43±7.01	79.28±7.31
15	0-15	95.53±7.50	97.87±9.37	81.15±7.75
	15-30	88.04±7.84	86.44±11.31	74.45±7.47
20	0-15	93.80±7.29	91.63±14.99	87.45±9.40
	15-30	86.31±5.55	93.97±12.30	81.22±9.21
30	0-15	91.76±6.36	101.65±6.13	78.99±3.82
	15-30	80.88±6.86	91.81±7.78	69.22±2.70
40	0-15	79.08±8.74	109.06±7.05	78.72±5.94
	15-30	74.43±7.09	98.24±8.94	72.97±4.02

ANOVA: Stand ages $F_{5,288}$ = 0.56, not significant; Season $F_{2,288}$ =12.89, P<0.0001; Depth $F_{1,288}$ = 8.76, P < 0.003. Interactions not significant.

Table 7.11. Seasonal variation in'soil available phosphorus (mg $100g^{-1}$soil) at two soil depths in the age series of *Alnus*–cardamom plantation stands. Values are mean ±SE, n=9

Stand age (year)	Depth (cm)	Season		
		Winter	Spring	Rainy
5	0-15	6.78±1.95	9.21±2.16	7.87±1.21
	15-30	4.78±1.08	5.50±1.35	5.21±1.70
10	0-15	6.80±1.22	8.08±1.41	7.15±0.23
	15-30	5.30±1.49	6.06±1.44	5.25±1.54
15	0-15	7.87±1.10	8.22±2.19	8.09±1.78
	15-30	4.03±1.23	4.80±1.45	5.82±1.60
20	0-15	5.55±1.71	6.65±1.06	6.47±1.26
	15-30	3.76±1.06	5.71±1.24	4.27±0.75
30	0-15	5.52±0.30	6.71±2.23	6.49±0.96
	15-30	3.66±0.43	4.78±1.83	4.60±0.81
40	0-15	3.76±0.76	5.71±1.41	5.37±1.93
	15-30	2.59±0.64	4.78±1.17	4.27±0.29

ANOVA: Stand age $F_{5,288}$ = 7.96, P<0.001; Season $F_{2,288}$ = 4.59, P<0.01; Depth $F_{1,288}$ = 13.18, P<0.0001. Interactions not significant.

Table 7.12. Seasonal variation in fractionated forms of phosphorus in soil samples (0-30 cm depth) in the age series of *Alnus*-cardamom plantation stands. Values are mean ±SE, *n*=3

Stand age (year)	Season	Fractionated phosphorus			
		Al-P (μg g^{-1})	Fe-P (μg g^{-1})	Ca-P (μg g^{-1})	Occl. Fe-P (mg $100g^{-1}$)
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
Interactions not significant					

Table 7.13. Soil nutrient contents (30-cm soil depth) and nitrogen availability index (NAI) in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

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[ʃ] ($Mg\ ha^{-1}$)	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* ($kg\ ha^{-1}$)	21.9 ±4.2	30.8 ±5.0	38.0 ±9.4	28.9 ±8.0	26.6 ±7.4	17.5 ±4.1

[ʃ]Soil Organic Matter

Table 7.14. Soil phosphorus contents (30-cm soil depth) in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

Nutrient (kg ha^{-1})	Stand age (year)					
	5	10	15	20	30	40
Total–P	2285 ±105	2312 ±110	2554 ±121	2457 ±139	2255 ±129	2192 ±136
Inorganic–P	110 ±19	117 ±14	162 ±20	126 ±21	120 ±19	107 ±25
Available–P	135 ±17	137 ±19	182 ±26	147 ±16	143 ±16	130 ±13

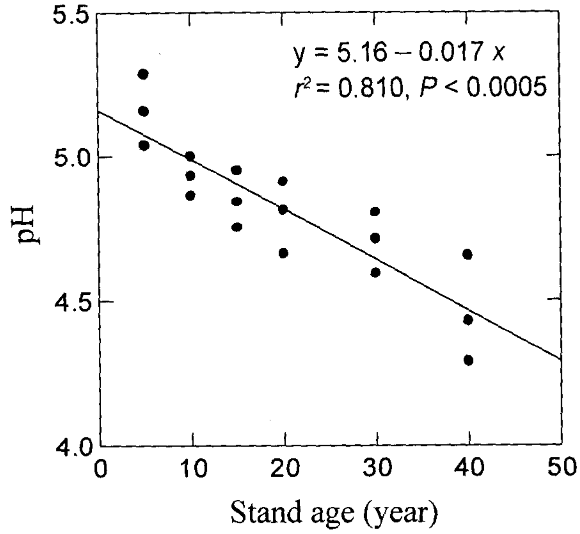


Fig. 7.1. Relationship between soil pH with stand age in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

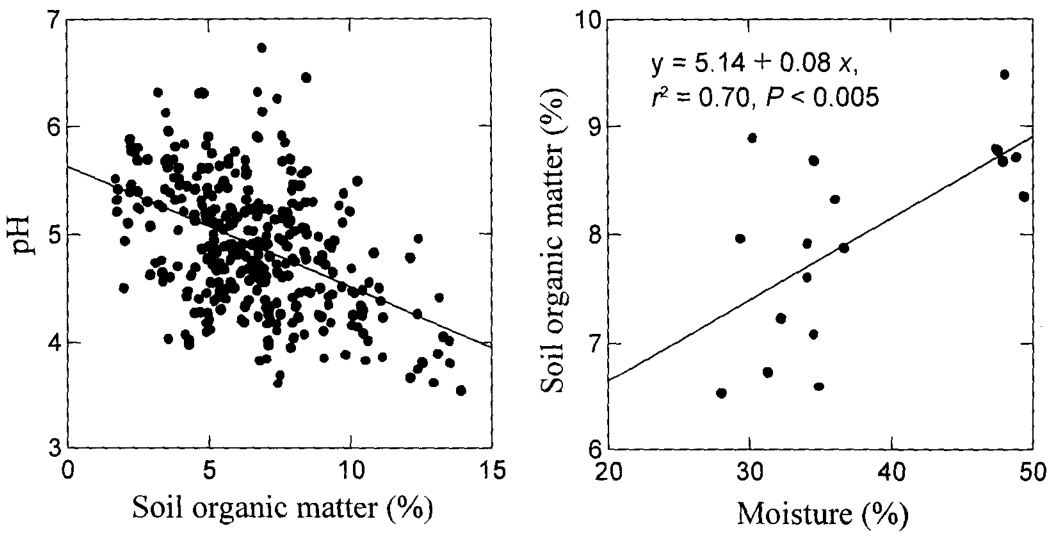
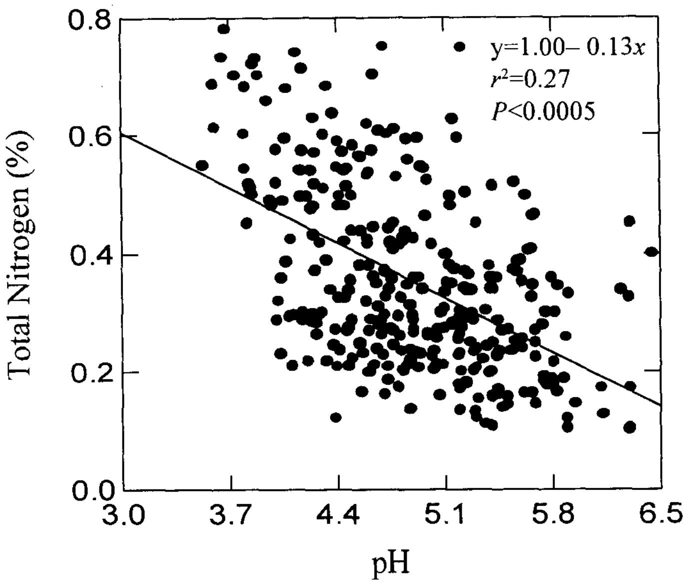


Fig. 7.2. Relationships between soil organic matter with soil pH (y=16.17–1.96x, r^2=0.23, P<0.001) and soil moisture in the age series of *Alnus*-cardamom plantation stands.



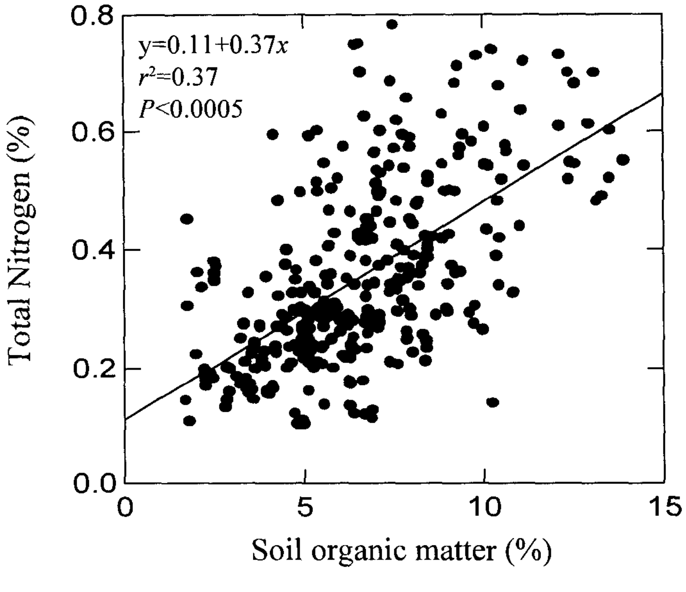


Fig. 7.3. Relationships between total nitrogen with soil pH and soil organic matter in the age series of *Alnus*-cardamom plantation stands.

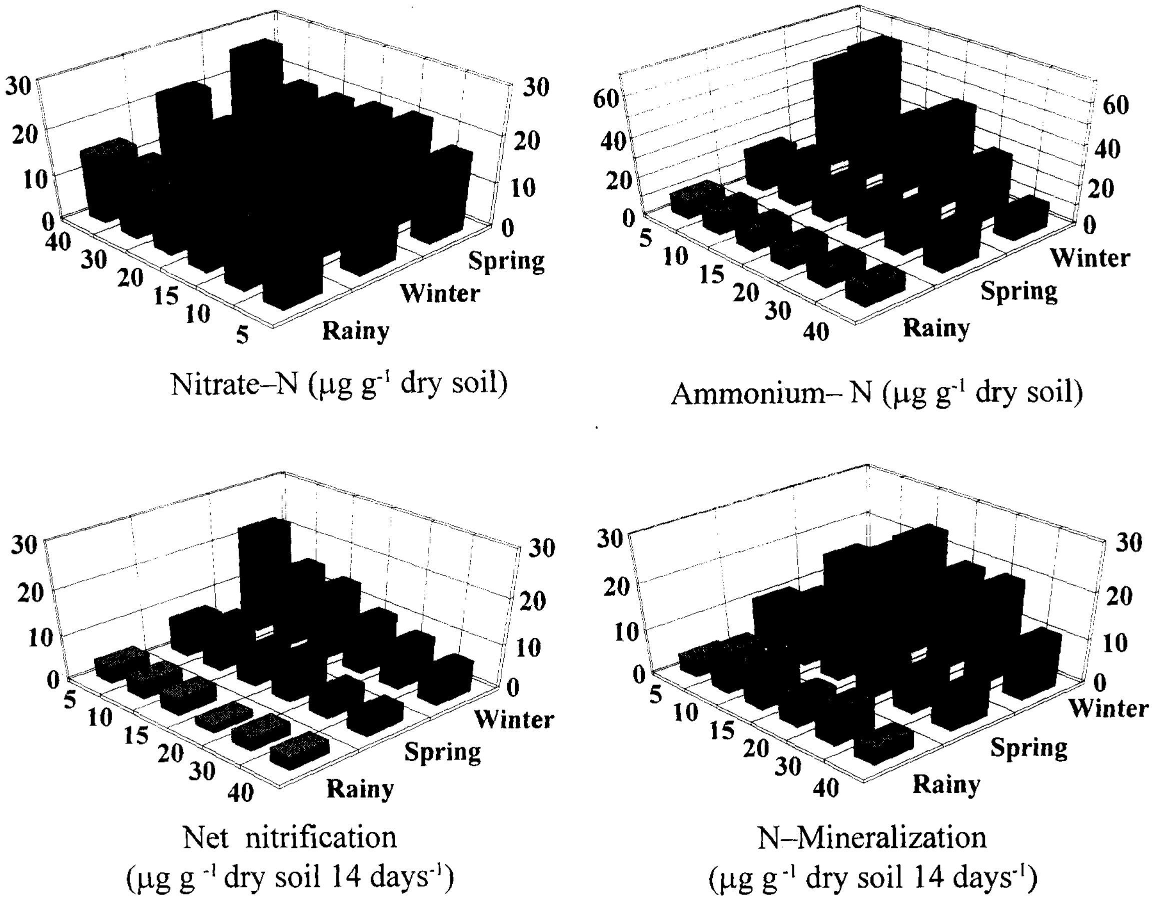
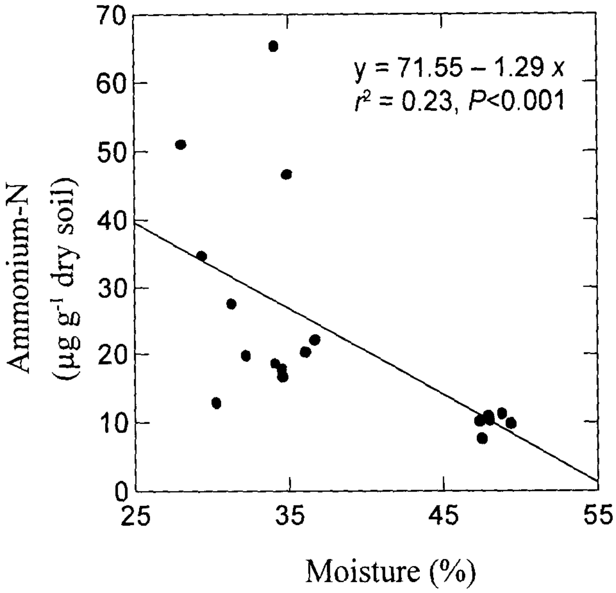


Fig. 7.4. Seasonal variation of nitrate-N and ammonium-N, and net nitrification and N-mineralization in the age series of *Alnus*-cardamom plantation stands. *ANOVA*: Nitrate-Stand age $F_{5,90} = 5.9$, $P < 0.001$, Season $F_{2,90} = 35$, $P < 0.001$, Stand age x season $F_{10,90} = 1.29$, $P < 0.02$, LSD (0.05) = 1.56; Ammonium- Stand age $F_{5,36} = 12$, $P < 0.0001$, Season $F_{2,36} = 140$, $P < 0.0001$, Stand x Season $F_{10,36} = 11$, $P < 0.0001$, LSD (0.05) = 3.7; Nitrification - Stand age $F_{5,36} = 3.04$, $P < 0.022$, Season $F_{2,36} = 27$, $P < 0.0001$, Stand age x Season = NS; N-Mineralization - Season $F_{2,90} = 12$, $P < 0.0001$, Stand age $F_{5,90} = 1.14$, NS; Stand age x Season = NS.



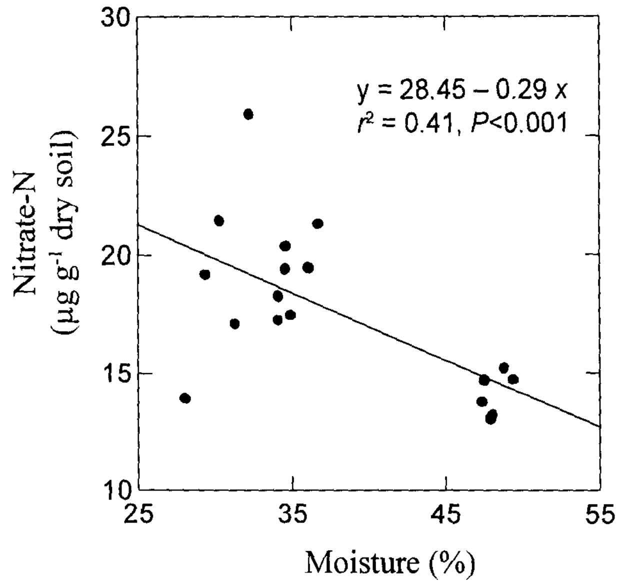


Fig. 7.5. Relationships between ammonium-N and nitrate-N with soil moisture in the age seires of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

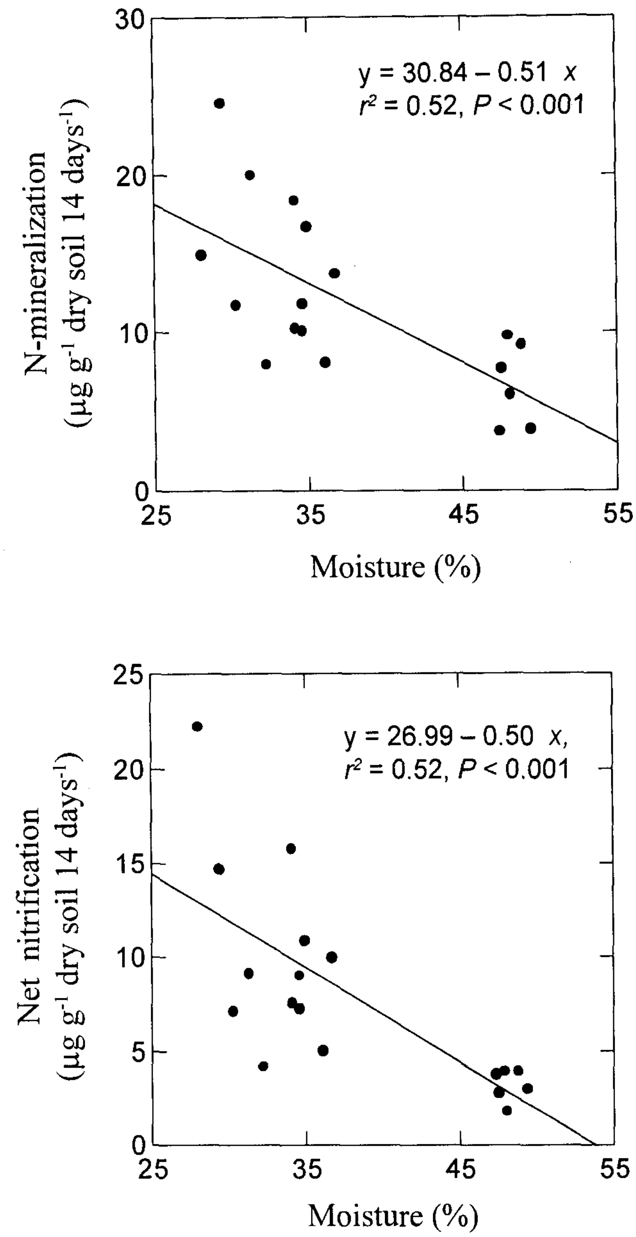


Fig. 7.6. Relationships between N-mineralization and net nitrification rates with soil moisture in an age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

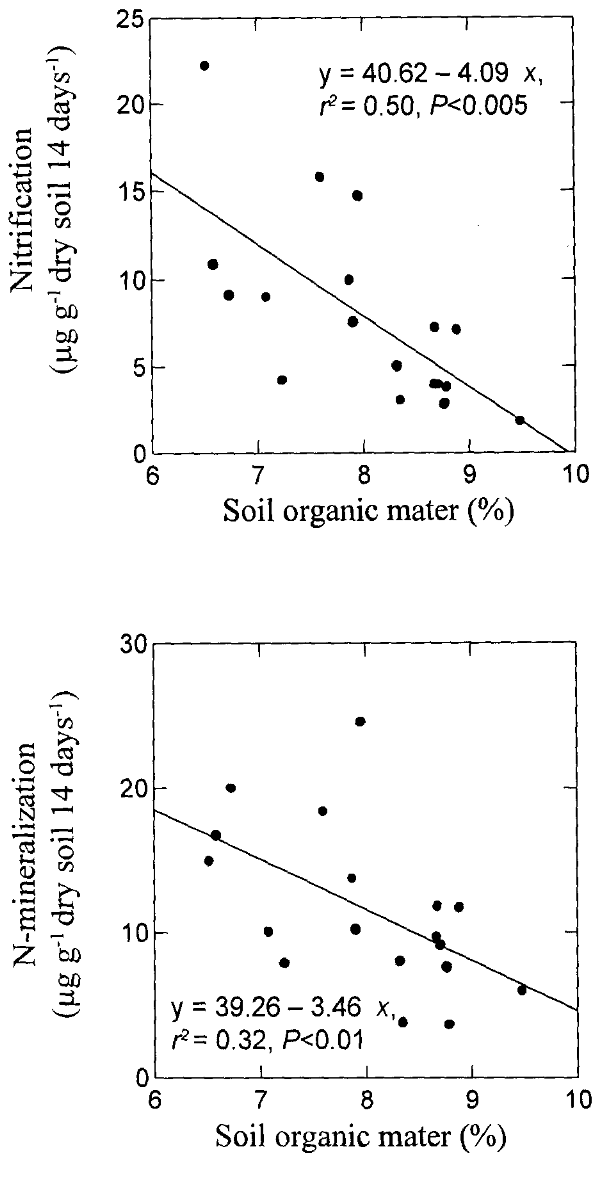


Fig. 7.7. Relationships between rates of net nitrification and N-mineralization with soil organic matter in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

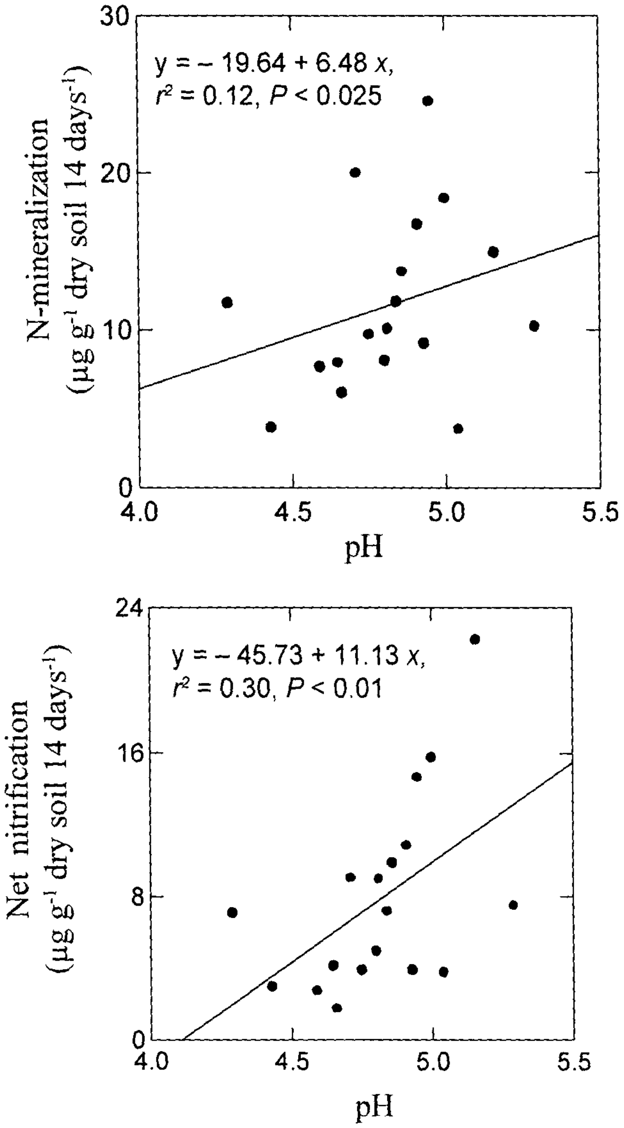


Fig. 7.8. Relationships between rates of N-mineralization and net nitrification with pH in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

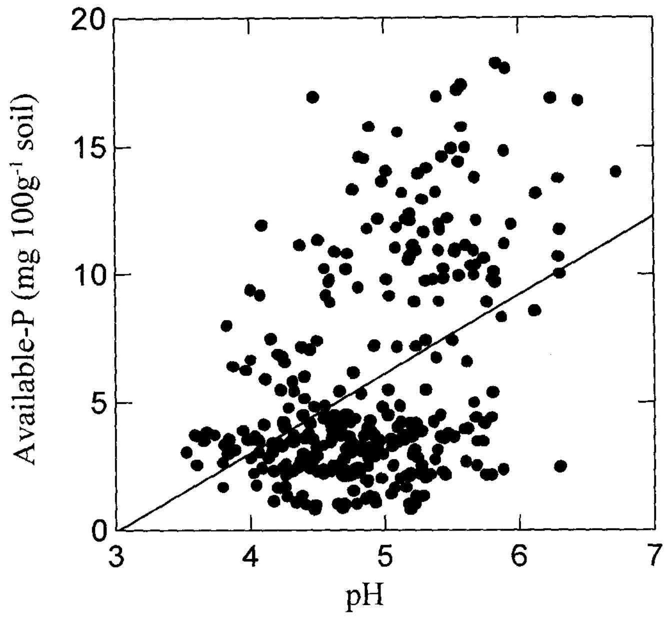


Fig. 7.9. Relationship between available phosphorus and soil pH (y = – 9.35 + 3.09 ×, $r^2 = 0.32$, $P<0.005$, $F_{1,322} = 75.68$) in the age series of *Alnus*-cardamom plantation stands across all the sites.

STAND NUTRIENT DYNAMICS

8.1 Introduction

Nutrient elements play fundamental roles in physiological activities of plants. The primary production of plantations is influenced by the availability of nutrients, and this in turn depends on distribution and rates of cycling. Concentration of nutrients within any part of an ecosystem usually depends upon a functional balance within the system. Information is scanty on the functional balance of nutrients within ecosystems where mixtures of N_2-fixing and non-N_2-fixing plants are managed.

Recently, agroforestry systems are strengthened by incorporating the N_2-fixing tree species as an intervention for influencing the soil fertility. A considerable study on the effects of N_2-fixing *Alnus* (Binkley *et al.* 1992a; Carlson and Dawson 1985; Sharma and Ambasht 1991; Bashkin and Binkley 1998; Garcia-Montiel and Binkley 1998) in agroforestry and N_2-fixing *Albizia* in *Eucalyptus* plantations (DeBell *et al.* 1989; Dukin 1989; Binkley and Giardina 1997) are available. Agroforestrey systems are dynamic in nutrient fluxes compared to forests, but studies on biogeochemical fluxes in such agroforestry systems are lacking.

Nutrient dynamics in relation to plantation age is quite important, given that the structure and functions of plantations do not remain constant as stands mature. This was reported in pure monoculture plantations of alder (Sharma 1993) in the Himalaya and lodgepole pine (Binkley *et al.* 1995) in North America. Binkley *et al.* (1992b) and DeBell *et al.* (1997) have studied nutrient availability and performance of mixtures of different percentage combinations of N_2-fixing *Albizia* and non-N_2-fixing *Eucalyptus*. However, information on nutrient dynamics for mixtures of N_2-fixing and non-N_2-fixing stands with respect to stand age and maturity is limiting. Establishment of plantation mixtures (agroforestry) of large cardamom (*Amomum subulatum* Roxb.) and N_2-fixing Himalayan alder (*Alnus nepalensis* D. Don) is a common practice in the eastern Himalaya. These *Alnus*-cardamom plantations form a good system for understanding the impact of stand age on performance of mixtures of N_2-fixing and non-N_2-fixing plants.

This chapter deals with studies on concentration, standing state, uptake, return, turnover and cycling of nutrients, nutrient use efficiency and nitrogen accretion through fixation in an age series of plantation mixtures of *Alnus* and cardamom in the Sikkim Himalaya.

8.2 Materials and methods

8.2.1 Field sampling and nutrient analysis

Sample plots of 30×40 m were marked at each of the six age series of plantation stands in all the three sites, numbering 18 plots altogether. All plant and soil samplings were made from these sample plots. Plant samples of different components (leaf, twig, catkin, branch, bole, root and root nodules of *Alnus*, and leaf, pseudo-stem, capsule, rhizome and root of cardamom) were collected in replicates (n=9; 3 samples × 3 site replicates) from all the six age group stands. These samples were oven dried at 80°C to a constant weight for determining fresh weight to dry weight ratios and ground to pass a 2-mm sieve. Total-N in these samples was analyzed using modified Kjeldahl method and P by ascorbic acid method (Anderson and Ingram 1993). Nutrient retranslocation during the senescence of leaf and twigs from the *Alnus* tree was analyzed by taking the difference of nutrients in intact and senescent parts (Rawat and Singh 1988).

Soil samples were collected for 0-15 and 15-30 cm depths from all the 18 plots representing six age groups during rainy, winter and spring seasons (see Chapter VII). Samples were air dried, ground to pass through a 2-mm sieve and used for nutrient analysis. Soil total-N and total-P were estimated by modified Kjeldahl and ascorbic acid methods, respectively (Anderson and Ingram 1993). The amount of nutrients in each horizon (0-15 and 15-30 cm) of soil was estimated using bulk density, soil volume and nutrient concentration values. The amount of nutrients estimated in both the horizons was summed to obtain total nutrient contents down to 30-cm depth.

8.2.2. Nutrients standing states and flow rates

Standing biomass, net primary productivity, litter production and cardamom yield are presented in Chapter IV and were used for quantifying nutrient contents in different plant components, floor-litter and their flow rates. Nutrient contents in different plant components were obtained by multiplying dry weight of components with their mean nutrient concentration. Monthly tree litterfall estimation was carried out for a 2-year period (1998-1999) using five litter traps of 1 m^2 collecting area in each sample plot and pooled to annual values. Cardamom tillers that have fruited in the current year were slashed to remain on the stand floor after the harvest as a management practice because it does not fruit again. Nutrient flow from tree litterfall and slashed cardamom tillers was estimated by multiplying with the nutrient concentration. The mean nutrient content of the floor litter was estimated by analyzing samples in different layers at five random (1×1 m) areas in each of the plots. Decomposition rates were calculated by enclosing litter fractions separately in nylon bags, and values of all the fractions pooled to achieve annual nutrient release.

Root nodules of five average sized *Alnus* trees from all the 18 plots were recovered for estimation of biomass and nutrient contents. Nutrient release from the root nodules of *Alnus* was estimated using nodule turnover and decomposition rate conversion factor (Sharma and Ambasht 1986b) and nutrient concentration in root nodules.

8.2.3. Computation of nutrient uptake, retention, return and turnover time

The values of nutrient contents of different plant components of both *Alnus* and cardamom were summed to obtain nutrient storage in vegetation. The sum of nutrient contents of *Alnus* trees, understorey cardamom and floor-litter represented standing state of a stand. The annual nutrient uptake was the sum of the production of nutrients in all plant components. In the case of nitrogen, the difference between total annual uptake and fixation in a stand was the net uptake from the soil. Nutrient retention was the difference between annual uptake and return through decomposition of the stand floor-litter and root nodules. Turnover time of nutrients in the standing vegetation was computed by taking the ratios of standing state and the annual uptake (Chaturvedi and Singh 1987; Sharma 1993). The turnover time for each nutrient on stand floor was calculated following Olson (1963).

8.3 Results

8.3.1. Nutrient concentrations and standing states

Nutrient concentrations of *Alnus* and cardamom components in the age series of *Alnus*-cardamom plantations are presented in Table 8.1 & 8.2. Concentrations of nutrients were highest in leaves and lowest in boles of *Alnus*, and highest in leaves and lowest in rhizomes of cardamom. The highest concentration of N in *Alnus* leaf was 11 times greater than the lowest concentration in the bole, while seven times greater in leaf than that of rhizome in cardamom. Tremendous variation of about 100 times greater P concentration was recorded in leaf (highest value) compared to bole (lowest value) of *Alnus*, and about 84 times greater in leaf than rhizome of cardamom. Mean N concentrations of different components of *Alnus* tree decreased in the order leaf>catkin>root>twig>branch>bole, similar order was recorded for P except higher concentration in twig than root. In cardamom, it followed the order leaf>capsule>root>pseudo-stem≈rhizome for N, and similar trend for P was recorded with distinctly higher value in pseudo-stem than rhizome. Foliar nutrient concentrations of *Alnus* decreased with the advancing age groups of plantations and showed inverse relationships with stand age (Fig. 8.1). Both N- and P-concentrations of foliage, decreased by about one-fourth in the 40-year stand to that of the 5-year stand.

Stand total and component wise standing stocks of nutrients are presented in Table 8.3. Standing states of N increased from the 5-year stand conspicuously which doubled by the 15-year stand, and then slightly increased to be highest at the 40-year stand. It was 2.43 times greater in the 40-year stand than that of the 5-year stand. Standing state of P also increased by 2.5 times from the 5-year stand to the 15-year stand, and then decreased to a value of 7 kg ha^{-1} in the 40-year stand. Increment in perennial parts such as branch, bole and root of *Alnus* mainly contributed nutrient buildup in biomass. The contribution of different components of cardamom to the standing state decreased after 15-year stand with advancing age.

Standing states of N including that of floor-litter was recorded lower (554 kg ha^{-1}) in the 5-year stand to a highest value (1084 kg ha^{-1}) in the 15-year stand, thereafter it slightly decreased in the advancing age. Phosphorus in the standing states was also recorded highest (48 kg ha^{-1}) in the 15-year stand, it increased from 5-year to the greatest value at the 15-year stand and then declined with advancing age.

8.3.2. Nutrient return to floor and turnover rates

Annual inputs of nutrients to the floor was mainly contributed by litterfall of *Alnus* (leaf and twig, and catkin) and slashed cardamom tillers (Table 8.4). Total nutrient return to stand floor from both *Alnus* and cardamom ranged from 3.57 kg ha^{-1} $year^{-1}$ P and 62 kg ha^{-1} $year^{-1}$ N in the 40-year stand to 7.35 kg ha^{-1} $year^{-1}$ P and 163 kg ha^{-1} $year^{-1}$ N in the 15-year stand (Table 8.4). The contribution of *Alnus* leaf and twig for both the nutrients was always highest (59–69% N; 45–62% P) in all the stands. The contribution of cardamom leaf and pseudo-stem ranged from 17–44% P and 17–32% N. Floor-litter biomass and its nutrient contents increased from the 5-year to a highest value at the 15-year and declined to a lowest value at the 40-year stand (Table 8.5). Nitrogen in the floor litter was 2.48–3.43 times greater and P

2.54–4.51 times greater than the annual input through litterfall and slashed cardamom tillers.

The values of turnover rates and times for different nutrients on the stand floor are given in Table 8.6. The turnover time of N ranged from 2.5 years in the 5-year stand to 3.4 years in the 30-year stand. P turnover time also ranged from a similar minimum value of 2.5 years at the 5-year stand to a highest value of 4.5 years at the 15-year stand. Turnover rate of N ranged from 0.29 in the 30-year stand to 0.40 in the 5-year stand, and P ranged from 0.22 in 15- and 20-year stand to 0.39 at the 5-year stand.

8.3.3. Nutrient uptake, retranslocation and turnover time

Nutrient uptake from the soil, retention in biomass and return to the soil, and standing states in the age series of plantation stands are presented in Table 8.7. Cardamom tillers that have fruited in any year are slashed immediately as a management practice because it does not fruit again. Nitrogen uptake that included addition through biological fixation was lowest (90 kg ha^{-1} $year^{-1}$) in the 40-year stand and highest (239 kg ha^{-1} $year^{-1}$) in the 15-year stand. Phosphorus uptake also showed similar pattern having the lowest value (3.83 kg ha^{-1} $year^{-1}$) at the 40-year stand and highest (10.60 kg ha^{-1} $year^{-1}$) at the 5-year stand. Annual return of N to the soil through decomposition to that of uptake ranged from 32–58% being higher in younger stands whereas P ranged from 44–66% being highest at 15- and 20-year stands.

Nutrient retranslocation from the senescent *Alnus* leaves is presented in Fig. 8.3a, b & c and 8.4a, b & c. Nitrogen retranslocation rates were lower in the youngest stand and it increased with plantation age. In the case of P, reverse was recorded having higher values in the youngest plantation that decreased with advancing age. Nitrogen retranslocation showed strong positive relationship with stand age while the relationship was inverse in P (Fig. 8.5).

Turnover time (year) of nutrients in the standing vegetation in the age series of *Alnus*-cardamom is presented in Table 8.8. Turnover time of N in the standing vegetation of both *Alnus* and cardamom increased from 1.83 years at the 5-year stand through subsequent ages to a highest value of 8.32 years at the 40-year stand. Overall turnover time for P was low ranging from 1.1 years in the 5-year stand to 1.83 years in the 40-year stand. The turnover time of both the nutrients was not much variable in cardamom components; however N turnover time increased tremendously after 15-year stand in *Alnus* whereas P remained nearly the same.

8.3.5. Nutrient use efficiency and nutrient cycling

Nutrient use efficiency (kg annual net primary productivity per kg nutrient taken up) for both N and P decreased with plantation age (Table 8.9). Nitrogen use efficiency was 98 at the 5-year stand, which decreased with increasing age to 81 at the 40-year stand. Similarly, P use efficiency at the 5-year stand was 2439 that decreased with increase in age to a minimum value of 1914 at the 40-year stand. Average P use efficiency of all stands was greater by about 25 times than that of N use efficiency.

Computation of ratios (nutrient uptake): (energy fixation efficiency) takes into account both aboveground and belowground production of plantations, and the ratios (nutrient release): (energy dissipated) are based on floor-litter and root nodule disappearance (Table 8.10). Nitrogen and P uptake per unit energy fixed remained almost similar in the younger stands and slightly increased with plantation age. Amount of nutrient released per unit energy dissipated was highest in the 5-year stand and decreased with increasing age to a minimum value in the 30-year stand.

Nitrogen distribution and flow rates in the age series of *Alnus*-cardamom plantation stands are presented in Figure 8.3a, b & c. Annual N uptake from soil in the 5-year stand was greater by 1.4 times that of 15-year stand and 3.8 times that of 40-year stand. Nitrogen accretion through fixation was highest in the 15-year stand, which was 3 times greater than that of the 5-year and 2.6 times that of the 40-year stand. About 61% of the total annual N uptake is allocated to aboveground components of *Alnus* and 15% in the cardamom in the 15-year stand. The allocation shifted to 87% in *Alnus* and just 4% in cardamom at the 40-year stand. Nitrogen exit in terms of cardamom capsule (agronomic yield) was greatest

(2.89 kg ha^{-1} year^{-1}) in the 15-year stand being 2.8 times higher that of the 5-year stand and 7.6 times of the 40-year stand.

Phosphorus distribution and flow rates in the components of both *Alnus* and cardamom in the age series of plantation stands are presented in Figure 8.4a, b & c. Annual P uptake from soil was highest in the 15-year stand (10.6 kg ha^{-1} year^{-1}) that was 1.5 times greater than the 5-year stand and 2.8 times that of the 40-year stand. In the stands up to 15 years age, allocation of P from the annual uptake remained between 30–40% in large cardamom which decreased with increasing age to just 6% allocation by the 40 years age. At the oldest stand of 40 years, 93% of annual P uptake from soil was allocated in the aboveground components of *Alnus*. Phosphorus exit from the system in the form of agronomic yield was highest in the 15-year stand (0.29 kg ha^{-1} year^{-1}), which was 2.4 times greater than the 5-year stand and 7.25 times that of the 40-year stand. Nutrient content in vegetation, litter and soil and their ratios in certain forest ecosystems of the world and a comparison of the present study are presented in Table 8.11.

8.4. Discussion

Nitrogen concentrations in different plant components of *Alnus* were higher than the respective components of cardamom. This is attributed to high rates of N_2-fixation by *Alnus* (Sharma and Ambasht 1984; Sharma *et al.* 1994). Foliar nutrient (N and P) concentrations in *Alnus* decreased consistently from the young to the older plantations. A similar trend was recorded in *Alnus rubra* by DeBell and Radwan (1984). This result suggests that the supplies of these nutrients may become limiting after certain age in the older plantation stands.

The distribution of nutrients in different components in an age series of *Alnus*-cardamom plantations depended considerably on component biomass and nutrient concentration. The standing state of nutrients in different components increased with increase in their biomass and the role of nutrient concentration was minimized. Similar report was also made by Sharma (1993) in an age series of *Alnus nepalensis* plantations, and by Rawat and Singh (1988) in *Quercus* forests in the central Himalaya. Ranges of standing states of nutrients (N 313–760 kg ha^{-1}; P 6–15 kg ha^{-1}) in the present study was compared with the range given for deciduous forests: 530–1200 kg ha^{-1} for N and 40–100 kg ha^{-1} for P (Rodin and Bazilevich 1967; Duvingnuead and Devnaeyer De-Smet 1970; Nihlgard 1972). Nitrogen standing state was within the range while P was much lower. The nutrient storage in the understorey cardamom was very high (N 2–31%; P 8–59%) and highest being at the 15-year stand. Normally, the contribution of understorey vegetation in temperate forests and plantations are below 2% (Sharma 1993; Rawat and Singh 1988; Whittaker *et al.* 1979). Substantial amount of N is extracted out from the system due to thinning of *Alnus* and extraction of fuel-wood that causes lowering of N storage in the older stands. Pressure of cattle on the older stands, overland flow and leaching of nutrients are the primary source of nutrient depletion in these stands. The higher nutrient storage in understorey cardamom of the present study is mainly attributed to the management of this cash crop. It is quite interesting that relative percentage contribution of cardamom is almost double for P compared to N.

Total annual N fixation in the monoculture stands of different ages of *Alnus nepalensis* was reported from 29–117 kg ha^{-1}, the highest recorded at the youngest stand (Sharma and Ambasht 1988). However in the present, *A. nepalensis* in combination with cardamom showed slightly higher N accretion ranging from 52–155 kg ha^{-1} $year^{-1}$. Seasonal N accretion in all the plantation stands showed that the highest values were recorded during the rainy season between July to September. Average annual N fixation recorded in this study (155 kg ha^{-1}) was higher than 130 kg ha^{-1} in *A. rubra* (Binkley 1981) and 117 kg ha^{-1} in *A. nepalensis* (Sharma and Ambasht 1988). Newton *et al.* (1968) reported annual N fixation as high as 320 kg ha^{-1} between 2- to 15-year-old *A. rubra* stands. Contribution of N accretion through fixation to the total uptake ranged from 30–65% and the highest percentage was recorded in 10-, 15- and 20-year old stands.

Annual input of N and P to the plantation floor through litterfall and slashed pseudo-stems of cardamom increased from the youngest stand to be highest in the 15-year stand and then decreased with increase in plantation age. The contribution of cardamom to the total annual input ranged from 17–32% for N and 17–44% for P. The concentration increased from the youngest stand to peak at the 15-year stand and then decreased with advancing age exactly following N accretion trend. This indicates that the nitrogen levels in cardamom components were also influenced by N accretion either by the element being available to in the soil or more allocation from soil uptake to cardamom, as *Alnus* did not compete for soil N. However, P contribution of cardamom was highest in the youngest stand and decreased with advancing age to a minimum value in the oldest stand.

Nutrient retranslocation of senescent *Alnus* leaf showed positive relationship in case of N and negative in P with stand age. The retranslocation of N in young *Alnus* trees was minimum because this nutrient was sufficiently available through fixation; however with advancing age the demand became more as contribution from fixation decreased that affected greater back translocation. In the case of P, its demand for growth was high in younger stands where effective retranslocation was recorded. It decreased with advancing stand age. *Alnus* showed entirely different physiological behaviour for both N and P at different stages of age governed mostly by demand and availability of these nutrients.

Nutrient use efficiency may be expected to drop as utilization of that nutrient increases because availability of some other resource (such as water, energy, or light) limits production (Melillo and Gosz 1983; Binkley *et al.* 1992a). The nutrient use efficiencies for both N and P in *A. nepalensis* pure monoculture plantations decreased with plantation age (Sharma 1993). In the case of mixture of *Alnus* and cardamom plantations in this study, the nutrient use efficiencies were generally consistent with the above hypothesis and decreased with plantation age. *Alnus*-cardamom mixed stands used P less efficiently compared to pure stands of the same species of *Alnus* (Sharma 1993). The *Alnus*-cardamom plantations also used N less efficiently compared to mixed *Alnus rubra*-conifer stands of USA. Comparison between *A. rubra* and conifers showed less efficiency in *A. rubra* than conifers (Binkley *et al.* 1992a).

Total uptake in *Alnus*-cardamom plantations was 90–239 kg ha^{-1} $year^{-1}$ for N and 3.8–10.6 kg ha^{-1} $year^{-1}$ for P, being lower for N and higher for P compared to monoculture plantations of *A. nepalensis* (Sharma 1993). Rawat and Singh (1988) estimated nutrient uptake in a Himalayan oak forest and reported 230 kg ha^{-1} $year^{-1}$ N and 13 kg ha^{-1} $year^{-1}$ P. These comparisons revealed that pure *Alnus* plantations showed higher N uptake and lower P uptake, and in the mixed stands cardamom N uptake decreased while P uptake increased. The low P uptake in pure *A. nepalensis* was attributed to a negative effect of *Alnus* on the P economy mostly by increasing soil acidity (Sharma 1993), which causes a transition of phosphate into less soluble compounds with Fe and Al (Brozek 1990; Sharma *et al.* 1997b). Furthermore, a heavy accumulation of organic matter in soils of pure *Alnus* plantation stands could have shifted P from a plant available pool to an organically bound pool (Sharma 1993). The combination of *Alnus* with cardamom is a system where N and P uptakes are balanced compared to either pure stands of N_2-fixing species or non-N_2-fixing species. Therefore, plantation systems with mixture of N_2-fixing and non-N_2-fixing species like *Alnus*-cardamom of the present study are advantageous in balancing N and P cycling.

Turnover time in standing vegetation reflects the rate of nutrient cycling, and the mean turnover time of P was lower than N. The P turnover time remained between 1 to 2 years at all the plantation age, while N increased from 2 year in youngest stand to more than 8 years in oldest stand. The N turnover of the stand was mostly affected by *Alnus* component than the cardamom. Sharma (1993) also reported lower turnover time of P than N in an age series of pure *A. nepalensis* plantations; however they were greater for both N and P than the mixed *Alnus*-cardamom plantations of the present study. The turnover time of nutrients on the plantation floor however was slightly higher for P than N. This finding suggests that P cycling in vegetation was much quicker than N in stands with mixture of N_2-fixing and non-N_2-fixing species.

Consistently high net primary production in the age series of *Alnus*-cardamom is in conformity with marked retention of nutrients by the plants over the annual cycles. Ratio of nutrient uptake and net energy fixation remained almost similar in all the ages of *Alnus*- cardamom plantations. However, N and P uptake per unit energy fixed was higher than results of the present study and the ratios increased with plantation age in monocultures of *A. nepalensis* stands (Sharma 1993).

Performance of cardamom under the influence of N_2-fixing *Alnus* in an age series of plantations with regards to nutrient use efficiencies, nutrient dynamics and cycling suggest the system to be sustainable up to 20 years, and adoption of replantation after 20 years for both *Alnus* and cardamom would be highly beneficial and sustainable ❖

Table 8.1. Per cent nitrogen (N) and phosphorus (P) concentrations in *Alnus* tree components in an age series of *Alnus*-cardamom plantation stands. Values are mean ±SE, n=3

Plant components	Nutrient	Stand age (year)					
		5	10	15	20	30	40
Tree							
Leaf	N	3.641 ±0.21	3.490 ±0.350	3.162 ±0.310	2.932 ±0.531	2.852 ±0.310	2.631 ±0.122
	P	0.205 ±0.03	0.180 ±0.08	0.170 ±0.08	0.167 ±0.04	0.162 ±0.03	0.151 ±0.016
Twig	N	0.810 ±0.02	0.780 ±0.128	0.942 ±0.110	0.703 ±0.210	0.950 ±0.036	0.847 ±0.15
	P	0.052 ±0.01	0.017 ±0.003	0.024 ±0.001	0.027 ±0.003	0.031 ±0.001	0.021 ±0.001
Catkin	N	2.430 ±0.21	2.618 ±0.14	2.655 ±0.21	2.705 ±0.120	2.645 ±0.01	2.624 ±0.02
	P	0.130 ±0.01	0.150 ±0.014	0.161 ±0.013	0.182 ±0.011	0.163 ±0.003	0.156 ±0.007
Branch	N	0.640 ±0.01	0.580 ±0.002	0.591 ±0.001	0.642 ±0.004	0.612 ±0.005	0.656 ±0.003
	P	0.004 ±0.00	0.003 ±0.0001	0.003 ±0.0002	0.006 ±0.0003	0.005 ±0.0001	0.003 ±0.0001
Bole	N	0.33 ±0.01	0.294 ±0.008	0.332 ±0.001	0.343 ±0.002	0.321 ±0.001	0.355 ±0.002
	P	0.002 ±0.00	0.003 ±0.0001	0.003 ±0.0002	0.004 ±0.0001	0.002 ±0.0001	0.003 ±0.0001
Root	N	1.20 ±0.01	1.310 ±0.001	1.415 ±0.003	1.513 ±0.032	1.210 ±0.024	1.115 ±0.036
	P	0.005 ±0.002	0.006 ±0.0001	0.007 ±0.001	0.004 ±0.002	0.005 ±0.001	0.005 ±0.0032

Table 8.2. Per cent nitrogen (N) and phosphorus (P) concentrations in plant components of cardamom in the age series of *Alnus*-cardamom plantation stands. Values are mean ± SE, n=3

Plant components	Nutrient	Stand age (year)					
		5	10	15	20	30	40
Cardamom							
Leaf	N	2.067 ±0.021	2.155 ±0.012	2.091 ±0.031	2.075 ±0.013	1.973 ±0.031	2.095 ±0.002
	P	0.115 ±0.009	0.137 ±0.007	0.158 ±0.01	0.167 ±0.02	0.139 ±0.004	0.091 ±0.006
Pseudo-stem	N	0.364 ±0.021	0.398 ±0.030	0.367 ±0.008	0.607 ±0.001	0.577 ±0.004	0.325 ±0.014
	P	0.061 ±0.001	0.080 ±0.005	0.067 ±0.003	0.077 ±0.004	0.088 ±0.006	0.032 ±0.005
Capsule	N	0.910 ±0.176	0.849 ±0.149	0.938 ±0.166	1.00 ±0.102	0.854 ±0.261	0.952 ±0.122
	P	0.107 ±0.015	0.0929 ±0.002	0.094 ±0.002	0.089 ±0.008	0.091 ±0.002	0.092 ±0.001
Rhizome	N	0.620 ±0.011	0.487 ±0.003	0.520 ±0.002	0.503 ±0.002	0.310 ±0.020	0.542 ±0.002
	P	0.002 ±0.000	0.002 ±0.000	0.003 ±0.000	0.002 ±0.000	0.004 ±0.000	0.002 ±0.000
Root	N	0.612 ±0.01	0.544 ±0.01	0.635 ±0.04	0.543 ±0.005	0.611 ±0.002	0.630 ±0.03
	P	0.089 ±0.0001	0.054 ±0.0002	0.082 ±0.005	0.083 ±0.003	0.091 ±0.004	0.092 ±0.005

Table 8.3. Standing state of nutrients (kg ha^{-1}) in different *Alnus* and cardamom components in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates (± s.e.; $n = 9$)

Stand age (year)	Nutrients	*Alnus*					Cardamom			Stand total
		LT	CT	BR	BO	RT	CL	PS	RR	
5	N	42.04 ±2.61	7.35 ±0.94	43.71 ±4.21	51.88 ±9.61	106.33 ±14.29	12.82 ±1.23	6.79 ±0.65	42.09 ±6.00	313
	P	2.43 ±0.14	0.39 ±0.05	0.29 ±0.03	0.28 ±0.01	0.83 ±0.06	0.94 ±0.09	1.14 ±0.11	0.14 ±0.01	6
10	N	61.94 ±2.66	11.49 ±1.66	55.66 ±7.30	66.23 ±5.77	122.93 ±5.27	26.69 ±6.16	14.85 ±3.43	65.54 ±15.09	425
	P	2.86 ±0.14	0.67 ±0.11	0.37 ±0.05	0.36 ±0.03	1.31 ±0.02	1.70 ±0.39	2.98 ±0.69	0.30 ±0.01	11
15	N	54.15 ±3.18	13.91 ±1.91	87.16 ±20.80	115.38 ±32.80	178.67 ±52.00	48.57 ±20.02	25.65 ±10.56	131.56 ±26.65	655
	P	2.56 ±0.06	0.81 ±0.12	0.59 ±0.14	0.63 ±0.18	1.61 ±0.23	3.67 ±1.51	4.68 ±1.93	0.58 ±0.12	15
20	N	44.45 ±5.32	14.81 ±2.13	112.53 ±20.77	158.18 ±29.13	242.25 ±34.64	21.98 ±2.14	19.30 ±1.89	54.27 ±3.98	668
	P	2.37 ±0.29	0.99 ±0.14	0.76 ±0.14	0.87 ±0.16	1.86 ±0.15	1.77 ±0.17	2.44 ±0.24	0.24 ±0.02	11
30	N	34.64 ±3.06	14.04 ±1.85	121.03 ±21.48	194.65 ±33.46	246.12 ±43.26	14.60 ±4.46	8.28 ±2.57	24.68 ±7.65	658
	P	1.77 ±0.16	0.85 ±0.14	0.81 ±0.15	0.97 ±0.18	1.39 ±0.19	1.01 ±0.32	1.93 ±0.38	0.18 ±0.05	9
40	N	30.88 ±0.49	13.78 ±2.46	165.57 ±44.36	264.74 ±19.00	266.09 ±54.76	6.31 ±2.02	2.86 ±0.98	9.38 ±1.01	760
	P	1.63 ±0.02	0.79 ±0.14	1.11 ±0.29	1.44 ±0.43	1.46 ±0.24	0.28 ±0.58	0.28 ±0.09	0.03 ±0.004	7

LT = leaf and twig; CT = catkin; BR = branch; BO = bole; RT = root and root nodule; CL = cardamom leaf; PS = pseudo-stem; RR = root and rhizome; N = nitrogen; P = phosphorus

Table 8.4. Annual input of nitrogen and phosphorus (kg ha^{-1}) to the stand floor through litter production in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates (± s. e.; $n = 9$)

Stand age (year)	Nutrients	*Alnus* leaf & twig	*Alnus* catkin	Cardamom leaf & pseudo-stem	Stand total
5	N	63.52±2.61	7.35±0.94	26.06±0.55	96.93
	P	2.49±0.14	0.39±0.52	2.28±0.05	5.16
10	N	75.09±2.70	11.49±1.66	27.69±2.18	114.27
	P	2.54±0.12	0.67±0.11	2.40±0.19	5.61
15	N	97.86±3.20	13.31±1.91	51.36±1.03	162.53
	P	3.96±0.10	0.81±0.12	2.58±0.52	7.35
20	N	68.53±5.32	14.81±2.13	22.11±5.05	105.45
	P	3.00±0.28	0.99±0.14	2.01±0.46	6.00
30	N	64.88±3.10	14.03±1.85	16.44±1.71	95.36
	P	3.16±0.16	0.85±0.11	1.39±0.14	5.40
40	N	36.80±0.50	13.78±2.46	11.74±0.69	62.32
	P	2.18±0.02	0.79±0.14	0.60±0.03	3.57

N = nitrogen; P = phosphorus

Table 8.5. Floor-litter biomass and nutrient content in the age series of *Alnus*-cardamom plantation stands. Values are means of three site replicates.

Stand age (year)	Floor-litter ($t\ ha^{-1}$)	Nutrients ($kg\ ha^{-1}$)	
		Nitrogen	Phosphorus
5	18.51 ±0.25	240.63 ±18.19	13.14 ±2.45
10	23.16 ±2.06	305.71 ±10.73	22.00 ±5.77
15	34.91 ±1.24	429.39 ±11.52	33.16 ±4.89
20	28.05 ±1.44	339.41 ±12.42	26.96 ±1.23
30	24.27 ±0.58	327.65 ±13.49	18.20 ±1.9
40	14.67 ±1.04	176.04 ±14.00	11.88 ±2.68

Table 8.6. Turnover rate (k) and turnover time (t, years) of nutrients on stand floor in the age series of *Alnus*-cardamom plantation stands. Values are pooled from three site replicates.

Stand age (year)	Nitrogen		Phosphorus	
	k	*t*	*k*	*t*
5	0.40	2.5	0.39	2.5
10	0.37	2.6	0.26	3.9
15	0.38	2.7	0.22	4.5
20	0.31	3.2	0.22	4.4
30	0.29	3.4	0.29	3.6
40	0.35	3.0	0.30	3.4

Table 8.7. Uptake, retention, return and standing state of nutrients in the age series of *Alnus*-cardamom plantation stands. Values are pooled from three site replicates.

Nutrients	Stand age (year)	Uptake	Return	Retention	Standing state ** (kg ha^{-1})
		(kg ha^{-1} year^{-1})			
Nitrogen	5	171.04*	71.26	99.78	553.64
	10	202.36*	102.37	99.99	731.04
	15	238.83*	126.46	112.37	1084.44
	20	168.85*	68.93	99.92	1006.87
	30	150.47*	66.50	83.97	970.84
	40	90.12*	44.97	45.15	926.14
Phosphorus	5	6.86	3.77	3.09	19.58
	10	8.77	4.88	3.89	32.55
	15	10.60	5.56	5.04	48.29
	20	7.62	3.74	3.88	38.26
	30	6.79	3.09	3.70	27.11
	40	3.83	2.51	1.32	18.90

* Includes biological nitrogen fixation

** Includes floor litter nutrient

Table 8.8. Turnover time (year) of nutrients in the standing vegetation of *Alnus* and cardamom in the age series of *Alnus*-cardamom plantation stands. Values are pooled for three site replicates.

Stand age (year)	Nitrogen			Phosphorus		
	Alnus	Cardamom	Stand total	*Alnus*	Cardamom	Stand total
5	1.87	1.69	1.83	0.89	1.02	1.10
10	2.08	2.16	2.10	1.12	1.32	1.20
15	2.66	3.23	2.74	0.89	2.17	1.43
20	4.18	2.78	3.95	1.25	2.07	1.48
30	4.96	2.06	4.62	1.09	2.08	1.31
40	8.67	3.09	8.32	1.78	2.68	1.83

Table 8.9. Nutrient use efficiency in the age series of *Alnus*-cardamom plantation stands. Values are pooled from three site replicates.

Stand age (year)	Total net primary productivity ($t\ ha^{-1}\ year^{-1}$)	Nutrient use efficiency	
		Nitrogen	Phosphorus
5	16.73	97.81	2438.78
10	19.57	96.71	2231.47
15	22.40	93.71	2111.32
20	14.72	87.18	1934.36
30	13.06	86.79	1923.42
40	7.35	81.34	1913.84

Table 8.10. Ratios between nutrient uptake (NU) and net energy fixation (NEF), and nutrient release (NR) and energy dissipation (ED) in the age series of *Alnus*-cardamom plantation stands. NU and NR are quantified as kg ha^{-1} $year^{-1}$ and NEF and ED as kJ ha^{-1} $year^{-1}$. Values are pooled from three site replicates

Ratio	Stand age (year)	Nitrogen	Phosphorus
NU: NEF	5	0.531	0.021
	10	0.520	0.023
	15	0.538	0.024
	20	0.554	0.025
	30	0.577	0.026
	40	0.585	0.030
NR: ED	5	0.67	0.024
	10	0.52	0.022
	15	0.46	0.019
	20	0.31	0.012
	30	0.28	0.012
	40	0.37	0.013

Table 8.11. Nutrient content (kg) in vegetation (V), litter (L) and soil (S) and their ratios in certain forest ecosystems of the world.

Forest	Parameter	N	P	Ca	Mg	K	Reference
Pinus banksiana (Ontario, Canada)	V	165	14	112	18	82	Foster & Morrison (1976)
	L	328	43	500	116	524	
	S (0-30 cm)	3729	29a	118b	29b	388b	
	L/V	2	3	5	6	5	
	S/V	23	2	2	2	5	
Pine forest, Central Himalaya, India	V	1145	148	540	212	378	Chaturbedi & Singh (1987)
	L	131	11	83	20	24	
	S (0-20 cm)	3964	218	2883	319	248	
	L/V	0.11	0.07	0.15	0.09	0.06	
	S/V	3.46	1.47	5.33	1.50	0.66	
Alnus nepalensis, Eastern Himalaya	V	3516	27	758	-	1264	Sharma & Ambasht (1993)
	L	975	27	115	-	147	
	S (100 cm)	32740	811	873	-	440	
	L/V	0.28	1.0	0.15	-	0.12	
	S/V	9.3	30.0	1.15	-	0.35	
Alnus-cardamom plantations, Sikkim Himalaya	V	313-750	6.44-15.13				Present study
	L	176-149	11.88-33.20				
	S(0-30 cm)	8360-11663	2192-2554				
	L/V	0.23-0.77	1.69-2.19				
	S/V	11.98-26.71	169-355				

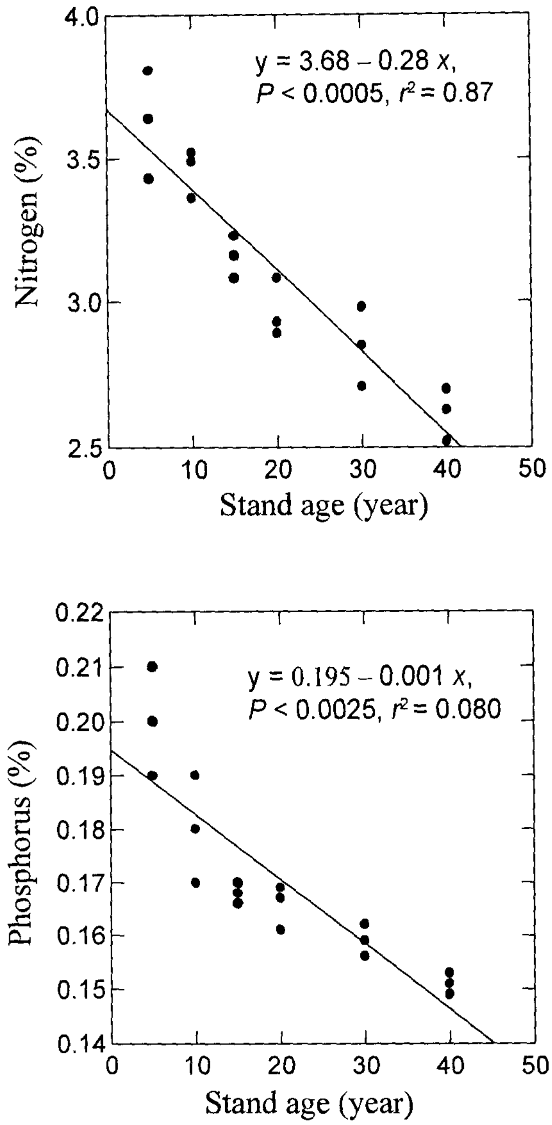


Fig. 8.1. Relationships between foliar nitrogen and phosphorus concentration of *Alnus nepalensis* with stand age in an age series of *Alnus*-cardamom plantation stands.

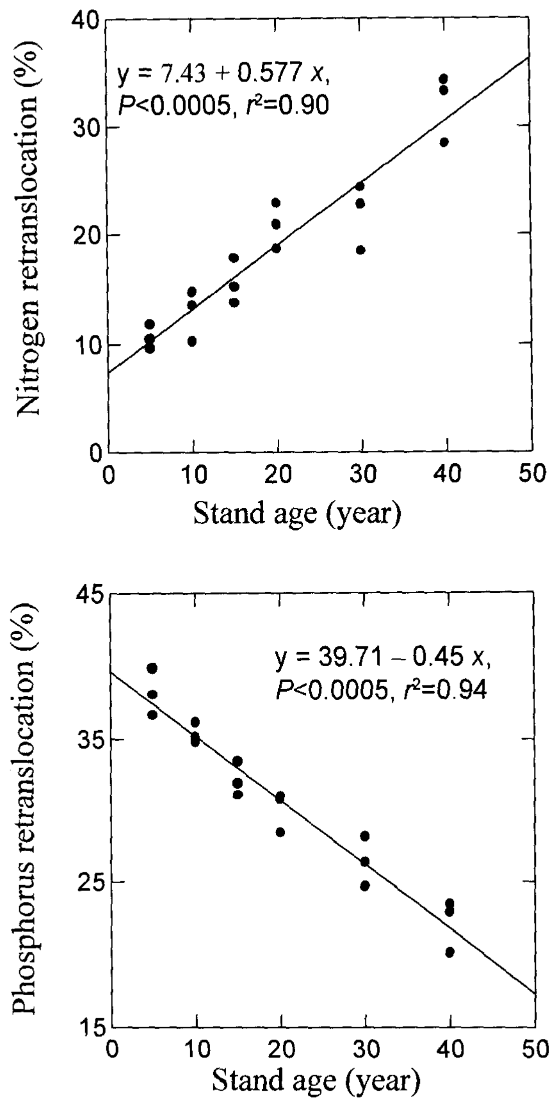
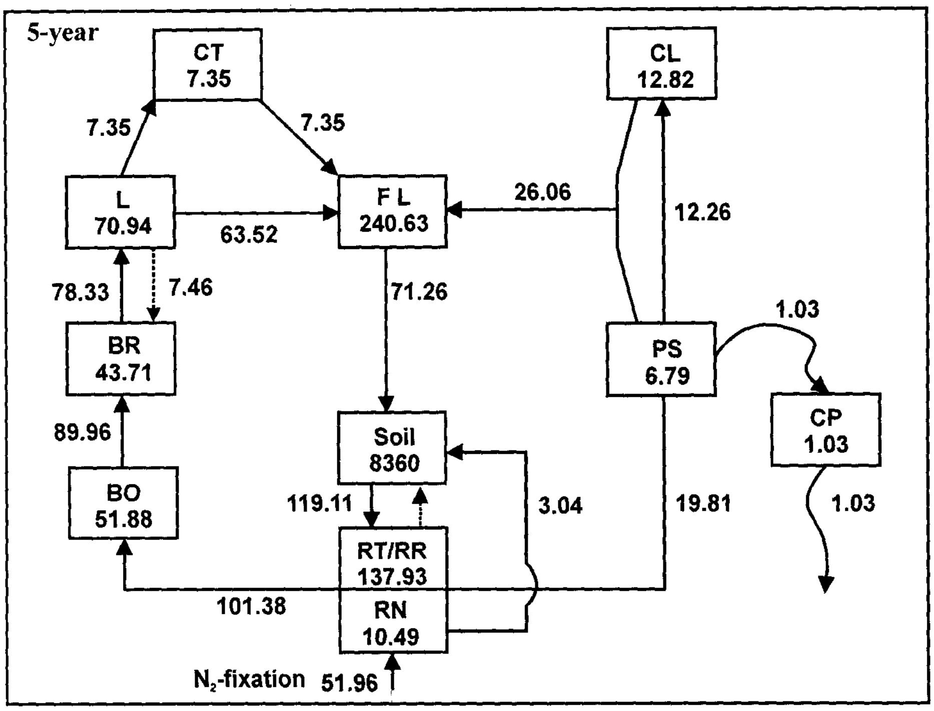


Fig. 8.2. Relationships between nitrogen and phosphorus retranslocation with stand age in the age series of *Alnus*-cardamom plantation stands.

Fig. 8.3a. D stribution of nitrogen and flow rates in the plant component of *Alnus* and cardamom in 5- and 10-year *Alnus*-cardamom plantation stands. Units are kg ha^{-1} for compartme its and kg ha^{-1} $year^{-1}$ for flows. Soil total nitrogen is presented for top 30 cm depth. Broken lines indicate re ranslocation. CT=catkin, L=leaf, BR=branch, BO=bole, R =root, RR=rhizome, RN=root nodule, FL=floor litter, CL=cardamom leaf, PS=pseudo-stem, CP=cardamom capsule


5-year
CT
7.35
CL
12.82
7.35
7.35
L
70.94
F L
240.63
26.06
12.26
63.52
78.33
7.46
71.26
1.03
BR
43.71
PS
6.79
CP
1.03
89.96
Soil
8360
BO
51.88
119.11
3.04
19.81
1.03
RT/RR
137.93
101.38
RN
10.49
N₂-fixation
51.96

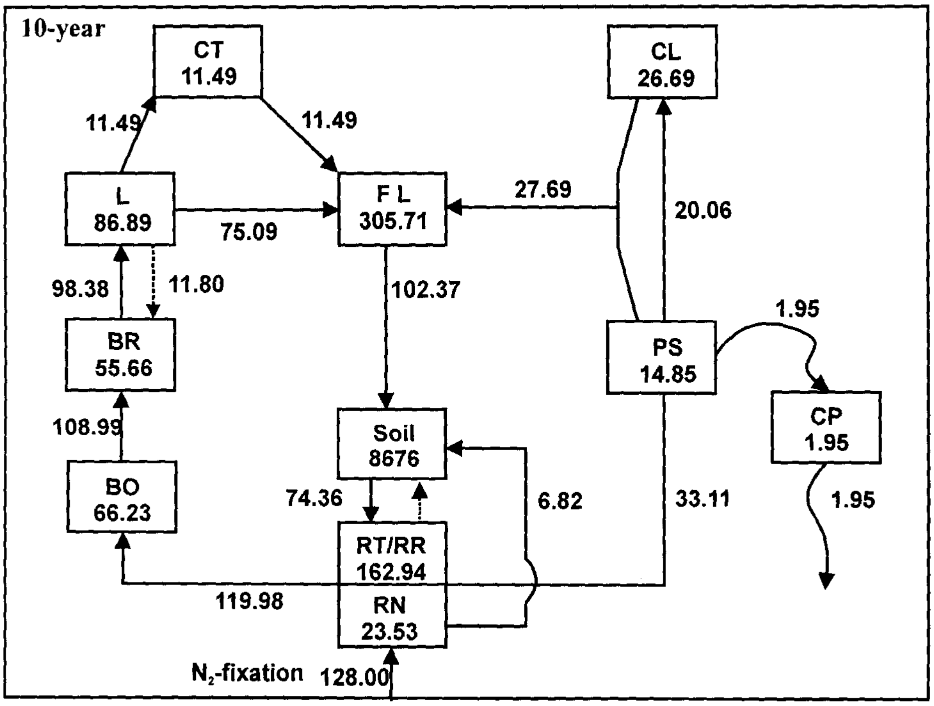
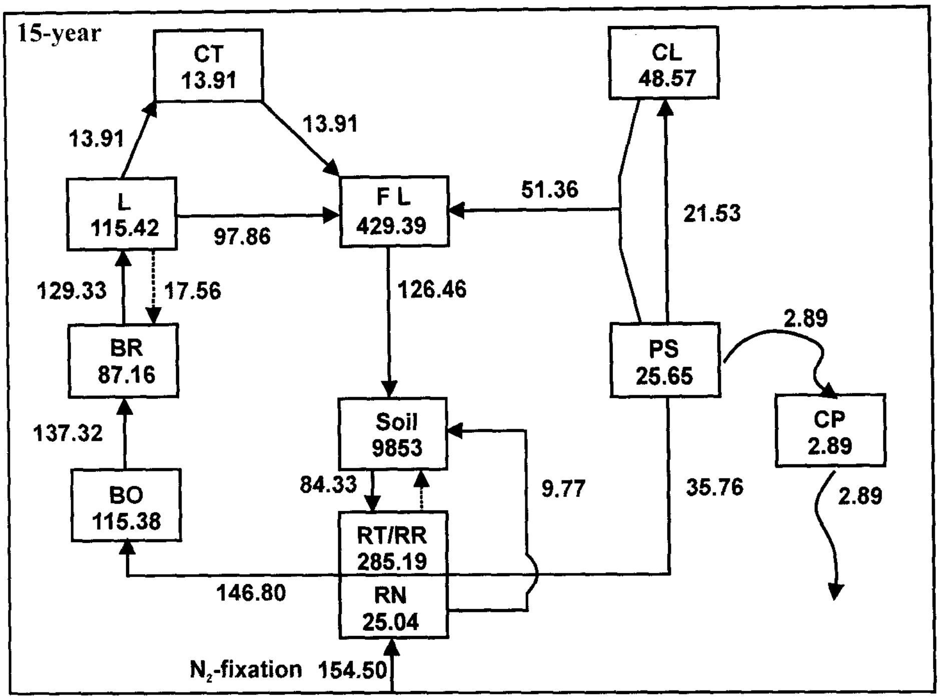

10-year
CT
11.49
CL
26.69
11.49
11.49
L
86.89
F L
305.71
27.69
20.06
75.09
98.38
11.80
102.37
1.95
BR
55.66
PS
14.85
CP
1.95
108.99
Soil
8676
BO
66.23
74.36
6.82
33.11
1.95
RT/RR
162.94
119.98
RN
23.53
N₂-fixation
128.00

Fig. 8.3b. Distribution of nitrogen and flow rates in the plant components of *Alnus* and cardamom in 15- and 20-year *Alnus*-cardamom plantation stands. Units are kg ha^{-1} for compartments and kg ha^{-1} $year^{-1}$ for flows. Soil total nitrogen is presented for top 30 cm depth. Broken lines indicate retranslocation. CT=catkin, L=leaf, BR=branch, BO=bole, RT=root, RR=rhizome, RN=root nodule, FL=floor litter, CL=cardamom leaf, PS=pseudo-stem, CP=cardamom capsule


15-year
CT
13.91
CL
48.57
13.91
13.91
L
115.42
97.86
F L
429.39
51.36
21.53
129.33
17.56
126.46
BR
87.16
PS
25.65
2.89
CP
2.89
137.32
Soil
9853
BO
115.38
84.33
9.77
35.76
2.89
RT/RR
285.19
146.80
RN
25.04
N2-fixation 154.50

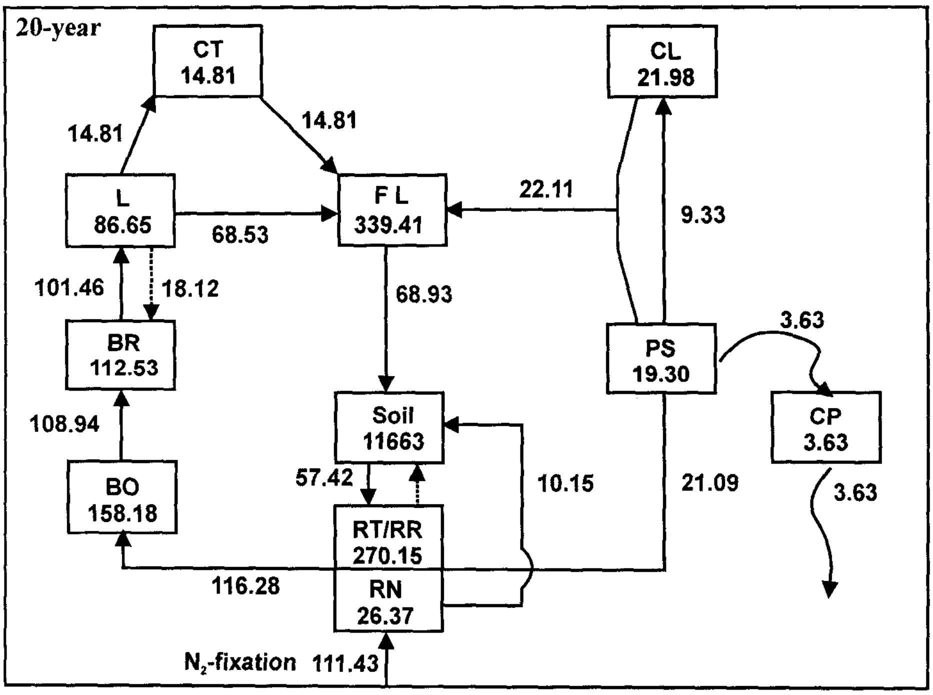
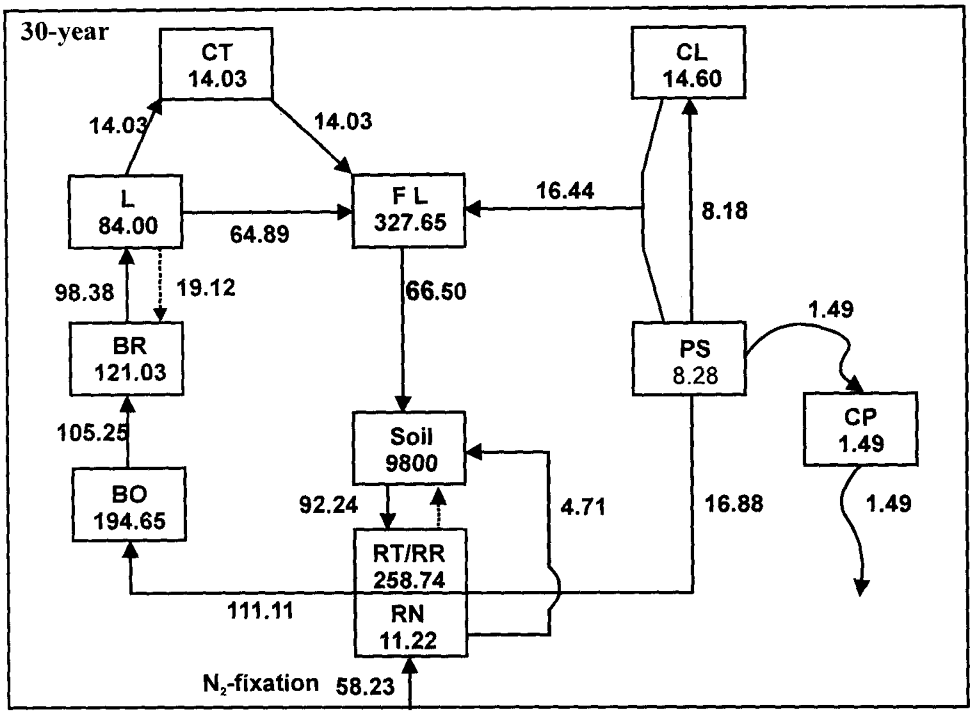

20-year
CT
14.81
CL
21.98
14.81
14.81
L
86.65
68.53
F L
339.41
22.11
9.33
101.46
18.12
68.93
BR
112.53
PS
19.30
3.63
CP
3.63
108.94
Soil
11663
BO
158.18
57.42
10.15
21.09
3.63
RT/RR
270.15
116.28
RN
26.37
N2-fixation 111.43

Fig. 8.3c. D stribution of nitrogen and flow rates in the plant component ; of *Alnus* and cardamom in 30- and 40-year *Alnus*-card mom plantation stands. Units are kg ha^{-1} for compartme its and kg ha^{-1} $year^{-1}$ for flows. Soil total nitrogen is presented for top 30 cm depth. Broken lines indicate re translocation. CT=catkin, L=leaf, BR=branch, BO=bole, R =root, RR=rhizome, RN=root nodule, FL=floor litter, CL=c rdamom leaf, PS=pseudo-stem, CP=cardamom capsule


30-year
CT
14.03
14.03
14.03
CL
14.60
L
84.00
F L
327.65
16.44
8.18
64.89
98.38
19.12
66.50
1.49
BR
121.03
PS
8.28
CP
1.49
105.25
Soil
9800
BO
194.65
92.24
4.71
16.88
1.49
RT/RR
258.74
111.11
RN
11.22
N₂-fixation 58.23

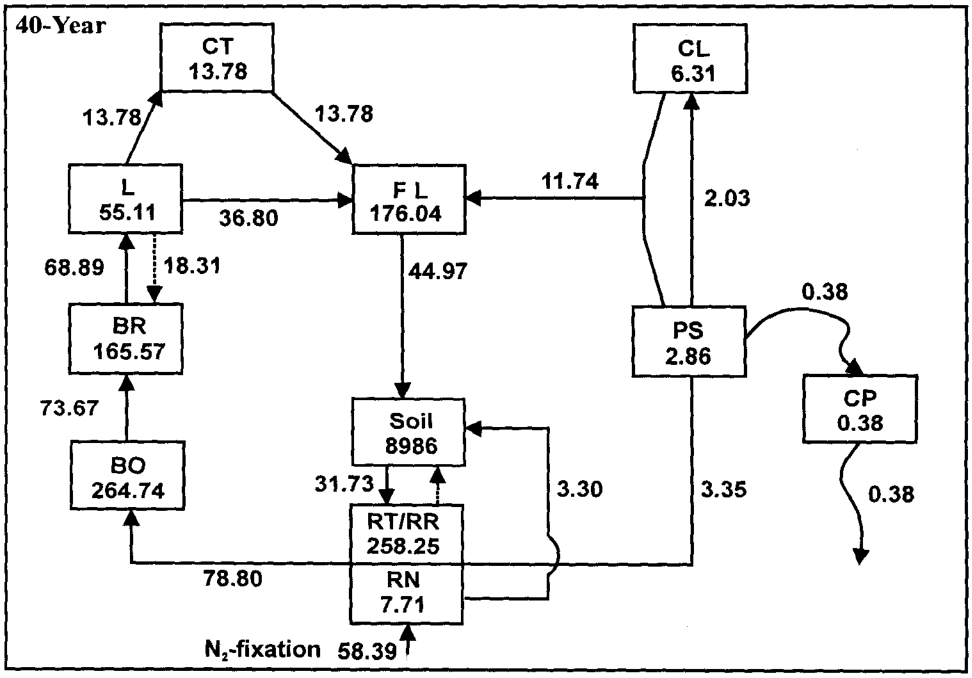
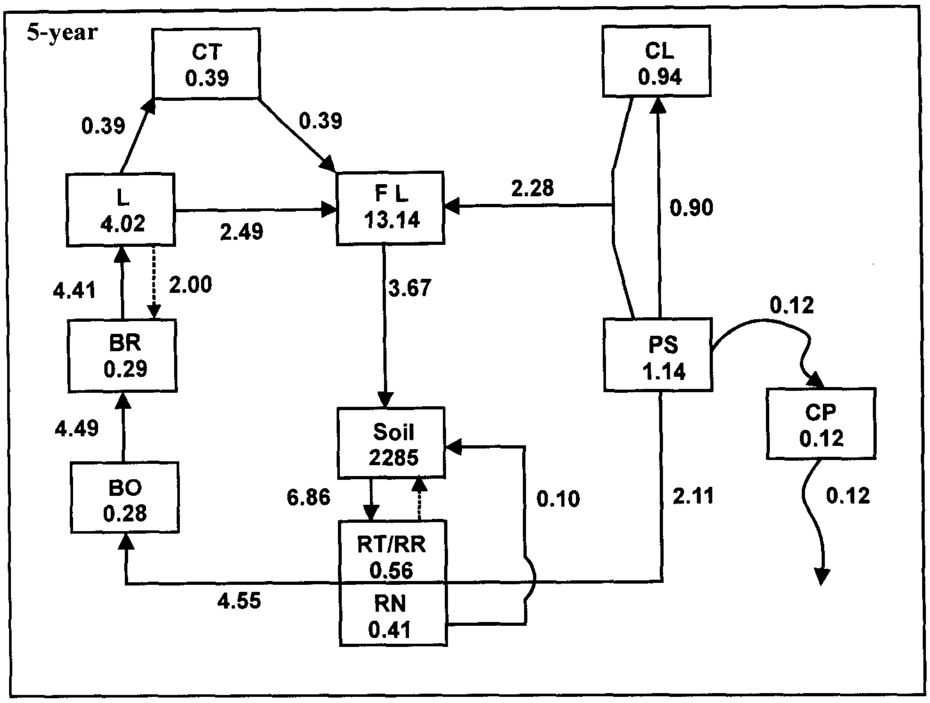

40-Year
CT
13.78
CL
6.31
13.78
13.78
L
55.11
F L
176.04
11.74
2.03
36.80
68.89
18.31
44.97
0.38
BR
165.57
PS
2.86
CP
0.38
73.67
Soil
8986
BO
264.74
31.73
3.30
3.35
0.38
RT/RR
258.25
78.80
RN
7.71
N₂-fixation 58.39

Fig. 8.4a. Distribution of phosphorus and flow rates in the plant components of *Alnus* and cardamom in 5- and 10-year *Alnus*-cardamom plantations stands. Units are kg ha^{-1} for compartments and kg ha^{-1} $year^{-1}$ for flows. Soil total phosphorus is presented for top 30 cm depth. Broken lines indicate retranslocation. CT=catkin, L=leaf, BR=branch, BO=bole, RT=root, RR=rhizome, RN=root nodule, FL=floor litter, CL=cardamom leaf, PS=pseudo-stem, CP=cardamom capsule


5-year
CT 0.39
0.39
0.39
CL 0.94
L 4.02
2.49
F L 13.14
2.28
0.90
4.41
2.00
3.67
0.12
BR 0.29
PS 1.14
4.49
Soil 2285
CP 0.12
BO 0.28
6.86
0.10
2.11
0.12
RT/RR 0.56
4.55
RN 0.41

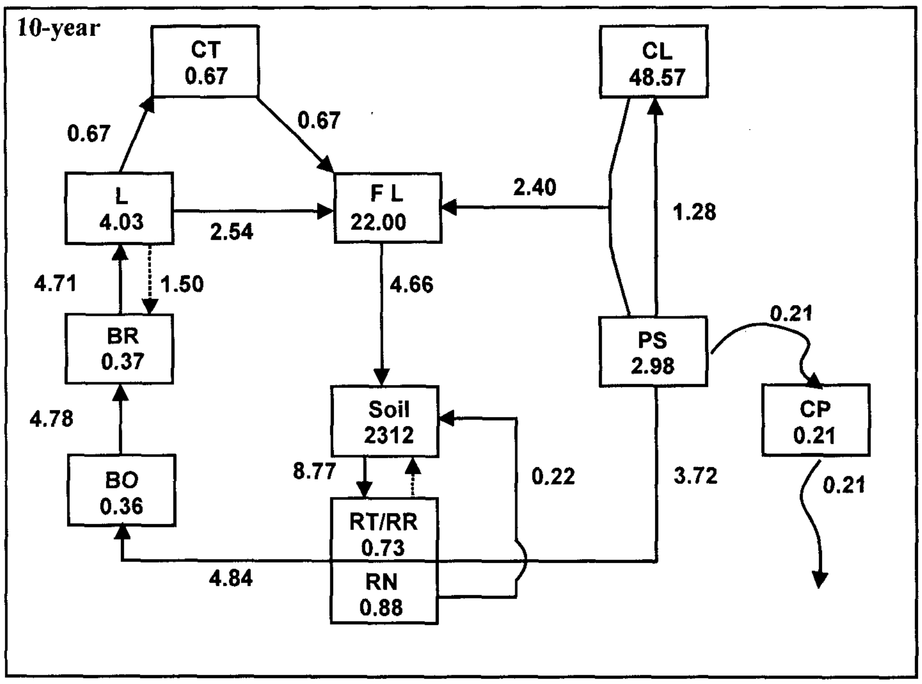
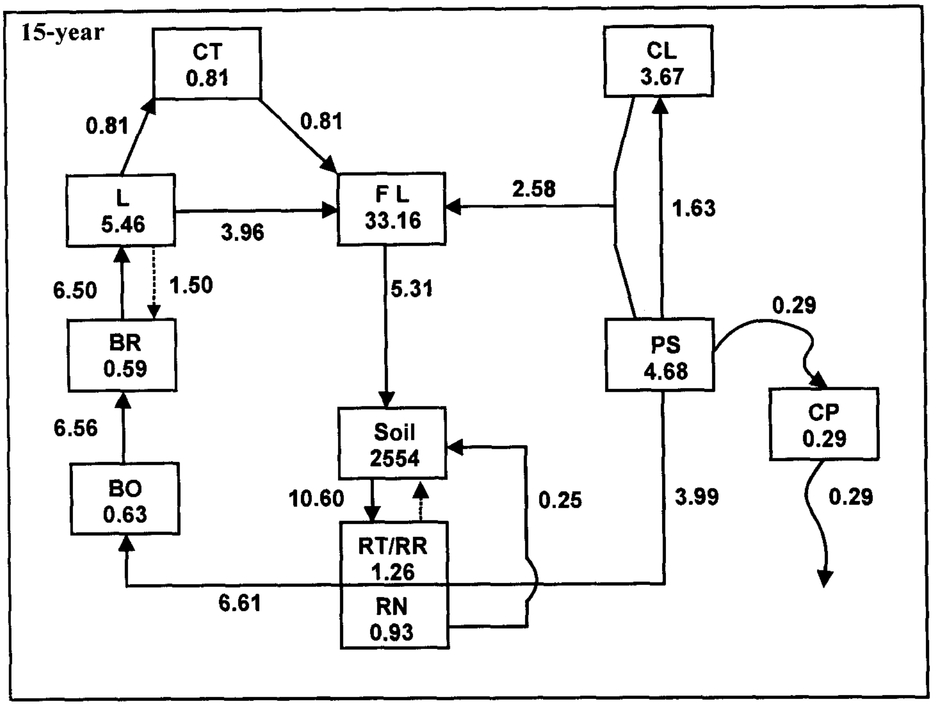

10-year
CT 0.67
0.67
0.67
CL 48.57
L 4.03
2.54
F L 22.00
2.40
1.28
4.71
1.50
4.66
0.21
BR 0.37
PS 2.98
4.78
Soil 2312
CP 0.21
BO 0.36
8.77
0.22
3.72
0.21
RT/RR 0.73
4.84
RN 0.88

Fig. 8.4b. Distribution of phosphorus and flow rates in the plant components of *Alnus* and cardamom in 15- and 20-year *Alnus*-cardamom plantation stands. Units are kg ha^{-1} for compartments and kg ha^{-1} year^{-1} for flows. Soil total phosphorus is presented for top 30 cm depth. Broken lines indicate retranslocation. CT=catkin, L=leaf, BR=branch, BO=bole, RT=root, RR=rhizome, RN=root nodule, FL=floor litter, CL=cardamom leaf, PS=pseudo-stem, CP=cardamom capsule


15-year
CT
0.81
CL
3.67
0.81
0.81
L
5.46
F L
33.16
2.58
1.63
3.96
6.50
1.50
5.31
0.29
BR
0.59
PS
4.68
CP
0.29
6.56
Soil
2554
BO
0.63
10.60
0.25
3.99
0.29
RT/RR
1.26
6.61
RN
0.93

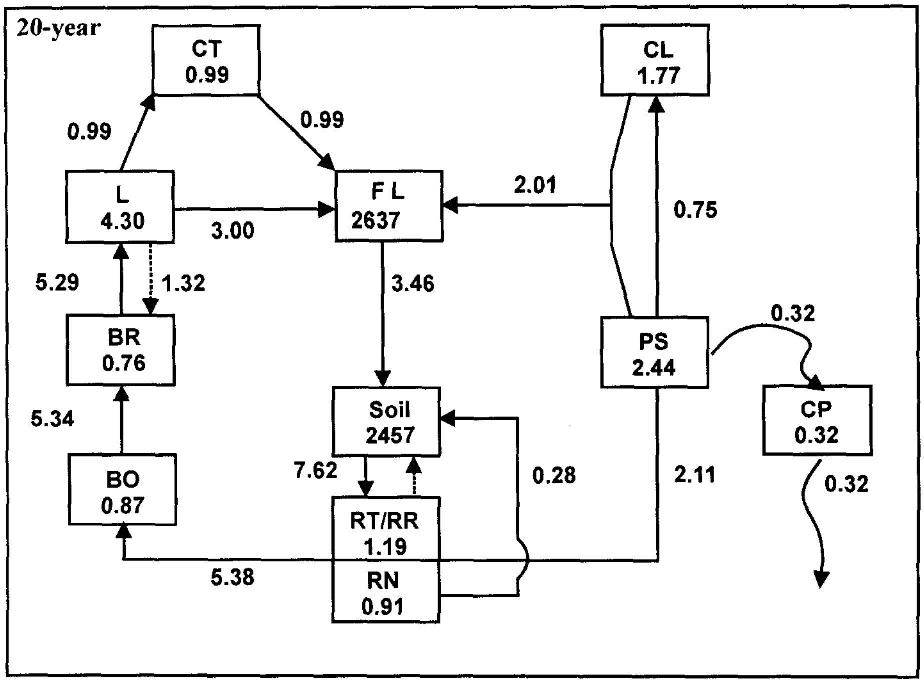
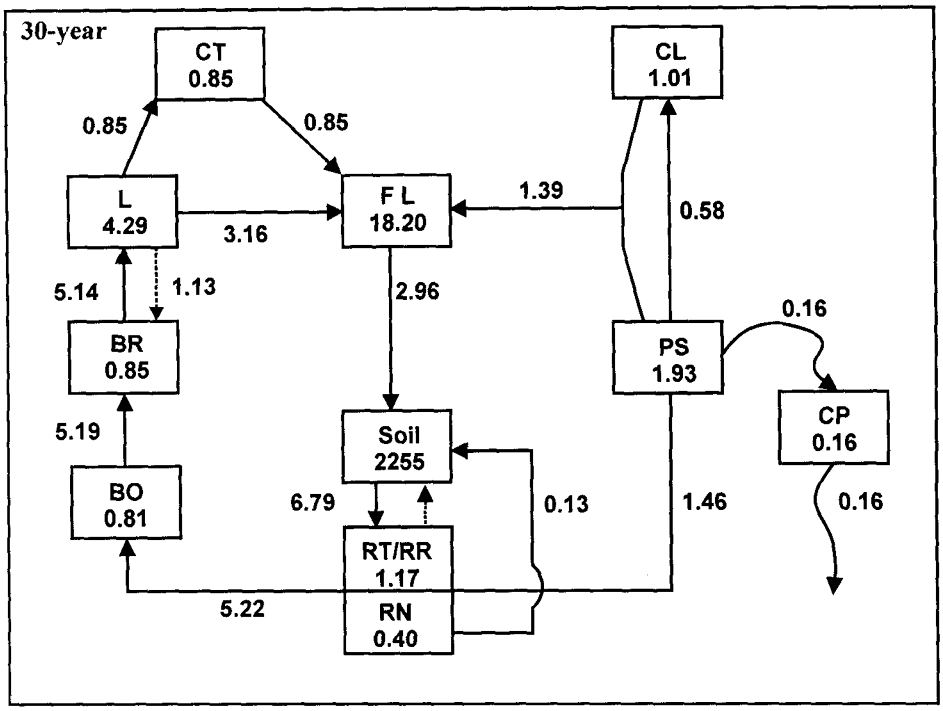
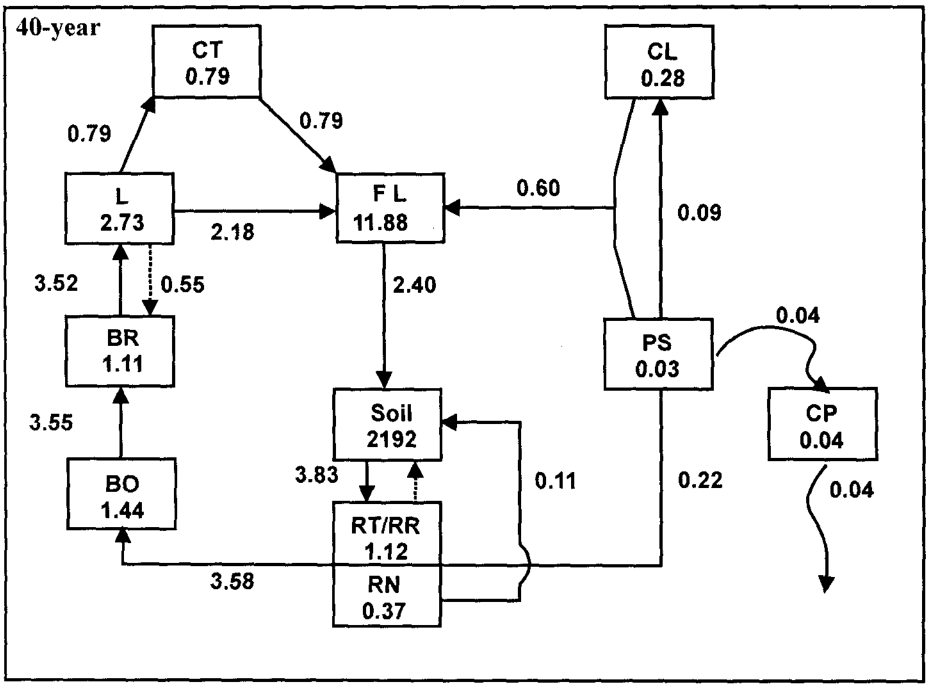

20-year
CT
0.99
CL
1.77
0.99
0.99
L
4.30
F L
2637
2.01
0.75
3.00
5.29
1.32
3.46
0.32
BR
0.76
PS
2.44
5.34
Soil
2457
CP
0.32
BO
0.87
7.62
0.28
2.11
0.32
RT/RR
1.19
5.38
RN
0.91

Fig. 8.4c. Distribution of phosphorus and flow rates in the plant components of *Alnus* and cardamom in 30- and 40-year *Alnus*-cardamom plantations stands. Units are kg ha^{-1} for compartments and kg ha^{-1} year^{-1} for flows. Soil total phosphorus is presented for top 30 cm depth. Broken lines indicate retranslocation. CT=catkin, L=leaf, BR=branch, BO=bole, RT=root, RR=rhizome, RN=root nodule, FL=floor litter, CL=cardamom leaf, PS=pseudo-stem, CP=cardamom capsule


30-year
CT 0.85
0.85
0.85
CL 1.01
L 4.29
F L 18.20
1.39
3.16
0.58
5.14
1.13
2.96
0.16
BR 0.85
PS 1.93
5.19
CP 0.16
Soil 2255
6.79
0.13
1.46
0.16
BO 0.81
RT/RR 1.17
5.22
RN 0.40


40-year
CT 0.79
0.79
0.79
CL 0.28
L 2.73
F L 11.88
0.60
2.18
0.09
3.52
0.55
2.40
0.04
BR 1.11
PS 0.03
3.55
CP 0.04
Soil 2192
3.83
0.11
0.22
0.04
BO 1.44
RT/RR 1.12
3.58
RN 0.37

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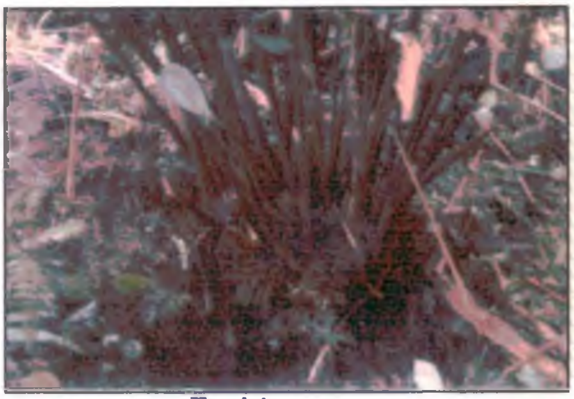
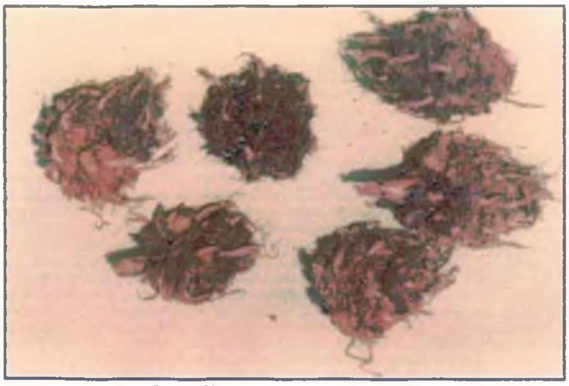
Cardamom bush

Flowering buds

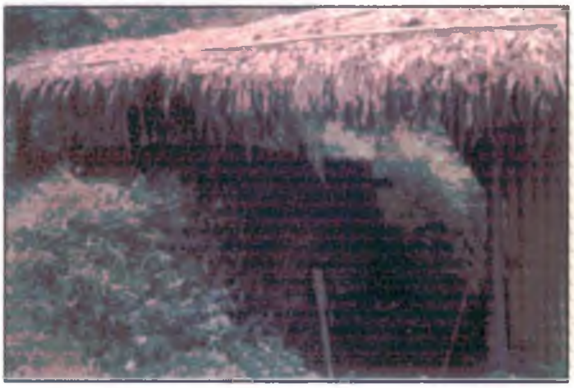
Cardamom in bloom



Fruiting stage



Harvested inflorescence with capsules



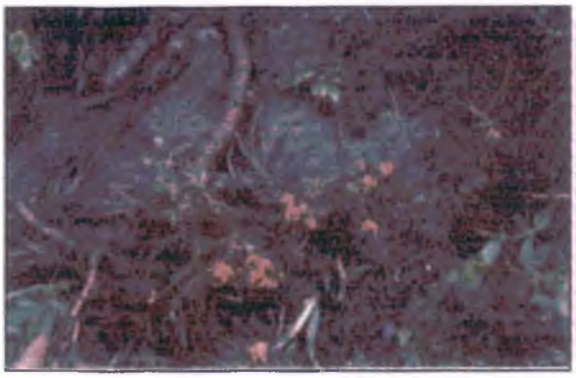
Traditional cardamom curing kiln

5-year *Alnus*-Cardamom plantation

10-year *Alnus*-Cardamom plantation


15-year *Alnus*-Cardamom plantation


20-year *Alnus*-Cardamom plantation


Alnus root nodules


Split rhizomes with pseudo-stems


Split rhizomes for replantation


Firewood storage


Firewood extraction from plantation


Firewood transport to curing kilns