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 ❖