

STUDIES ON ROOTING-BEHAVIOUR, NODULATION OF VARIOUS NFTS AND THEIR EFFECT ON SOIL PROPERTIES

Thesis

by

RANJAN KUMAR KAR

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Dr. Yashwant Singh Parmar

University of Horticulture and Forestry

Nauni-Solan -173 230 (H.P.)

INDIA

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Dr. Y.S. Parmar University of
Horticulture & Forestry

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Dept - Horticulture

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**In the cherished
memory of my
beloved grand parents**

Dr. S.D. Kashyap
Deputy Director of Research
(Agroforestry)

Directorate of Research
Dr. Y.S. Parmar University of Horticulture
and Forestry, Nauni, Solan (H.P.) - 173 230

CERTIFICATE-I

This is to certify that the thesis entitled "**Studies on rooting behaviour, nodulation of various NFTs and their effect on soil properties**", submitted in partial fulfilment of the requirements for the award of degree of **MASTER OF SCIENCE in AGROFORESTRY** to Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Solan (H.P.) is a bonafide research work carried out by **Mr. Ranjan Kumar Kar (F-96-9-M)** under my guidance and supervision. No part of this thesis has been submitted for any other degree or diploma.

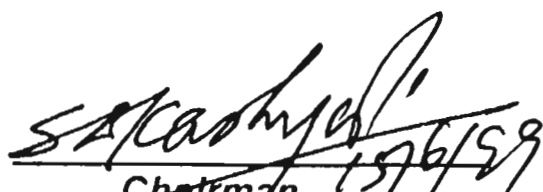
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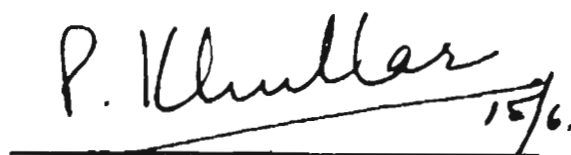
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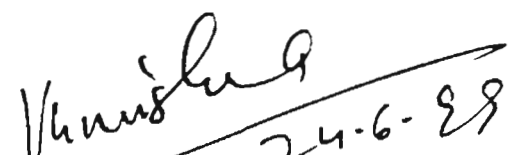

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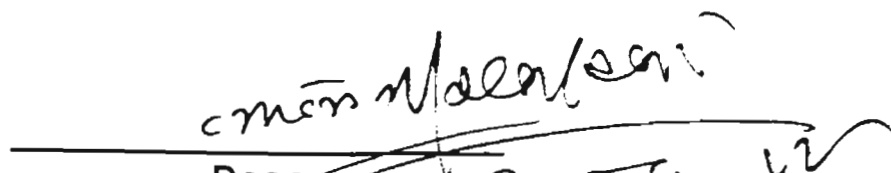
CERTIFICATE-II

This is to certify that the thesis entitled "**Studies on rooting behaviour, nodulation of various NFTs and their effect on soil properties**" submitted by **Mr. Ranjan Kumar Kar (F-96-9-M)** to Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Solan (HP), in partial fulfilment of the requirements for the award of degree of **MASTER OF SCIENCE in AGROFORESTRY** has been approved by the Student's Advisory Committee after an oral examination of the same in collaboration with the external examiner.


Chairman
Advisory Committee


External Examiner


Professor and Head
Department of Silviculture and Agroforestry


Dean
College of Forestry

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Place : Nauni
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Ranjan Kumar Kar
(Ranjan Kumar Kar)

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INTRODUCTION

CHAPTER-1

INTRODUCTION

The mountain areas are generally characterised by fragile and steep slopes which are prone to loss of top soil cover alongwith the soil biota; it causes the change in biogeochemical cycle of the soil as a result of deforestation. Intensive cultivation of these areas also leads to loss of their productivity which may get converted to wastelands.

The rooting pattern of forest tree species plays a vital role in the conservation of soil and improving its fertility. It is assumed that the tree roots intercept; absorb and recycle the nutrients in the soil that would otherwise be lost through leaching, thereby making more closed nutrient cycle. As enlisted by Rovira (1965), tree roots release 10 sugars, 23 amino acids, 10 vitamins, flavonones and enzymes and increase the microbial population in rhizosphere (Kramer, 1969) which in association with root exudates enrich the organic matter of soil (Sauerbeck and Helal, 1986; Whipps and Lynch, 1986). The deep rooted plant pumps nutrients from deeper soil layers to which lateral roots scavenge horizontally (Garrity *et al.*, 1995). Besides, the extensive network of root with high surface area, root hair density and mucigel secretions also bind the soil to provide mechanical stability against erosion. In addition, root systems influence the structure, porosity as well as moisture retention of soil (Nair, 1990) and induce the rhizosphere for adaptation of plants during the adverse soil conditions (Marschner, 1991).

Root systems provide erect growth of shoot and metabolic activities of the plants by supplying hormones viz., auxins, cytokinins, gibberlins etc. (Kramer, 1969) and regulating the ion uptake (Bray, 1954). They determine the growth and field performance of any plant (Kormanik, 1986; Schultz and Thompson, 1990). Functional and healthy plant roots are essential for production of many of the resources on which the human prosperity depends (Waisel *et al.*, 1991). The

knowledge of their structural development is essential to understand the ecological niche of a tree species and to optimize the productivity of trees in various silvicultural and agroforestry systems (Huxley, 1983; Van Maydell, 1987; Toky *et al.*, 1989a, 1989b).

Nitrogen Fixing Tree species (NFTs) are among the most promising components of the agroforestry systems because of their ability to fix atmospheric nitrogen in root nodules and also complementarity with the neighbouring N-depleting crops (van Noordwijk and Dommergues, 1990). Most leguminous trees are associated with the bacteria (*Rhizobium* sp.), while few non-leguminous species are associated with actinomycetes (*Frankia* sp.), which synthesize nodules. Nodulation is the dominating mechanism of biological nitrogen fixation which utilizes the renewable source of elemental nitrogen without disturbing fossil fuel; checks nitrate contamination of ground water, nitrogen loss through leaching, denitrification (Hiechel, 1987) and serves as a fixed source of nitrogen for both plant and soil (Vance, 1991). The role of nodulating plants in improving the soil fertility has been described by various researchers (Anonymous, 1987; Cruz and Valdes, 1990; Galciana *et al.*, 1996;).

In the sub-Himalayan tracts of India some important NFTs viz. *Acacia catechu* Willd., *Albizia chinensis* (Osbeck) Merr. and *Alnus nitida* Endl. are grown to restore the soil fertility and to uplift the socio-economical status of the rural people. Although, there are numerous reports on various tree species with respect to their root distribution or potential on soil enrichment are available; yet, very meagre work has been done on the rooting pattern and nodulation status of the above mentioned NFTs and their impact on various soil parameters. Keeping this in view, the present investigations entitled "Studies on rooting behaviour, nodulation of various NFTs and their effect on soil properties" were carried out with the following objectives:

- i) To study and compare the rooting behaviour and nodulation status of various NFTs.
- ii) To study the impact of rooting behaviour and nodulation of various NFTs on different soil properties

REVIEW
OF
LITERATURE

CHAPTER-2

REVIEW OF LITERATURE

Roots, the hidden half of plants are highly mobile apparatus and conditioned to numerous environmental factors. The root systems vary widely both within and between species and have common properties and role. They determine the depth of regeneration of buds, aeration of inudated organs and have an ecological role in the improvement of soils. The available literature on rooting behaviour, their architecture, nodulation status and improvement in soil properties are reviewed as under:

2.1 ROOTING BEHAVIOUR

The rooting behaviour of different tree species in different climatic conditions have been described by various workers.

Nielsen (1982) noticed that the dynamic force required to pull over a tree was dependent on its root architecture. The root system of *Pinus contorta* penetrated deeper but lateral spread was lesser in comparison to other species of pine and that the number and length of roots were not affected by spacing. However, greater stability of plants were observed at wider spacing. Further, a positive correlation between root thickness and stem numbers was established.

Schulze (1983) enlisted the root/shoot dry matter ratio of forest plants based on the type to which they belong as tabulated on the following page :

Plant type	Root-shoot ratio
Evergreen trees (Tropical)	0.11
Deciduous tree (Temperate)	0.25
Evergreen trees (Boreal)	0.25
Alpine 'Krumholz' species	0.82
Ericaceae heath species	1.86
Gramineae species	5.67
Desert plants	5.67
Alpine plants	

Dabral *et al.* (1987) grouped root habits of *Eucalyptus* spp. Into four broad categories namely: distinct tap root with emerging lateral roots (tap root branching at bottom, middle or upper part of the root), lateral roots penetrating as deeply as tap roots and no tap root but well formed self grafted clusters. They also reported that the soil density was affected by rooting pattern.

Jonsson *et al.* (1988) observed the rooting patterns of *Cassia siamea*, *Eucalyptus tereticornis*, *Leucaena leucocephala* and *Prosopis chilensis* were similar to that of maize i.e. slow decrease in finer root biomass from 0 to 100 cm soil depth. In *E. camaldulensis* roots were evenly distributed down to 100 cm. On an average, the finer roots biomass of tree species was twice that of maize. It was concluded that, due to homogeneity of rooting patterns, these species may compete for nutrients and water in agroforestry.

Fahey *et al.* (1988) classified the roots of *Acer saccharum*, *Betula alleghaniensis*, *Fagus grandiflora* and *Picea rubens* into seven diameter classes i.e. <0.6, >0.6-1, >1-2.5, >2.5-5, >5-10, >10-20 and >20-100 mm to study the intensity of decay and nutrient return. They reported that the decay of finer roots in

soil had declined abruptly in the first summer. The ash free nutrient loss from woody roots decreased with increasing root diameter and was much slower than the decay rate of above ground tissues. They also found that the release of K and Ca was rapid for all roots, but the release of N and P was much faster in the finer roots than coarser roots.

Quine and Burnand (1991) analysed the early growth and root architecture of eight year old Sitka spruce (*Picea sitchensis*) and found an unexplained clustering of roots in an uphill direction. Moreover, there was a good vertical root development and better root spread by reducing water logging in the upper soil profile. In another study with fourteen year old plants of the same species, Quine *et al.* (1991) reported that the presence of stump close to the planting position, prevented the development of uniform root system and caused considerable clustering of roots away from the stump. Root systems of trees planted away from old stumps or on mounds were more uniform, although there was enhanced root growth in the direction of the mound centre for trees planted on the side of the mound.

Toky and Bisht (1992) observed the rooting patterns of six year old indigenous tree species viz., *Acacia catechu*, *Acacia nilotica*, *Albizia lebbek*, *Azadirachta indica*, *Dalbergia sissoo*, *Melia azedarach*, *Morus alba*, *Prosopis cineraria* and *Zizyphus mauritiana* and exotic species viz., *Eucalyptus tereticornis*, *Populus deltoides* and *Leucaena leucocephala* growing in sandy loam soil under semi-arid conditions. They reported that the roots of *Morus alba*, *Melia azedarach* and *Populus deltoides* were confined to top 80 cm soil depth; while, *Prosopis cineraria*, *Acacia nilotica* and *Eucalyptus tereticornis* roots penetrated maximum to a depth of 233 cm. The total number of roots ranged from 103 in *Acacia catechu* to 932 in *Eucalyptus tereticornis*. About 62-80 per cent of the roots were less than 2 mm in diameter and the branches of main root were more horizontal than those of lateral roots.

Osonubi *et al.* (1992) studied the drought tolerance characteristics of different Nitrogen Fixing Tree species. They observed that *Faldherbia alblida* (*Acacia alblida*) tolerated the drought stress by producing long tap root and similar weights of dry matter in shoot and root while *Acacia nilotica* tolerated the drought stress by developing a large root system and was thus capable to explore a greater volume of soil. In addition, leaf abscission also contributed to maintain a favourable Internal water status.

Gingras (1994) reported the possibility of producing balanced seedlings of *Picea mariana* in containers with good horizontal root system, high growth capacity and well developed root architecture for reforestation purpose.

Chitkara (1994) compared the rooting pattern of 12 years old peach and plum trees. In both the species, the maximum number of roots were found to be of diameter <2 mm as compared to the other diameter classes (>2-15 mm or >15 m). Each of the three diameter classes of root was more abundant in peach than in plum, although thick roots were observed below a soil depth of 50 cm in plum but not in peach.

Noordwijk *et al.* (1995) described the desirable root architecture of trees under different agroforestry systems (sequential and simultaneous). In sequential system, extensive tree root development may enhance nutrient capture to subsequent crops via organic pools, while in simultaneous system tree roots development in crop roots zone may cause competition for resources. They found relationship between proximal root diameter and total root length or surface area. The root branching was reported to be independent of root diameter which was tested in MPTs in an acid soil. There was a larger variability in roots than in stems. They further noticed that the shallowness of tree root increased the chances of competition with agricultural component.

Dhyani *et al.* (1996) estimated the above and below ground biomass production of *Eucalyptus tereticornis* stand growing in deep textured soil and river bed boundary lands of Doon valley. Above ground biomass production on these

two sites was 7.51 t ha⁻¹ and 11.04 t ha⁻¹, respectively. In deeper soil, 8.7 per cent of the total dry matter production was associated with fine roots, but it was more than 26 per cent on the riverbed lands. They also studied various root characteristics like root depth, lateral root spread, weight and percentage of roots under various depths. In deep heavy textured soil, *Eucalyptus* developed a sparse branching and deep penetrating root system, but in river bed more compact and intensive branched root system was recorded. However, coiling of roots was recorded on boundary lands. They also developed relationship between vertical root length and total root length.

Singh *et al.* (1996) compared rooting behaviour of 30 months old tree species (*Acacia nilotica*, *Leucaena leucocephala*, *Dalbergia sissoo*, *Prosopis cineraria*, *Prosopis juliflora*, *Azadirachta indica* and *Cajanus cajan*) and observed primary root angle of these species as 72°, 82°, 70°, 58°, 74°, 78° and 84°; the secondary root angle as 68°, 63°, 59°, 52°, 64°, 65° and 67° while root spread to crown spread ratio was 1.7, 1.74, 2.07, 1.29, 1.9, 1.41 and 1.48, respectively.

Nicoll *et al.* (1996) assessed the growth of tree root system in response to wind action and site conditions. They observed that the rooting depth was restricted by water table. The root system morphology got modified to resist the wind movement associated with shallow rooting. The spread of root system and the ratio of root mass to shoot mass (Root/shoot ratio) were negatively correlated to soil root plate depth. Root systems had more structural development on leeward side than the wind ward side.

Hooker and Atkinson (1996) described the root architecture as affected by arbuscular mycorrhizal fungi (AMF). Although, root architecture was previously not believed to be altered by AMF but significant alteration had been observed unequivocally for several plants. They further reported that most of the AMF colonized trees possessed a highly branched root system. AMF were found to affect plant cycle and altered the root system longevity.

Studies on root distribution of six fruit crops in acid soil (Singh and Sharma, 1997) showed the highest feeder root biomass in aonla (496 g m^{-2}) followed by jackfruit (470 g m^{-2}), mango (415 g m^{-2}) and lowest in sapota (334 g m^{-2}). Mango, jackfruit, litchi, guava at 0-10 cm, aonla at 10-20 cm and sapota at 20-30 cm soil depth produced more biomass than other depths.

2.2 NODULATION AND NITROGEN FIXATION

Ferguson and Bond (1953) found that the nodule bearing *Alnus glutinosa* grew vigorously and fixed more atmospheric nitrogen. Nodules formed freely at a pH range of 5.4 to 7.0 which also contributed to better development of plant.

Alnus rugosa and *Alnus glutinosa* had same nitrogen fixation rate and characteristics; they had increased the soil nitrogen contents significantly on favourable sites, the soil nitrogen accumulation under *Alnus rugosa* was observed to be 150 lb/acre/year (Daly, 1966).

Rodriguez (1966) compared the nodulation and N_2 fixing characters of various *Alnus* spp.; from seedlings grown in water culture (without N). *Alnus jorullensis* recorded vigorous growth, rich nodulation and high nitrogen accumulation than *Alnus glutinosa*. *Alnus jorullensis* produced downward growth of nodulated roots while *Alnus glutinosa* registered upward growth.

Silver (1969) observed nodulation potential of *Alnus* and suggested that the species under this genera have a great ecological role. Later, Allen and Allen (1965) also described *Alnus* spp. as, pioneer perennials due to the N accumulating capacity and their suitability for agriculturally uneconomic regions.

Nodulation generally slows early root growth, which may be due to higher respiration rate of nodulated root system (Bouma, 1970). However, Robin *et al.* (1984) reported higher total dry weight in nodulated plants than in non-nodulated plants. Cartwright and Snow (1962) observed a reduction in nodule number was affected by an increase in nodule size.

Goel *et al.* (1991) studied the characteristics of nodulation of *Acacia auriculiformis* as affected by external nitrogen application. They concluded that low levels of nitrate showed a reduction in nodule production when compared with low levels of ammonium. The highest level of both ammonium and nitrate reduced nodule production. Ammonium increased the total dry weight of plants whereas nitrate had no effect when compared with controls.

Taky *et al.* (1994) estimated the fresh weight (3.6 mg) and dry weight (3.2 mg), of nodules, and total nitrogen of root (1.3 mg), stem (2.2 mg), leaves (2.3 mg) and nodules (0.2 mg) per plant of 70 days old seedling of *Acacia nilotica* while, root, stem, and leaf weight were 81 mg, 109 mg and 123 mg, respectively and number of nodules was 3 only. In *Acacia* species, lack of water inhibited nodule formation (Deans *et al.*, 1993).

XiaoLi *et al.* (1994) studied nodulation and nitrogen fixation of *Mimosa rubra* and found higher nodulation, growth and nitrogen fixation in garden soil than in red soil. Adequate water supply was required for nodule increment e.g. 3.52 g/plant. However, nodulation and nitrogen fixation activities were maximum during the months of June and October.

Beniwal *et al.* (1995) observed a significant and positive correlation between number and mass of nodules with total nitrogen content fixed by *Acacia nilotica*. Besides, it was categorized as best for amelioration of wastelands. Similarly, Ekblad and Huss (1995) showed positive correlation between nodule biomass and nitrogen fixed in alder (*Alnus incana*). They observed that regulation of nitrogen fixation was via nodule growth rather than nodule specific activity and that 510 mg N was fixed by one g of nodule (dry weight). However, the activity of N depended on level of phosphorus.

Raverkar and Bhandari (1996) assessed the nodulation and nitrogen fixation status of various leguminous tree species of Himachal Pradesh and reported that *Acacia catechu* had 10-25 nodules and 11-25 mg dry weight of

nodules; 1.8 and 1.9-2.25 per cent nitrogen content of root and shoot, respectively in 6 to 9 months old plants. The nitrogen uptake was 25-229 mg/seedling. In 6 months old *Albizia chinensis* seedlings these parameters were recorded to be 7-20, 9.9-101 mg, 1.18 - 1.6 per cent, 1.8-2.1 per cent and 8.8 to 93 mg/ seedling, respectively.

Purohit *et al.* (1997) assessed the nodulation of *Oogenia dalbergiodes*, *Albizia chinensis*, *A. lebbek* and *Dalbergia sissoo* of 9 months old seedlings. Among the three species, maximum fresh weight (285.6 mg), dry weight (74.70 mg), total nitrogen content/nodule (0.37 mg), nodule nitrogen content per plant (2.93 mg) as well as nodule nitrogen percentage (3.92) were recorded in *Albizia chinensis*. However, maximum nodules were reported in *Dalbergia sissoo* i.e. 18.

Singh and Pokhriyal (1998) reported 246.51, 201.69 and 268.92 kg/ha/year nitrogen accretion in one year old seedlings of *Acacia catechu*, *Albizia chinensis* and *Alnus nepalensis*, respectively in polythene bags. However, in non-leguminous species nitrogen fixation rate varied from 15 kg to 350 kg/ha in *Myrica cerifera* (Silver and Magne, 1970) and *Alnus rubra* (Newton *et al.*, 1968), respectively

2.3 SOIL PROPERTIES

Volobuey (1964) reported that plant roots play a prominent role on soil properties, i.e. exert mechanical action on the soil, affect the soil moisture regime, and cause changes in chemical characteristics and bulk density of soil. They also act as loci of an intimate interaction between higher plants and micro-organisms and thereby enhance the formation of soil structure.

Alder (*Alnus rubra*) ameliorated the deglaciated area of Glacier Bay, Alaska as well as affected the forest environment of coastal region of Northern Japan by interacting with chemical and biological soil properties (Anonymous, 1968). Petrov and Egorova (1992) discussed the role of alder (*Alnus* spp.) in improving the soil by accumulation of nitrogen as well as influencing nitrogen content of soil of self and other associated species.

Singh and Gupta (1983) studied roots and soil binding capacity of some grasses in Karyighat area of Himachal Pradesh and found that *Chrysopogon serulatus*, *Arundinella nepalensis*, *Arundinella setosa* and *Cymbopogon martinii* had better soil binding capacity in descending order of merit as compared to *Heteropogon contortus*, *Themeda anathera* and *Apluda mutica* under similar climatic and edaphic conditions.

✓ Pathak and Gupta (1987) reported that organic matter addition through leaf litter in a 2 year old plantation of *Leucaena leucocephala* was about 5.6 tonnes/ha which improved the soil tilth, cation exchange capacity, water holding capacity; reduced soil bulk density and also changed the soil pH from alkaline to normal.

MacDicken (1988) classified the NFTs, tolerant to saline, acidic and alkaline soils of poor soil drainage and prolonged dry seasons (3-4 months). He also grouped them on the basis of their potential to ameliorate wastelands.

✓ Singh (1989) assessed the potential of *Acacia nilotica*, *Leucaena leucocephala* and *Prosopis juliflora* for reclamation of alkaline soil of the Gangetic alluvial plains of UP and found that *Leucaena* was most promising species for afforestation on substandard soils. After 5 years of afforestation soil properties were improved significantly, showing marked reduction in pH, EC, ESP and an increase in organic carbon content.

✓ In a study of legumes in water stable aggregates in alkaline soil Singh et al., 1990 noticed that nitrogen fixing plants increased organic carbon from 0.98 to 1.19 per cent in soil, water stable aggregate from 18.28 to 29.6 per cent and mean weight diameter from 0.48 to 0.59. They also found that extensive root system as a result of increased phosphate fertilization and increased microbial activity through nitrogen fixation, thereby established a significant correlation between total phosphorus and organic carbon with soil structural indices.

Ohta (1990) found that the soil change associated with plantation of *Acacia auriculiformis* consisted of improved bulk density and reduction of porosity in the thin (0-5 cm) superficial soil layer and increased conductivity in surface soil. Available nitrogen content and its proportion to total nitrogen content in top soil increased significantly with advancement of plantation age upto 5 years.

Montagnini and Sancho (1990) compared soil fertility status under, i) 2.5 year old plantation, and ii) grassland. High soil N levels and organic matter were found under the plantation than under grass. Within the plantation, there was an apparent trend of higher soil nitrate content under *Stryphnodendron excelsum* and *Dalbergia tucurensis*.

Gulteridge (1990) suggested that nitrogen fixing trees serve as leaf mulch in acid podzolic soil (alfisol) and cultivation of maize therein showed good results than non-nitrogen fixing trees used as leaf mulch.

Fitter (1991) reported the nature of bond between individual roots and soil is determined by root surface area, root hair density, extent of mucigel production, nature of rhizosphere and mechanical characters of roots.

Mazzarino *et al.* (1991) calculated the annual N mineralization rate under *Prosopis* and *Larrea* to be 150 kg/ha and 95 kg/ha, respectively. Nitrogen produced in wet season (spring - summer months) represented 90 per cent of the accumulated N/year. Nitrogen mineralization was positively correlated with soil moisture and temperature. They also found higher levels of nitrogen and organic carbon in surface soil and carbon and phosphorus in subsoil of *Prosopis* plantation than that of *Larrea*.

Danso *et al.* (1992) described the ecological role of biological N₂ fixation of nitrogen fixing trees which have the ability to establish in nitrogen defficient soil.

They make major contributions to agriculture by restoring and maintaining soil fertility besides combating erosion and desertification.

Shield and Gray (1992) reported that roots reinforce the levee soil and increase shear resistance in a measurable manner. They provide environmental benefit by enhancing structural integrity of soil.

✓ Garg and Jain (1992) investigated ecological potential of babul (*Acacia nilotica*) and mesquite (*Prosopis juliflora*) and reported that the percentage of exchangeable Na and soil pH decreased under both species in alkali soil but reduction under *Prosopis* was higher than that of babul. They further observed that reduction in surface soil bulk density, enhancement of porosity and water holding capacity, made the soil more friable.

✓ In alley cropping studies of acid soils (Dalland et al., 1993) observed that *Leucaena* and *Flemingia* improved nitrogen, organic carbon, Mg, K, CEC and pH values than control during 2 years and concluded that *Leucaena* was more beneficial than *Flemingia*. The higher levels of organic carbon obtained in alley cropping improved soil physical properties viz., decreasing bulk density, increasing porosity and infiltration rate. Bulk density decreased from 1.52 to 1.43 gm cm⁻³ while pore space increased from 43 to 46.3 per cent.

Shukla and Mishra (1993) studied the improvement of sodic soil under 2 year old tree cover and reported that the maximum reduction in soil pH (9.49-8.87) was observed under *Prosopis juliflora* followed by *Dalbergia sissoo* and *Acacia nilotica*. Increase in organic carbon was maximum (0.182-0.368 per cent) in *Acacia nilotica* plots followed by *Prosopis juliflora* and *Dalbergia sissoo*. The maximum reduction of exchangeable sodium content (8.80 to 5.08 ml/100 g) was observed under *Prosopis juliflora* followed by *Acacia nilotica* and *D. sissoo*. *Prosopis juliflora* was more effective in raising calcium content while the soil nitrogen enrichment potential was recorded as highest in *P. juliflora*, followed by *D. sissoo* and *A. nilotica* in a descending order.

Bell *et al.* (1993) suggested a superior clonal line of *Eucalyptus camaldulensis* with an aim to reclaim saline soils having compact root habit of which architecture was concentrated in upper 20 cm of soil profile. Nine months old plants of the same registered more than 2.5 m height, 500 g for above ground biomass and total root length exceeding 8 Kms.

Garrity *et al.* (1994) observed an increment of nutrients and organic matter contents brought about by root systems by the introduction trees in agricultural fields and detailed the mechanisms involved in nutrient pumping from deeper soil horizons and scavenging of leached nutrients through horizontal roots. Nutrient pumping was limited to humid and highly acidic soils where, the contribution of phosphorus by trees usually was far below the crop requirement.

Wulfschleger *et al.* (1994) discussed the effect of root biology on soil biota, soil ecosystem of plant interface and suggested that both the coarse as well as fine roots of plants have important roles in uptake of N and P from greater depth for which there was significance of root architecture. The effect of elevated CO₂ levels on root and microbial biomass and on nutrient dynamics in the rhizosphere had also been reported.

Mathew *et al.* (1997) compared effect of tree species on alfisol and found high difference in pH, EC, phosphorus, organic carbon, potassium and total nitrogen content under a 3 years old plantation as compared to control. Highest values of pH (5.83) under *Artocarpus hirsutus*; EC (3.88 m mhos cm⁻¹) and available P (55.25 kg/ha) under *Pterocarpus marsupium*; total nitrogen (0.13%) under *Paraserianthes falcataria* and available potassium (173.33 kg/ha) under *Artocarpus heterophyllus* plantation as compared to the control (open) pH, EC, total N, available P and K as 5.03, 5.85 m mhos cm⁻¹, 0.06 per cent, 27.84 kg/ha and 110 kg/ha, respectively.

Thus, the characteristics of root with respect to its architecture, nodulating property and overall effect on environment (soil), prompted attention of root geneticists to use advanced techniques of genetic transformation and mutation such as, modification of polygenic nature of root to single gene form and preparation of therefrom lines (Zobel, 1975; 1986) to explore the genetic potential for ecological rehabilitation and enhancing plant growth with proper adsorption and assimilation of nutrients in nutrient deficient soil.

MATERIALS
AND
METHODS

CHAPTER-3

MATERIALS AND METHODS

The Nitrogen Fixing Tree species (NFTs) viz., *Acacia catechu*, *Albizia chinensis* and *Alnus nitida* were selected to carry out the present investigations entitled "Studies on rooting-behaviour, nodulation of various NFTs and their effect on soil properties". The first two species selected were leguminous, whereas, the third one was non-leguminous. The study was carried out in the nursery of Department of Silviculture and Agroforestry, Dr. Y.S. Parmar University of Horticulture and Forestry, Nauni, Solan (H.P.) during the year 1997-98. The details of the experiments conducted and methodology are given as under :

3.1 SITE DESCRIPTION

3.1.1 Location and Climate

The experimental site (nursery area) is situated in the mid-hills sub-humid zone (zone II) of Himachal Pradesh which lies between 35°51'N latitude and 76°11'E longitude, at an altitude of 1200 m above mean sea level. The annual temperature ranges between 2°C to 36°C. May and June are the hottest months and December and January are coldest (Appendix I). The area receives a moderate and average annual rainfall of 1140 mm; of which major part occur during monsoon and some in winter. During winter, frost is of common occurrence but snow is rare.

3.1.1 Soil Characteristics

The physico-chemical status of the surface soil, used to fill the polythene bags for raising the seedlings as well as to transfer them in the big polybags, is given in table 1.

Table 1. Physico-chemical status of the surface soil used for raising the plants

Sr. No.	Physical		Chemical	
	Parameter	Test value	Parameter	Test value
1.	Particle density (g/cm ³)	2.34	Electrical conductivity (dsm ⁻¹)	0.35
2.	Bulk density (g/cm ³)	1.29	pH	7.11
3.	Porosity (%)	44.87	Organic carbon (%)	1.69
4.	Water stable aggregates (%) (>0.25 mm)	70.63	Available nutrients (kg/ha)	
			i) Nitrogen	448.76
			ii) Phosphorus	44.83
			iii) Potassium	328.01
5.	Mean weight diameter (mm)	1.11		
6.	Soil strength (lb/inch ²)	27.14		
7.	Particle size distribution	Sand 38% Silt 35% Clay 22%		
8.	Texture	Loam		

3.2 EXPERIMENTAL METHODOLOGY

3.2.1 Description of Trial

Seeds of *Acacia catechu* and *Albizia chinensis* were collected from 'Sabathu' area of Solan district and the University Campus, respectively, sown in polythene tubes (5 cm x 11.5 cm) during March, 1997 and subsequently transferred to bigger polybags (30cm x 45 cm) after 3 months. The polythene bags were filled

with well sieved nursery soil in which the original seedlings were raised. In case of *Alnus nitida* 15 days old seedlings were brought from the state forest nursery at Bhuntar, Kullu, to the experimental site with earthen balls around their root systems to ensure minimal disturbance. These seedlings were then transferred to bigger polybags (30 cm x 45 cm) after 2.5 months as described above.

The rooting behaviour and nodulation status of each species were investigated at different stages i.e. T_1 , T_2 and T_3 , where,

T_1 = time of sampling at transfer of seedlings i.e. at the age of 3 months; during June, 1997 (Pre-monsoon),

T_2 = time of sampling after six months of transfer i.e. at the age of 9 months; during December, 1997 (early-winter) and

T_3 = time of sampling after fifteen months of transfer i.e. at the age of 18 months; during September, 1998 (post-monsoon).

The various soil properties were recorded at the end of the experiment, when the plants were 18 months old. The soil from polybags containing no plant were treated as control. Plant samples (root and shoot) were analysed at the time of transfer of seedlings and at end of the experiment to estimate total N-content and also the nitrogen fixed by each species.

3.2.2 Experimental Design

The experiment was laid out using Completely Randomized Design. The three tree species selected were considered as 3 treatments. Each treatment was replicated seven times with five plants per replication, and evaluated at 3, 9 and 18 months stage for rooting behaviour and nodulation. In case of soil studies, soil under each tree species was considered as one treatment and compared with control. The nitrogen contents of each species were studied at 3 months and 18 months. The details of the treatment combinations for various studies are presented in table 2.

Table 2. Treatment details for statistical analysis

Root & nodule parameters	Soil studies	Nitrogen content and uptake
1. $S_1T_1 = A. catechu$ at 3 months	$S_1 = A. catechu$ at 18 months	$S_1T_1 = A. catechu$ at 3 months
2. $S_1T_2 = A. catechu$ at 9 months	$S_2 = A. chinensis$ at 18 months	$S_1T_2 = A. catechu$ at 18 months
3. $S_1T_3 = A. catechu$ at 18 months	$S_3 = A. nitida$ at 18 months	$S_2T_1 = A. chinensis$ at 3 months
4. $S_2T_1 = A. chinensis$ at 3 months	$S_0 = \text{control}$ at 18 months	$S_1T_3 = A. chinensis$ at 18 months
5. $S_2T_2 = A. chinensis$ at 9 months		$S_2T_2 = A. nitida$ at 3 months
6. $S_2T_3 = A. chinensis$ at 18 months		$S_2T_3 = A. nitida$ at 18 months
7. $S_3T_1 = A. nitida$ at 3 months		
8. $S_3T_2 = A. nitida$ at 9 months		
9. $S_3T_3 = A. nitida$ at 18 months		

3.3 OBSERVATIONS RECORDED

3.3.1 Rooting Behaviour

Preparation of sample plants

The root systems of sample plants were carefully exposed prior to studying their rooting behaviour. For this purpose, the polythene bags were cut carefully and plants with ball of earths were transferred to a large tub in which constant water was allowed to flow. However, roots having penetrated in the earth through the polythene bags were excavated carefully, ensuring minimum breakage. In this way all soil particles were washed away and the root system of each sample plant was completely exposed without disturbing their dimensional structure as well as finer roots and nodule present on them. Each root system so obtained after washing was spread on a blotting paper to get their original morphology. The collar diameter of each sample plant was measured with the help of an electronic digital calliper and then separated into root and shoot portions. Each portion was separately studied for different parameters.

3.3.1.1 Root and shoot length and length of primary root

Root length was measured from the collar to the tip of the root using a measuring tape. In order to find out the primary, secondary and tertiary roots, the developmental classification (Dutta, 1980; Rose, 1983) was followed. The tap root developed through direct elongation of the radicle was considered as a primary root. In some cases, when taproot appeared to be forked, the root showing minimum angle of deviation from the main root axis, maximum root diameter at the point of emergence or maximum penetration length was considered as primary root. The shoot length was also measured from the collar region to the tip of the shoot with the help of measuring tape.

3.3.1.2 Maximum lateral root spread and maximum lateral branch spread

Maximum lateral root spread was measured as the maximum horizontal length of the root system with respect to root axis. Similarly, maximum lateral branch spread was recorded as a maximum horizontal spread of shoot with respect to plant axis.

3.3.1.3 Angle of emergence of secondary and tertiary roots

The root system of each sample plant was arranged on the plane of paper in such a manner that it did not lose its original identity. The points where root(s) emerged and had better resistance against mechanical shock or water spray to maintain their configuration were chosen for measurement of angle.

The root angle was measured with the help of protractor. The angle at which a secondary root emerged from primary root was designated as angle between primary-secondary roots. Similarly, the angle at which a tertiary root emerged from the secondary root was considered as angle between secondary-tertiary roots. All root angles between primary-secondary or between secondary-tertiary roots observed from the proximal, middle and distal part of the root system were pooled and averaged to calculate the angle of emergence for each species.

3.3.1.4 Diameter, number and length of lateral roots

The primary, secondary and tertiary roots of each plant were measured separately for their basal diameter and length; and subsequently classified into ten diameter classes viz., 0-0.5 mm, >0.5-1 mm, >1-2 mm, >2-5 mm, >5-10 mm, >10-15 mm, >15-20 mm, >20-25 mm, >25-30 mm and >30-35 mm. The number of roots were separately classified for each class. Further, they were also grouped into primary, secondary and tertiary roots and pooled to obtain total number of roots per plant.

3.3.1.5 Fresh biomass of root and shoot

The roots which were grouped as primary, secondary or tertiary were weighed separately for fresh biomass with the help of electronic digital balance. The fresh biomass of individual roots was pooled to obtain total fresh root biomass. Similarly, the shoot portion of each plant was assessed for fresh biomass.

3.3.1.6 Dry biomass of root and shoot

The plant samples used for recording the fresh biomass were oven dried in a hot air oven at $65 \pm 5^\circ\text{C}$ to constant weight and used to determine the dry biomass of primary, secondary and tertiary roots of each sample plant. The root biomass of each class was grouped for total root biomass. The shoot biomass of each plant was also recorded.

3.3.1.7 Root-shoot ratio

Various root-shoot ratios were calculated based on length, lateral spread, fresh biomass and dry biomass for each species.

3.3.1.8 Root architecture

The root architecture of each species was developed after excavating carefully one healthy representative plant of each species after 18 months. Each root system was arranged on a big graph paper after separating it from the shoot. Each root(let) was pressed on the plane of paper using the thumb and forefinger of left hand, and the border was marked with pencil. The same procedure was repeated for the entire root system of each plant species to prepare a complete rough outline. The original sketch was reduced to standard size of a paper (A₄) after continuous reductions on a photostat machine, traced on a transparent paper and then scanned by computer to obtain a copy of each root system.

3.3.2 Nodulation Pattern

3.3.2.1 Number of nodules and biomass

Nodules present on primary, secondary and tertiary roots were counted separately irrespective of their size for each species. Their fresh and dry biomass were also recorded for individual root classes i.e. primary, secondary and tertiary which were subsequently pooled together to obtain the total number of nodules as well as their respective biomass.

3.3.2.2. Structure of nodules

The structure of nodules for each species were recorded from the bunch of nodulation in the respective root systems.

3.3.3 Soil Properties

To find out the effect of each species on the soil properties, the composite sample from the surface soil of each polybag upto the depth of 15 cm of the rhizosphere was used.

3.3.3.1 Physical parameters

Mechanical composition

The particle size distribution was observed by the International Pipette Method (Piper, 1950) and texture of the soil was computed using textural diagram.

Bulk density

Bulk density was determined by the core method using mass-volume relationship (Singh, 1980), while the moisture content of the fresh soil determined by gravimetric method.

Particle density

Particle density was determined by standard pycnometer method using disturbed soil samples (Richards, 1954).

Porosity

Percentage of pore space was calculated according to Richards (1954).

$$\% \text{ pore space} = \frac{(1 - \text{Bulk density})}{\text{Particle density}} \times 100$$

Water stable aggregates

Water stable aggregates were determined by standard wet-sieving procedure (Yodder, 1936). For this purpose, 50 g of sieved soil sample was saturated overnight. A standard Yodder apparatus consisting of four nests each assembled with four sieves (Geologists Syndicate India Ltd., Calcutta) in descending order of their pore size. The soil sample was kept on the top of each set and immersed in water at $20 \pm 5^\circ\text{C}$ contained in the drum and the assemblage oscillated vertically and rhythmically, so that water was made to flow up and down

through the sieves and the assemblage of aggregates. At the end of 10 minutes the nest of sieves was removed from the water, and the fraction of soil retained on each sieve were collected and their oven-dry weight determined. The results were corrected for coarse primary particles by dispersing the material collected from each sieve, with a mechanical stirrer and sodic (1 N NaOH) dispersing agent, and then passed the material back through the same sieve. The weight of sand retained was subtracted from the total weight of undispersed material retained after first sieving and the percentage of stable aggregates (SA%) determined according to Kemper, (1965).

$$SA(\%) = \frac{\text{Wt. obtained} - \text{Wt. of sand}}{\text{Wt. of total sample} - \text{Wt. of sand}} \times 100$$

Mean weight diameter

The mean weight diameter (MWD) was calculated by using the following mathematical equation (Van Bavel, 1949)

$$MWD = \sum_{i=1}^n d_i w_i$$

where,

d_i = the diameter of each size fraction

W_i = the proportion of the sample weight retained on a particular sieve

Soil strength

Soil strength was determined by using penetrometer and expressed as the pressure required to penetrate soil crust upto the elevated mark. The reading was noted from the pressure gauge of the penetrometer and expressed in the unit lb/inch².

3.3.3.2 Chemical analysis

The collected soil samples were air dried, ground, sieved and then chemically analyzed for the following properties.

pH and electrical conductivity

The soil pH was determined in 1:2.5 soil water suspension by using Beckman's pH meter. For recording the electrical conductivity of the supernatant liquid the method detailed by Jackson (1973) was used.

Organic carbon

The organic carbon content of soil was determined by the Wakley and Black rapid titration method and expressed in terms of percentage (Jackson, 1958).

Available nutrients (kg/ha)

Nitrogen

To estimate the available nitrogen (N) content of soil, alkaline potassium permanganate method was followed (Subbiah and Asija, 1956).

Phosphorus

Available phosphorus was extracted using 0.5 M NaHCO_3 adjusted to pH 8.5 (Olsen *et al.*, 1954) and determined by stannous chloride reduced ammonium molybdate method in HCl system (Jackson, 1973).

Potassium

Available K was extracted using neutral normal ammonium acetate and determined on flame photometer (Merwin and Peech, 1951).

Total nitrogen content of root, shoot and nodules

The dried samples of roots, shoots and nodules were ground and a composite sample of each part was chemically analyzed to get the total nitrogen content. Each sample was digested with concentrated H_2SO_4 by using digestion

mixture and total nitrogen content determined by micro-kjeldahl method (Black, 1965).

3.3.4 Uptake of Nitrogen in Plant

The nitrogen uptake of a plant at each stage was determined by using following common formula:

$$\text{N uptake (mg/plant)} = \frac{(\text{Root dry biomass (gm)} \times \text{Root N\%}) + (\text{Shoot dry biomass (gm)} \times \text{Shoot N\%})}{100} \times 1000$$

3.3.4.1 Nitrogen fixed

Nitrogen fixed by each plant was estimated by difference method as the sum of the enrichment of available nitrogen in soil and utilization (uptake) of nitrogen by plant. The figures were expressed in terms of kg/ha/yr. The nitrogen uptake per hectare was calculated by considering plant to plant distances i.e. the diameter of polythene bag under nursery condition and 3 m under field condition. The nitrogen utilization per year of a plant under the nursery condition was estimated over an area of cross section of a polythene bag, and then total nitrogen utilization over an area of 1 hectare (10,000 m²) was worked out as follows:

Nitrogen fixed (kg/ha/yr) =

$$12 \times \left[\frac{(\text{Nitrogen enrichment in soil (kg/ha)})}{\text{Time elapsed after transferring (months)}} + \frac{\text{Nitrogen uptake by plant (mg)}}{\text{Area of cross section of a soilfilled polybag (m}^2\text{)}} \times \frac{10,000 \times 10^{-6}}{\text{Age of the NFTs (months)}} \right]$$

The similar method was followed for estimating the nitrogen fixed under field conditions.

3.4 STATISTICAL ANALYSIS

3.4.1 Comparison of NFTs

The three NFTS were compared through three time intervals with respect to each parameter of rooting behaviour and nodulation status and the data from individual experiments were pooled. To compare the three species at each interval (timing) and also to observe the effect of time, the treatments were decomposed into four orthogonal components each carrying 2 degrees of freedom on the basis of time and species. The nitrogen content of the species were compared for two timings only using the same procedure. The soil enrichment potential was compared using Completely Randomized Design (Appendices II-V) . All statistical analyses were carried out using standard procedures and the treatment means compared using the least significant difference as described by Cochran and Cox (1963).

EXPERIMENTAL
RESULTS

CHAPTER-4

EXPERIMENTAL RESULTS

Results of the studies detailed in the previous chapters are presented as under:

4.1 ROOTING BEHAVIOUR

4.1.1 Root Length

At pre-monsoon sampling when the seedlings were 3 months old, the root length of *Acacia catechu* was maximum (9.10 cm) followed by *Albizia chinensis* (8.00 cm) and *Alnus nitida* (5.75 cm). With increase in age of the plant, root length increased significantly. The root length of *Alnus nitida* was maximum at 9 and 18 months age (49.55 cm and 94.00 cm, respectively). Whereas, *Acacia catechu* seedlings had minimum root length (71.50 cm) after 18 months (Plates 1, 2 and 3). *Albizia chinensis* roots had 34.64 cm length at 9 months of age which increased to 90.52 cm during 18 months (Table 3).

4.1.2 Length of Primary Root

The primary root length of three species studied, varied significantly when the seedlings were 3 months and 18 months old; but, at 9 months age *Acacia catechu* and *Alnus nitida* had registered almost same length. At the time of transfer of seedlings (at 3 months of age); *Acacia catechu* had maximum length (12.00 cm) followed by *Albizia chinensis* (8.86 cm) and *Alnus nitida* (7.10 cm), as evident from table 3. Although, length of primary root of *Albizia chinensis* was minimum when the plants were 9 months old; it increased significantly and attained maximum length (119.01 cm) at 18 months. In case of *Acacia catechu*, the development of primary root was slower than other species during 9-18 months period and resulted

Table 3. Root length, lateral root spread and angle of emergence of laterals in the root systems of various NFTs

Species Time of sampling	Root length (cm)			Length of primary root (cm)			Length of lateral roots (cm)						Maximum lateral root spread (cm)			Angle of emergence (deg.)	
	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	Secondary			Tertiary			T ₁	T ₂	T ₃	Angle between	
							T ₁	T ₂	T ₃	T ₁	T ₂	T ₃				Primary - secondary	Secondary -tertiary
<i>Acacia catechu</i>	9.10	46.43	71.50	12.00	41.03	61.90	2.50	22.66	29.93	1.25	6.47	16.00	5.80	13.66	18.50	73.36	63.88
<i>Albizia chinensis</i>	8.00	34.64	90.52	8.86	28.82	119.01	2.30	17.99	45.01	1.10	5.03	24.00	4.10	9.34	24.75	70.29	64.39
<i>Alnus nitida</i>	5.75	49.55	94.00	7.10	40.52	84.32	2.03	25.18	34.63	0.98	7.90	23.00	3.90	23.89	38.00	71.41	60.68
Mean	7.62	40.18	85.31	9.32	36.79	88.41	2.28	21.94	35.52	1.11	6.46	21.0	4.60	15.37	27.08		
Species at each stage	SE _m 1.27	CD _{0.05} 3.59		SE _m 0.36	CD _{0.05} 1.03		SE _m 0.18	CD _{0.05} 0.52		SE _m 0.12	CD _{0.05} 0.33		SE _m 0.29	CD _{0.05} 0.83		SE _m CD _{0.05} 0.39 1.10	SE _m CD _{0.05} 0.18 0.50
Timings	0.73	2.07		0.21	0.59		0.10	0.30		0.07	0.19		0.17	0.48			

T₁, T₂ and T₃ indicate times of sampling i.e. after 3 months, 9 months and 18 months, respectively



Plate 1. *Acacia catechu*



Plate 2. *Albizia chinensis*



Plate 3. *Alnus nitida*

Root development of the three species during 18 months

in minimum length i.e. 61.90 cm at 18 months though this species was having maximum length at the time of transfer and at 9 months age. *Alnus nitida* had primary root length in between the other two species at 9 months and 18 months age i.e. 40.52 cm and 84.32 cm, respectively.

4.1.3 Length of Lateral Roots

From Table 3, it is evident that average length of secondary roots emerged in three species studied were almost same and varied between 2.03 cm in *Alnus nitida* to 2.50 cm in *Acacia catechu* before transfer; though, they differed significantly after transfer. *Alnus nitida* had maximum secondary root length i.e. 25.18 cm followed by *Acacia catechu* (22.6 cm) and *Albizia chinensis* (17.99 cm) after 9 months. At the later stage i.e. 18 months, there was a significant change in root length of *Albizia chinensis* and had maximum length i.e. 45.01 cm followed by *Alnus nitida* (34.63 cm) and *Acacia catechu* (29.93 cm).

The similar trend as that of secondary root was observed in tertiary roots. Maximum length of tertiary roots was observed in *Albizia chinensis* (24.00 cm) followed by *Alnus nitida* (23.00 cm) and *Acacia catechu* (16.00 cm) after 18 months when they also differed significantly among themselves. At the time of transfer of the seedlings, the three species studied had almost same length which varied between 0.98 cm in *Alnus nitida* to 1.25 cm in *Acacia catechu* when *Albizia chinensis* had 1.10 cm length. The maximum growth behaviour of tertiary roots was observed in *Alnus nitida* and *Albizia chinensis* after transfer i.e. they increased to 7.90 cm and 5.03 cm at the age of 9 months, and 23 cm and 24 cm at the age of 18 months, respectively.

4.1.4 Maximum Lateral Root Spread

Results of lateral root spread were very interesting (Table 3) among the three species studied with significant variation among the species. In the initial stage i.e. at the time of transfer, the root spread was maximum in *Acacia catechu* (5.80 cm) followed by *Albizia chinensis* (4.10 cm) and *Alnus nitida* (3.90 cm). After

transfer of the seedlings, they behaved in a different way. The maximum lateral root spread was obtained in *Alnus nitida* (23.89 cm) followed by *Acacia catechu* (13.66 cm) and *Albizia chinensis* (9.34 cm) at 9 months age which again changed and minimum lateral root spread was shifted from *Albizia chinensis* (24.75 cm) to *Acacia catechu* (18.50 cm), though, the maximum lateral root spread was recorded in *Alnus nitida* (38.00 cm) even after 18 months.

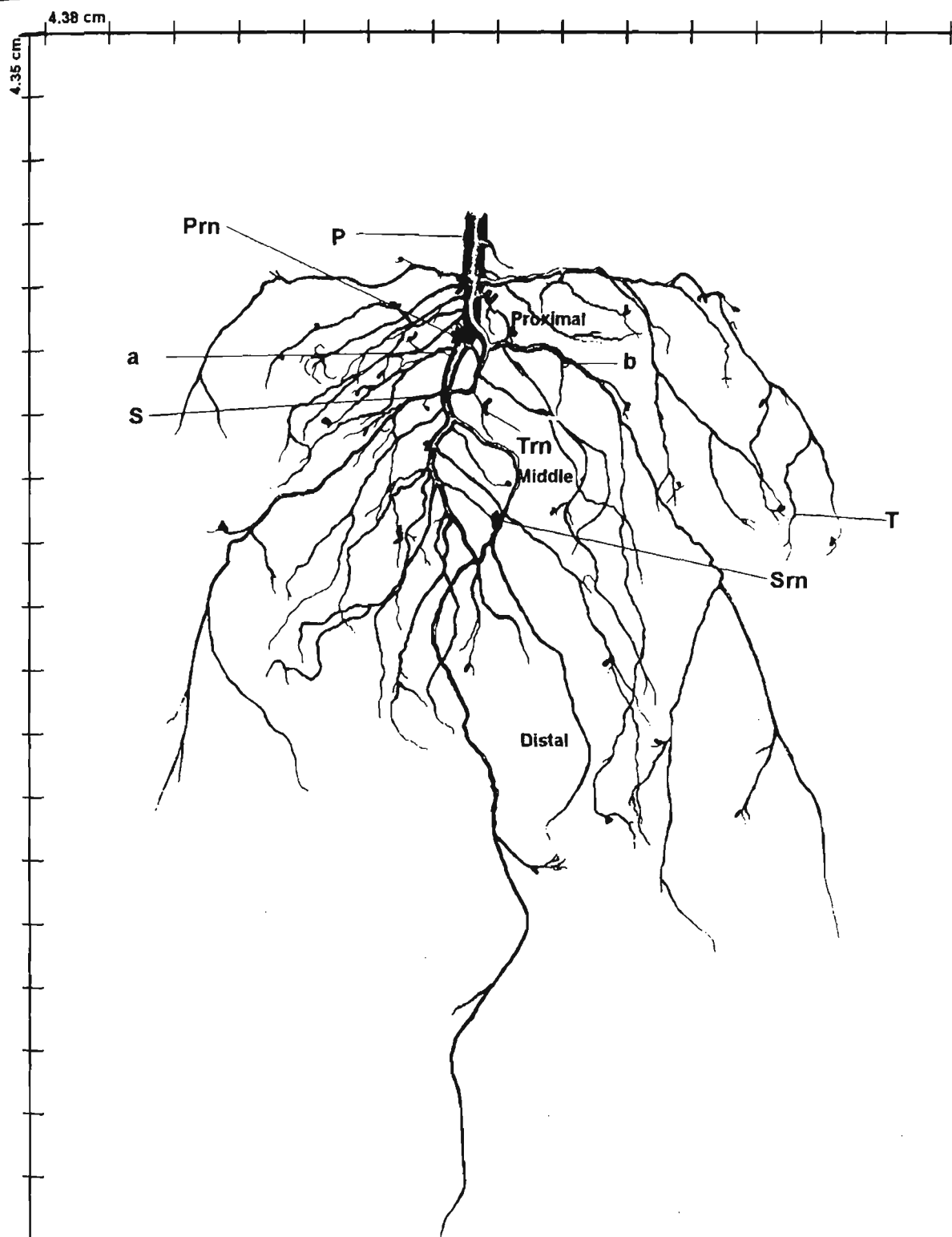
4.1.5 Angle of Emergence

The angle of emergence of secondary from primary and tertiary from secondary roots varied significantly (Table 3; figures 1, 2 and 3) among the species, but they remained unchanged with stages of observations. The angle between primary-secondary roots was observed to be maximum (73.36°) in *Acacia catechu* and minimum (70.29°) in *Albizia chinensis*. Whereas, the angle between secondary-tertiary roots of the three species ranged from 60.68° (*Alnus nitida*) to 64.39° (*Albizia chinensis*).

In general, the angle between secondary-tertiary roots was lower than the angle between primary-secondary roots in all the tree species studied. The difference in angle between 'primary-secondary' and 'secondary-tertiary' roots was about 10° in both *Acacia catechu* and *Alnus nitida*, however, it was approximately 6° in *Albizia chinensis* (Table 3).

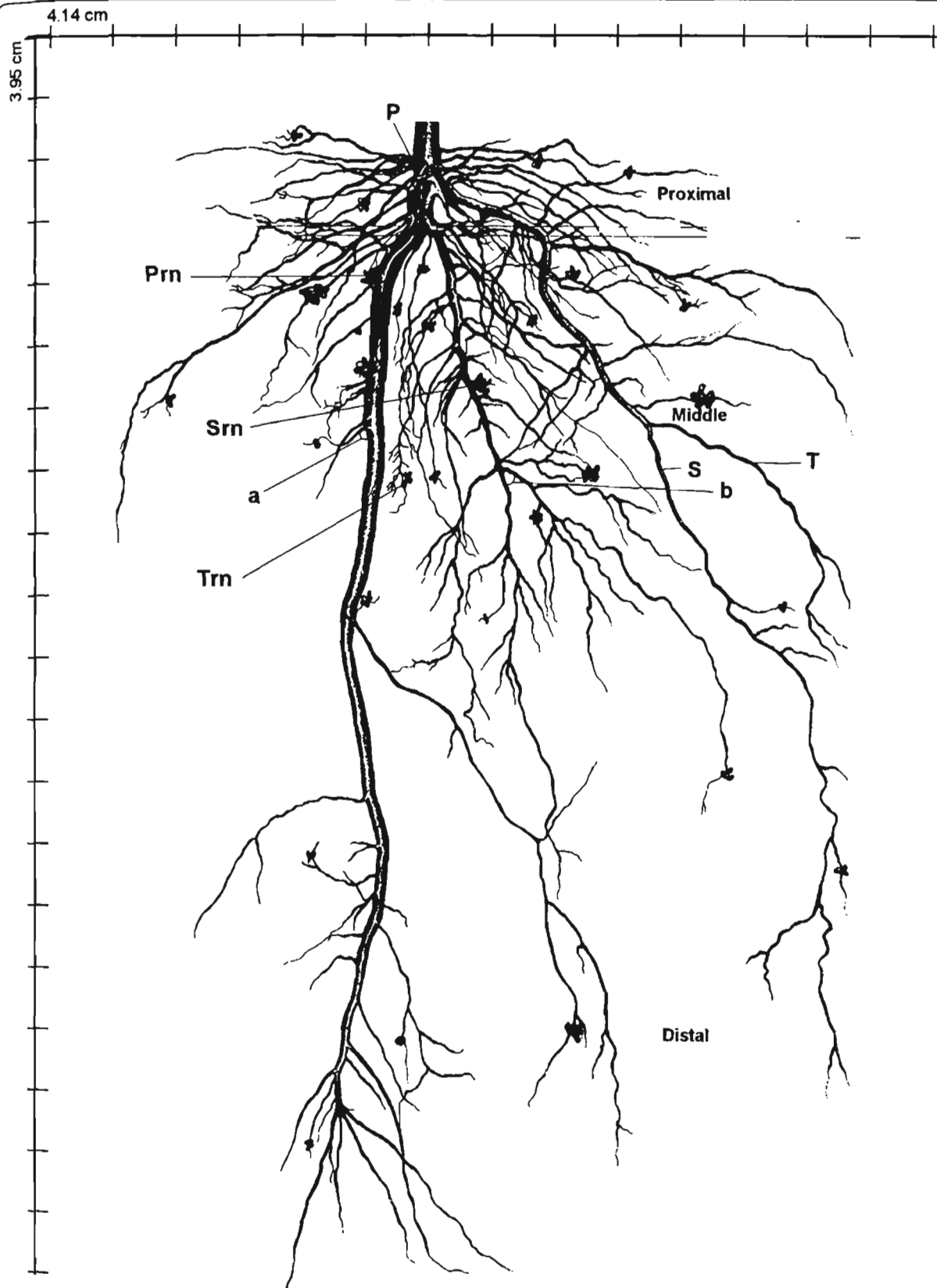
4.1.6 Collar Diameter

The collar diameter of the three species studied (Table 4), revealed that there was significant difference among the three species after transfer of seedlings viz. at 9 months and 18 months; though, before transfer i.e. 3 months after germination the diameter of the three species was almost same and ranged between 1.09 mm to 1.35 mm. After 9 months, the collar diameter of *Alnus nitida* increased to 15.06 mm followed by *Acacia catechu* (9.86 mm) and *Albizia chinensis* (5.58 mm). At the end of the experiment i.e. after 18 months, *Alnus nitida*



P = Primary root *Prn* = Primary root nodule
S = Secondary root *Sm* = Secondary root nodule
T = Tertiary root *Trn* = Tertiary root nodule
a = Angle between primary and secondary roots
b = Angle between secondary and tertiary roots

Fig. 1. *Acacia catechu* root system showing its development, distribution and angle between various rootlets

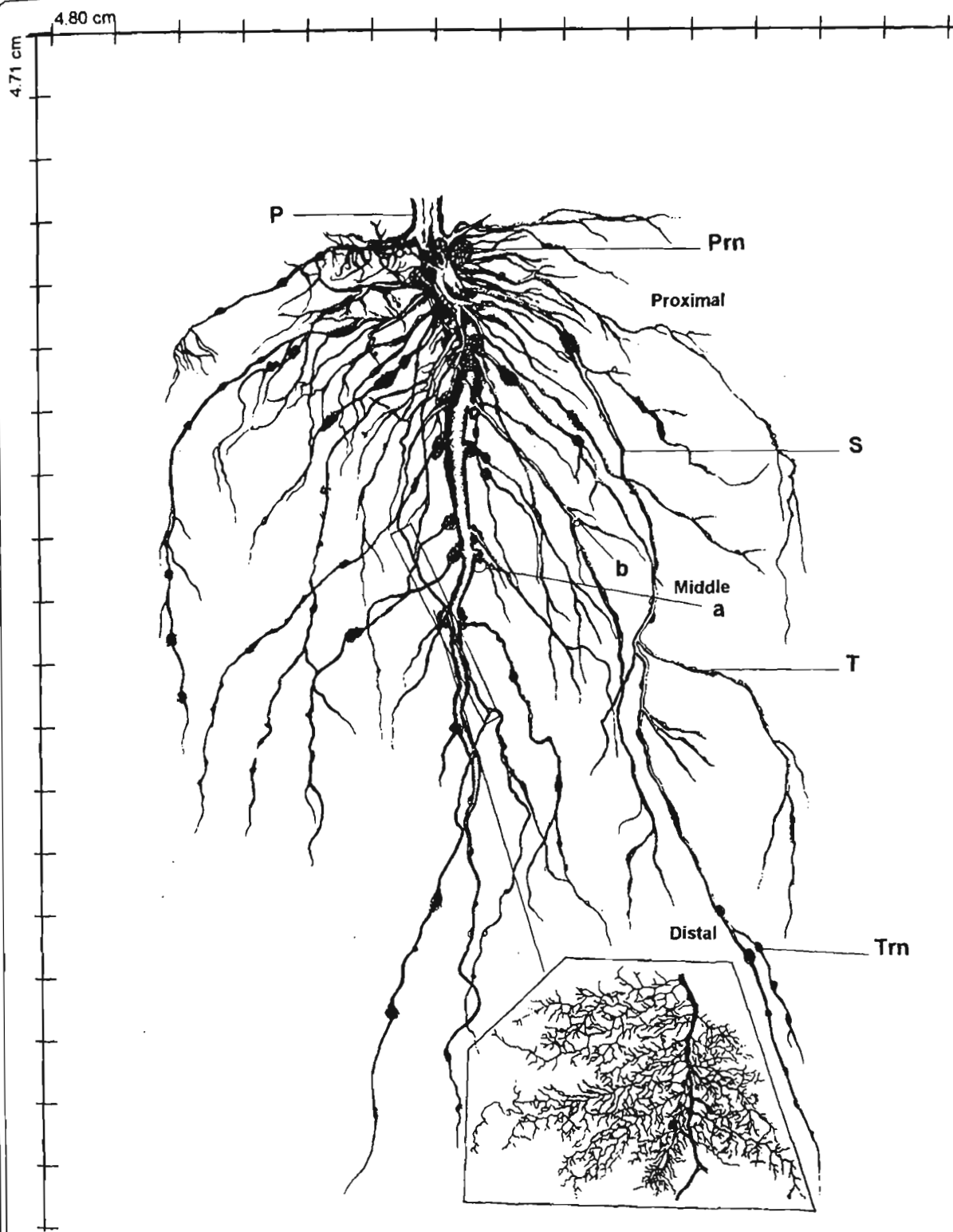


P = Primary root *Pm* = Primary root nodule
S = Secondary root *Sm* = Secondary root nodule
T = Tertiary root *Tm* = Tertiary root nodule

a = Angle between primary and secondary roots

b = Angle between secondary and tertiary roots

Fig. 2. *Albizia chinensis* root system showing its development, distribution and angle between various rootlets



- | | |
|--|----------------------------|
| P = Primary root | Prn = Primary root nodule |
| S = Secondary root | Sm = Secondary root nodule |
| T = Tertiary root | Trn = Tertiary root nodule |
| a = Angle between primary and secondary roots | |
| b = Angle between secondary and tertiary roots | |

Fig. 3. *Alnus nitida* root system showing its development, distribution and angle between various rootlets. *Inset:* Development of fibrous roots on secondary/ tertiary roots

Table 4. Basal diameter of root and diameter classification of rootlets of various NFTs

Species	Collar diameter (mm)			Number of rootlets under various diameter classes (mm)											
				0-0.5			0.5-1			1-2			2-5		
Time of sampling	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃
<i>Acacia catechu</i>	1.35	9.86	15.56	23	95	407	0	8	46	1	3	11	-	3	10
<i>Albizia chinensis</i>	1.23	5.58	20.23	34	111	564	0	7	91	1	2	7	-	1	5
<i>Alnus nitida</i>	1.09	15.06	33.81	24	2191	7407	0	27	315	1	16	149	-	10	121
Mean	1.22	10.17	23.20	27.00	799.00	2792.7		14.00	150.70	1.00	7.00	55.70	-	4.67	45.30
Species at each stage	SE _m 0.08	CD _{0.05} 0.21		SE _m 1.49	CD _{0.05} 4.22		SE _m 0.63	CD _{0.05} 1.77		SE _m 0.24	CD _{0.05} 0.68		SE _m 0.34	CD _{0.05} 0.95	
Timings	0.05	0.12		0.86	2.44		0.36	1.03		0.14	0.40		0.19	0.55	

Species	Number of rootlets under various diameter classes (mm)																	
	5-10			10-15			15-20			20-25			25-30			30-35		
Time of sampling	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃
<i>Acacia catechu</i>	-	1	4	-	1	1	-	-	1	-	-	-	-	-	-	-	-	-
<i>Albizia chinensis</i>	-	1	3	-	-	1	-	-	1	-	-	1	-	-	-	-	-	-
<i>Alnus nitida</i>	-	2	39	-	1	5	-	-	2	-	-	1	-	-	1	-	-	1
Mean		1.30	15.30	-	0.67	2.33	-	-	1.33	-	-	0.67	-	-	0.33	-	-	0.33
Species at each stage	SE _m 0.27	CD _{0.05} 0.77		SE _m 0.04	CD _{0.05} 0.11		SE _m 0.02	CD _{0.05} 0.06		SE _m 0.17	CD _{0.05} 0.30							
Timings	0.16	0.45		0.02	0.06		0.01	0.04		0.06	0.17							

T₁, T₂ and T₃ indicate times of sampling i.e. after 3 months, 9 months and 18 months, respectively

had maximum diameter of 33.81 mm and *Acacia catechu* had minimum diameter of 15.56 mm while, *Albizia chinensis* had 20.33 mm.

4.1.7 Number of Rootlets under Different Diameter Classes

The number of roots before transfer i.e. at 3 months age was only one in each species under diameter class >1-2 mm, and at the same time the number of lateral rootlets of 0.0-0.5 mm diameter was maximum in *Albizia chinensis* i.e. >34 followed by *Alnus nitida* (>29) and *Acacia catechu* (>23). During this stage no root was observed in other diameter classes (Table 4). In 9 months old seedlings, there was a significant increase in diameter as well as number of rootlets in all the three species. *Alnus nitida* and *Acacia catechu* had one rootlet of >10-15 mm diameter class in 9 months old seedlings, whereas, in other lower diameter classes i.e. >5-10 mm, >2-5 mm, >1-2 mm, >0.5-1.0 mm, and 0.0-0.5 mm the number of rootlets were 2, 1; 10, 3; 16, 3; 27, 8 and 2191 and 95, respectively. In *Albizia chinensis*, one root of maximum diameter >5-10 mm was obtained whereas in other diameter classes i.e. >2-5 mm, >1-2 mm, >0.5-1 mm and 0.0-0.5 mm the number of roots recorded were 1, 2, 7 and 111, respectively.

Significant difference was also observed among three species in the development of roots and rootlets of various diameter classes at 18 months age (Plates 1, 2 and 3). *Alnus nitida* recorded 1, 1, 1, 2, 5, 39, 121, 149, 315 and 7407 number of rootlets of different diameter classes i.e. >30-35 mm, >25-30 mm, >20-25 mm, >15-20 mm, >10-15 mm, >5-10 mm, >2-5 mm, >1-2 mm, >0.5-1.0 mm and 0-0.5 mm, respectively. One rootlet of *Albizia chinensis* and *Acacia catechu* had been reported in diameter class >10-15 mm and >15-20 mm and one rootlet of *Albizia chinensis* was observed in the diameter class of >20-25 mm. In other lower classes viz., >5-10 mm, >2-5 mm, >1-2 mm, >0.5-1.0 mm and 0.0-0.5 mm, the number of rootlets in *Albizia chinensis* and *Acacia catechu* were 3, 4; 5, 10; 7, 11; 91, 46 and 564 and 407, respectively.

4.1.8 Number of Primary Root

During the time of transfer of seedlings and at 18 months age, the primary roots were identified easily (Figs. 1, 2 and 3). However, at 9 months age, the tap

root was not well identifiable due to growth and increase of diameter of secondary roots which were developed and competed with tap root in morphology and emergence as it was observed in 86 per cent of samples of *Alnus nitida*, 36 per cent of *Acacia catechu* and 14 per cent of *Albizia chinensis*. During this stage, the tap root was observed to be forked at an average of 5.5, 1.8 and 1.2 in *Alnus nitida*, *Acacia catechu* and *Albizia chinensis*, respectively. Though, the forking marked at the collar region of *Alnus nitida* and at 7 to 8 cm distance below the collar region in *Acacia catechu* as well as *Albizia chinensis*, the primary root was always found to be single (Table 5).

4.1.9 Number of Laterals

It is evident from table 5 that the number of secondary roots in three species varied significantly among the species at each stage except *Acacia catechu* which did not differ with *Alnus nitida* at the time of transfer of seedlings i.e. 3 months age and with *Albizia chinensis* at 9 months age. Though, before transfer of seedlings, *Alnus nitida* reported to have minimum number (9) and *Albizia chinensis* had maximum number (17) of secondary roots, reverse trend was observed after transfer of seedlings, when *Alnus nitida* had shown maximum number i.e. 355 and 507 and *Albizia chinensis* had minimum number i.e. 40 and 80 at 9 months and 18 months respectively. *Acacia catechu* remained in between and had 42 and 88 number of secondary roots at the time of 9 months and 18 months, respectively.

The pattern of emergence of tertiary roots were quite different from that of secondary roots. During the time of transfer of seedlings to big polybags there was no statistical difference marked among the three species studied though, maximum number (17) of tertiary roots was obtained in *Albizia chinensis* and minimum (12) was observed in *Acacia catechu*. The three species differed significantly in number of tertiary rootlets emerged after transfer i.e. at the age of 9 months and 18 months. *Alnus nitida* had maximum number of rootlets i.e. 1847 and 5243 at 9 months and 18 months, respectively. *Acacia catechu* developed least number of tertiary roots i.e. 12, 57 and 362 at the age of 3, 9 and 18 months, respectively.

Table 5. Development of laterals : Number of rootlets of different categories produced on the root systems of various NFTs

Species	Number of Primary	Number of secondary			Number of tertiary			Total number of rootlets		
Time of sampling		T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃
<i>Acacia catechu</i>	1	11	42	88	12	57	362	24	110	480
<i>Albizia chinensis</i>	1	17	40	80	17	75	569	35	121	673
<i>Alnus nitida</i>	1	9	355	507	14	1847	5243	25	2247	8041
Mean		12.43	146.00	225.00	14.30	659.00	2058.00	28.00	826.00	3064.00
Species at each stage		SE _m		CD _{0.05}	SE _m		CD _{0.05}	SE _m		CD _{0.05}
		0.99		2.79	2.87		8.10	7.08		20.04
		0.57		1.61	1.65		4.68	409		11.57

T₁, T₂ and T₃ indicate times of sampling i.e. after 3 months, 9 months and 18 months, respectively

Though, *Albizia chinensis* had possessed least number of secondary roots at the age of 9 and 18 months i.e. 40 and 80, respectively; the number of tertiary roots of this species were increased to 75 during the former stage and 569 during the latter stage and remained higher to those of *Acacia catechu* (Table 5).

4.1.10 Total Number of Rootlets

The total number of rootlets emerged in a plant was affected by the number of tertiary roots developed on it due to their large number. Hence, the sequence of the three species studied for total number of rootlets developed was same as that for number of tertiary roots observed. The three species did not vary significantly for total number of rootlets emerged at the time of transfer where maximum number was observed in *Albizia chinensis* (35) and minimum in *Acacia catechu* (24). During the succeeding stages (9 months and 18 months), they differed significantly when *Alnus nitida* recorded 2247 and 8041 number of total rootlets, respectively. However, *Albizia chinensis* recorded 673 number of rootlets during 18 months age.

4.2 SHOOT LENGTH AND LATERAL BRANCH SPREAD

4.2.1 Shoot Length

It is evident from the table 6 that the shoot length of the three species differed significantly after transfer. Though, at the time of transfer the minimum plant height was observed in *Alnus nitida* (6.9 cm), this species has shown significantly better increment of height after transfer i.e. 9 months and 18 months, as 63.09 cm and 118.10 cm, respectively, in comparison to other two species. *Albizia chinensis* recorded the height of 26.32 and 81.90 cm at the end of 9 months and 18 months, respectively and remained as minimum among the three species studied.

4.2.2 Lateral Branch Spread

Lateral branch spread of *Alnus nitida* and *Albizia chinensis* was almost same at 3 months age i.e. 5.05 and 5.76 cm, respectively. Whereas, *Acacia*

Table 6. Shoot length and lateral branch spread of different NFTs

Species Time of sampling	Shoot length (cm)			Lateral branch spread (cm)		
	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃
<i>Acacia catechu</i>	9.75	36.18	84.50	8.33	22.48	30.32
<i>Albizia chinensis</i>	8.20	26.32	81.90	5.76	16.29	67.20
<i>Alnus nitida</i>	6.90	63.09	118.10	5.05	28.40	94.48
Mean	8.28	41.86	118.10	6.38	22.39	74.00
Species at each stage Timings	SE _m		CD _{0.05}	SE _m		CD _{0.05}
	1.02		2.89	0.31		0.89
	0.59		1.67	0.18		0.51

T₁, T₂ and T₃ indicate times of sampling i.e. after 3 months, 9 months and 18 months, respectively

catechu registered maximum lateral branch spread (8.33 cm). After transfer, *Alnus nitida* performed better than *Acacia catechu* and *Albizia chinensis* which had minimum lateral branch spread at 3 months age, attained maximum spread i.e. 28.40 cm and 94.48 cm at 9 months and 18 months, respectively. *Acacia catechu* recorded the minimum lateral branch spread i.e. 30.32 cm and *Albizia chinensis* had 67.20 cm lateral branch spread at 18 months. At 9 months age, *Albizia chinensis* had minimum spread i.e. 16.29 cm followed by *Acacia catechu* had 22.48 cm only (Table 6).

4.3 BIOMASS ACCUMULATION OF ROOT AND SHOOT

4.3.1 Fresh Biomass of Root and Shoot

The fresh biomass of root did not differ significantly before transfer among the three species studied. However, they differed significantly at succeeding stages. The minimum fresh biomass of root was however, weighed in *Alnus nitida* before transfer (0.31 g), it increased significantly with the maximum value of 36.05 g and 156.43 g at 9 months and 18 months age, respectively. *Albizia chinensis* had 14.47 g at 9 months age which was lowest but at 18 months age it was 48.91 g while minimum was recorded in *Acacia catechu* i.e. 26.38 g (Table 7). The results of fresh weight obtained for all the three species showed that *Albizia chinensis* possessed the maximum weight of 0.38 g before transfer, while after 18 months, its biomass increased significantly and was much higher (48.91 g) than *Acacia catechu* (26.38 g).

Fresh shoot biomass varied significantly after transfer among the species; though before transfer no significant difference was marked. *Alnus nitida* had shown the least biomass (0.68 g) before transfer but after transfer i.e. 9 months and 18 months it increased significantly and possessed the maximum of 44.82 g and 311.53 g, respectively. *Acacia catechu*, which had shown maximum fresh weight (0.88 g) at 3 months after germination did not perform better during succeeding stages i.e. at 9 months it was almost same (18.19 g) to that of *Albizia*

Table 7. Fresh and dry biomass of root and shoot of different NFTs

Species Time of sampling	Fresh biomass (g)						Dry biomass (g)					
	Root			Shoot			Root			Shoot		
	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃
<i>Acacia catechu</i>	0.32	15.11	26.38	0.88	18.19	34.24	0.16	7.71	14.33	0.35	9.18	17.09
<i>Albizia chinensis</i>	0.38	14.47	48.91	0.73	17.20	59.66	0.19	7.18	24.25	0.32	8.35	28.38
<i>Alnus nitida</i>	0.31	36.05	156.43	0.68	44.82	311.53	0.15	17.83	77.15	0.31	21.89	143.03
Mean	0.34	21.88	77.24	0.76	26.73	135.14	0.17	10.91	38.58	0.32	13.14	62.84
Species at each stage Timings	SE _m CD _{0.05}		SE _m CD _{0.05}		SE _m CD _{0.05}		SE _m CD _{0.05}		SE _m CD _{0.05}		SE _m CD _{0.05}	
	0.49 1.40		1.11 3.15		0.20 0.58		0.27 0.75		0.15 0.44			
	0.29 0.81		0.64 1.18		0.12 0.33							

chinensis (17.20 g); and at the age of 18 months, *Acacia catechu* recorded the minimum biomass of 34.24 g while *Albizia chinensis* had 59.66 g (Table 7).

4.3.2 Dry Biomass of Root and Shoot

The shoot dry weight differed significantly among the species after transfer of the seedlings; though there was no statistical difference before transfer. The trend of dry biomass accumulation for the three species studied was similar as it was observed in case of fresh biomass root and shoot (Table 7). Maximum dry biomass of shoot after 18 months was observed in *Alnus nitida* (143.03 g) followed by *Albizia chinensis* (28.38 g) and *Acacia catechu* (17.00 g) while the dry biomass of roots of the three species observed to be 77.15 g, 24.25 g and 14.33 g, respectively.

4.4 ROOT-SHOOT RATIO

The ratio between different root and shoot characteristics has been presented in table 8.

4.4.1 Ratio Between Root and Shoot Length

The root:shoot length ratio did not vary significantly before transfer of seedlings, i.e. 3 months, among the species and it ranged between 0.83 to 0.98. Maximum ratio was obtained in *Albizia chinensis* and minimum in *Alnus nitida*. After transfer of seedlings to big polybags, increase in root length was comparatively much higher than the shoot length. Maximum root:shoot ratio was observed in *Albizia chinensis* (1.40) which was followed by *Acacia catechu* (1.28) and *Alnus nitida* (0.79). In *Alnus nitida* the comparative increment of root length was minimum than shoot length at 9 months and 18 months age and ratio in respect of length was observed to be 0.79 and 0.50, respectively. In *Acacia catechu* and *Albizia chinensis* root:shoot ratio was 0.85 and 1.10, respectively during 18 months age. The three species differed significantly among themselves

Table 8. Ratio between different root and shoot parameters of various NFTs

Species Time of sampling	Root length to shoot length			Max. lateral root spread to lateral branch spread			Root to shoot (fresh weight)			Root to shoot (dry wt.)		
	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃
<i>Acacia catechu</i>	0.93	1.28	0.85	0.70	0.61	0.31	0.37	0.83	0.79	0.44	0.84	0.82
<i>Albizia chinensis</i>	0.98	1.40	1.10	0.71	0.58	0.37	0.50	0.84	0.82	0.59	0.86	0.85
<i>Alnus nitida</i>	0.83	0.79	0.50	0.77	0.84	0.40	0.45	0.80	0.50	0.50	0.82	0.54
Mean	0.91	1.16	0.82	0.73	0.68	0.36	0.44	0.83	0.70	0.51	0.84	0.73
	SE _m CD _{0.05}			SE _m CD _{0.05}			SE _m CD _{0.05}			SE _m CD _{0.05}		
Species at each stage	0.03 0.09			0.009 0.03			0.03 0.07			0.013 0.04		
Timings	0.02 0.06			0.005 0.02			0.02 0.04			0.007 0.02		

T₁, T₂ and T₃ indicate times of sampling i.e. after 3 months, 9 months and 18 months, respectively

at 9 months and 18 months age with respect to their root:shoot length ratio while the maximum value was observed in *Albizia chinensis* and minimum *Alnus nitida*.

4.4.2 Ratio Between Lateral Root-Branch Spread

Lateral root spread to lateral branch spread ratio differed significantly among three species. The values of 3 months and 18 months were ranged between 0.70 to 0.77 and 0.31 to 0.40, respectively for all the three species studied. The comparative lateral root spread was more than lateral branch spread in *Alnus nitida* followed by *Albizia chinensis* and *Acacia catechu*.

4.4.3 Fresh and Dry Biomass Ratio

The ratio between fresh weight of root and shoot differed significantly among three species at 3 months and 18 months age but, it became non-significant during 9 months. At the age of 3 months, *Albizia chinensis* had shown the maximum ratio of 0.50 followed by *Alnus nitida* (0.45) and *Acacia catechu* (0.37). The root:shoot fresh biomass ratio did not vary significantly among the species at 9 months and it ranged between 0.80 to 0.84; however, overall time comparison has depicted that, the development of root biomass was much higher than the shoot biomass during 9 months as compared to other time of samplings and was having the value of 0.83.

The ratio between dry matter accumulation in root and shoot followed the same pattern as that of root:shoot fresh biomass ratio. The three species differed at each stage except at 9 months age. The maximum ratio of root and shoot dry weight was observed in *Albizia chinensis* at every stage i.e. 0.59 at 3 months, 0.86 at 9 months and 0.85 at 18 months stage. At the termination of experiment, *Acacia catechu* was at par with *Albizia chinensis*. Though, the least values were observed in *Alnus nitida* at 9 and 18 months (0.82 and 0.54 respectively), *Acacia catechu* at the time of transfer recorded the least ratio between root and shoot dry biomass (0.44).

4.5 NODULATION STATUS

4.5.1 Number of Nodules on Primary Root

It is evident from the table 9 that there was a non-significant difference among the species for the number of primary root nodules at three months stage but, after transfer, they differed significantly. *Acacia catechu* and *Albizia chinensis* had shown statistically similar development of nodules. Before transfer, *Alnus nitida* did not have nodule on the primary root but after transfer there were maximum nodules i.e. 57 at 9 months and 189 at 18 months. The least number of nodules on primary root was observed in *Acacia catechu* (14) at 18 months age and in *Albizia chinensis* (5) at 9 months age.

4.5.2 Number of Nodules on Secondary Roots

There was no nodule at secondary root level during the time of transfer of seedlings. However, after transfer, there was a significant difference among the species studied (Table 9) *Acacia catechu* and *Albizia chinensis* at 9 months age had same number of nodules i.e. 11 but, in *Alnus nitida* there were 82 nodules. Maximum variation recorded at 18 months age, while *Alnus nitida* recorded highest number of nodules (338) which was followed by *Albizia chinensis* (42) and *Acacia catechu* (29).

4.5.3 Number of Nodules on Tertiary Roots

At the age of 3 months no nodule was observed on tertiary roots, however, with the increase in age of the seedlings, the development of the nodules also increased on the tertiary roots (Table 9). Maximum nodules were developed in *Alnus nitida* i.e. 63 at 9 months age and 273 at 18 months age. *Albizia chinensis* and *Acacia catechu* registered almost same number of nodules i.e. 5 and 7 at 9 months and 17 and 18 at 18 months age, respectively.

4.5.4 Total Number of Nodules per Plant

Based on the development of nodules on primary, secondary and tertiary roots in all the three species studied (Plates 4, 5 and 6), the total number of nodules per plant varied significantly; *Alnus nitida* produced maximum number of

Table 9. Nodulation status : number of nodules produced at different root levels of various NFTs

Species Time of sampling	Number of nodules on primary root			Number of nodules on secondary roots			Number of nodules on tertiary roots			Total number of nodules		
	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃
<i>Acacia catechu</i>	1	6	14	0	11	29	0	7	18	1	24	61
<i>Albizia chinensis</i>	1	5	16	0	11	42	0	5	17	1	21	75
<i>Alnus nitida</i>	0	57	189	0	82	338	0	63	273	0	202	800
Mean	0.67	22.67	73.00	0.00	34.67	136.30	0.00	25.00	102.67	0.67	82	312
	SE _m CD _{0.05}			SE _m CD _{0.05}			SE _m CD _{0.05}			SE _m CD _{0.05}		
Species at each stage	1.11	3.14		1.20	3.39		0.77	2.17		0.90	2.53	
Timings	0.64	1.81		0.69	1.96		0.44	1.25		0.52	1.46	

T₁, T₂ and T₃ indicate times of sampling i.e. after 3 months, 9 months and 18 months, respectively



Plate 4. *Acacia catechu*



Plate 5. *Albizia chinensis*



Plate 6. *Ainus nitida*

Nodulation pattern of the three species during 18 months

nodules i.e. 202 and 800 at 9 months and 18 months stages, respectively though, it did not produce any nodule in the three months old seedling. *Acacia catechu* and *Albizia chinensis* did not show much variation during all three age classes studied i.e. 1 and 1 at 3 month, 24 and 21 at 9 months and 61 and 75 at 18 months old plants, respectively (Table 9).

4.5.5 Shape and Size of Nodules

The proper shape of nodules was not observed at 3 months and 9 months of age, but at the age 18 months, all the three species had shown indeterminate type of nodules. However, the largest nodule size was observed in *Alnus nitida* followed by *Albizia chinensis* and *Acacia catechu*. In *Alnus nitida* more or less spherical impeded with small beads on the nodule surface, in *Albizia chinensis* palmate type and almost cylindrical shaped nodules were observed in *Acacia catechu* (Plates 7, 8 and 9). The largest size of nodules was observed on primary root and least on tertiary roots. The initial swelling of root for nodulation was marked in *Alnus nitida* (Plate 6).

4.6 BIOMASS OF NODULES

4.6.1 Fresh Biomass of Primary Root Nodules

The fresh biomass of primary root nodules did not differ significantly before transfer but differed among species at later stages, however, the weight of *Acacia catechu* nodules (98.80 mg) and *Albizia chinensis* nodules (96.80 mg) at 9 months was almost same. *Alnus nitida* did not form any nodule at 3 months stage, but its primary root nodules had maximum fresh biomass after transfer of seedlings i.e. 1223.20 mg at 9 months and 2360.20 mg at 18 months of age. During the termination of experiment, *Acacia catechu* noticed minimum fresh nodule weight of 290.40 mg while *Albizia chinensis* recorded 352.50 mg (Table 10).

4.6.2 Fresh Biomass of Secondary Root Nodules

There was no nodule observed on secondary roots before transfer of seedlings to big polybags, but after transfer a significant difference among the



Plate 7. *Acacia catechu*



Plate 8. *Albizia chinensis*



Plate 9. *Alnus nitida*

Shape and size of nodules of the three species during 18 months

Table 10. Fresh and dry biomass of nodules produced on different categories of roots of various NFTs

Species Time of sampling	Fresh biomass of nodules produced at different root levels (mg)									Fresh biomass of total nodules (mg)		
	Primary			Secondary			Tertiary			T ₁	T ₂	T ₃
	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃
<i>Acacia catechu</i>	2.60	98.80	290.40	0.00	121.40	466.90	0.00	94.30	319.50	2.60	314.60	986.00
<i>Albizia chinensis</i>	5.46	96.80	352.50	0.00	202.30	1574.60	0.00	118.30	449.60	5.46	412.50	2437.50
<i>Alnus nitida</i>	0.00	1223.20	2360.20	0.00	1250.90	2480.37	0.00	585.60	1224.30	0.00	2969.40	6065.00
Mean	2.69	479.90	1001.20	0.00	524.87	1507.29	0.00	260.40	664.47	2.69	1232.17	3162.80
Species at each stage Timings	SE _m		CD _{0.05}	SE _m		CD _{0.05}	SE _m		CD _{0.05}	SE _m		CD _{0.05}
	39.87		112.76	65.41		185.00	28.30		80.04	130.00		367.00
	23.06		65.07	37.83		107.00	16.40		46.39	75.00		212.00

Species Time of sampling	Dry biomass of nodules produced at different root levels (mg)									Dry biomass of total nodules (mg)		
	Primary			Secondary			Tertiary			T ₁	T ₂	T ₃
	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃	T ₁	T ₂	T ₃
<i>Acacia catechu</i>	1.20	27.00	82.80	0.00	33.00	133.10	0.00	25.70	91.10	1.20	85.90	281.10
<i>Albizia chinensis</i>	1.75	25.30	102.00	0.00	52.90	438.00	0.00	30.90	117.60	1.75	107.80	650.00
<i>Alnus nitida</i>	0.00	387.40	786.90	0.00	396.20	826.80	0.00	180.10	408.10	0.00	940.50	2021.70
Mean	0.98	146.57	323.90	0.00	160.70	465.96	0.00	78.90	205.60	0.98	378.06	984.27
Species at each stage Timings	SE _m		CD _{0.05}	SE _m		CD _{0.05}	SE _m		CD _{0.05}	SE _m		CD _{0.05}
	14.85		42.00	9.90		28.00	7.43		21.00	43.13		122.00
	8.57		24.00	5.71		16.00	4.24		12.00	24.80		70.00

T₁, T₂ and T₃ are 3 months, 9 months and 18 months respectively

species with respect to fresh biomass of nodules formed on secondary roots was marked. It is evident from table 10 that *Alnus nitida* produced the maximum fresh biomass of nodules synthesized on secondary roots i.e. 1250.90 mg and 2480.37 mg followed by *Albizia chinensis* i.e. 202.30 mg and 1574.60 mg and *Acacia catechu* i.e. 121.40 mg and 466.90 mg at the age of 9 months and 18 months, respectively.

4.6.3 Fresh Biomass of Tertiary Root Nodules

The fresh biomass of tertiary root nodules of the three species differed significantly at the age of 9 months and 18 months, however, at the age of 3 months no nodule was recorded on the tertiary roots of all the species studied. After transfer, the maximum values were associated with *Alnus nitida* i.e. 585.60 mg at 9 months and 1224.30 mg at 18 months, while, the minimum was recorded in *Acacia catechu* with respective values of 94.30 mg and 319.50 mg. Whereas, *Albizia chinensis* had 118.30 mg and 449.60 mg at 9 months and 18 months stages, respectively (Table 10).

4.6.4 Fresh Biomass of Total Root Nodules

The fresh biomass of total nodules observed per plant, differed significantly among the three species studied at every age class. *Alnus nitida* did not nodulate at 3 months age, but at 9 months and 18 months it nodulated profusely and produced the maximum total fresh nodule biomass as of 2969.40 mg and 6065.00 mg, respectively. While, in case of *Acacia catechu*, and *Albizia chinensis* fresh biomass of total nodules at 3 months age was 2.6 mg and 5.46 mg; at 9 months age was 314.60 mg and 412.50 mg and at 18 months age was 986.00 mg and 2437.50 mg, respectively.

4.6.5 Dry Biomass of Primary Root Nodules

The dry biomass of primary root nodules varied significantly and maximum biomass was recorded in *Alnus nitida* after transfer i.e. 387.4 mg at 9 months and 786.9 mg at 18 months; however, it did not produce any nodule on the roots of 3

months old seedling. During the stage of 9 months, *Acacia catechu* and *Albizia chinensis* remained at par with each other with respect to their dry biomass of primary root nodules with their respective values 27.00 mg and 25.30 mg. During the termination of experiment, the dry biomass of primary root nodules was observed to be 102.00 mg in *Albizia chinensis* and 82.80 mg in *Acacia catechu*.

4.6.6. Dry Biomass of Secondary Root Nodules

Similar trend as that of fresh biomass was also observed in dry biomass of secondary root nodules where maximum biomass was recorded in *Alnus nitida* i.e. 396.20 mg and 826.20 mg at 9 months and 18 months, respectively. In *Acacia catechu* and *Albizia chinensis* it was observed as 33.00 mg, 133.00 mg and 52.90 mg, 438.90 mg at 9 months and 18 months, respectively.

4.6.7. Dry Biomass of Tertiary Root Nodules

The nodule dry biomass of tertiary roots differed significantly after transfer and had the similar trend as it was observed in fresh biomass of tertiary root nodules. *Alnus nitida* had produced maximum dry weight of nodules on tertiary roots i.e. 180.1 mg at 9 months and 408.1 mg at 18 months. The minimum dry biomass of tertiary root nodules (25.70 mg) was registered in *Acacia catechu* which was at par with *Albizia chinensis* at 9 months (Table 10).

4.6.8. Dry Biomass of Total Root Nodules

The dry biomass of total nodules differed significantly among species. Though, *Alnus nitida* did not nodulate at the age of 3 months, it registered the maximum dry biomass of nodules to the tune of 940.50 mg at 9 months and 2021.70 mg at 18 months. *Acacia catechu* and *Albizia chinensis* produced the total nodule dry biomass of 1.20 mg and 1.75 mg during 3 months; 85.90 mg and 107.80 mg during 9 months and 281.10 mg and 650.00 mg during 18 months, respectively (Table 10).

4.7 TOTAL NITROGEN CONTENT

4.7.1 Nitrogen Per Cent of Root, Shoot and Nodules

It has been observed from the table 11 that the total nitrogen content of root differed significantly among the species studied and also between time of samplings i.e. 3 months and 18 months age. Maximum nitrogen was observed in *Acacia catechu* (1.34%) followed by *Alnus nitida* (1.29 %) and *Albizia chinensis* (0.95%) when the seedlings were 3 months old. At 18 months age, minimum nitrogen was observed in *Alnus nitida* root (1.32%) and maximum in *Acacia catechu* (2.11%), while *Albizia chinensis* had shown only 1.66 per cent of nitrogen.

The total nitrogen contents of shoot also differed statistically among the species at each stage of sampling. At the time of transfer the maximum nitrogen content of shoot (2.02%) was observed in *Alnus nitida* which was almost same as in *Acacia catechu* (1.96%). *Albizia chinensis* had minimum nitrogen i.e. 1.29 per cent. After 18 months, maximum nitrogen content was also observed in *Alnus nitida* (2.87%) followed by *Albizia chinensis* (2.75%) and *Acacia catechu* (2.51%). The nitrogen content of shoot also increased significantly with time (Table 11).

The total nitrogen contents in nodules which was determined only for 18 months old plants differed significantly among the species (Table 11). *Acacia catechu* had registered the maximum value (3.54%) followed by *Albizia chinensis* (3.37%) and *Alnus nitida* (3.25%).

4.7.2 Nitrogen Uptake by Plant

The nitrogen uptake was non-significant at 3 months after germination though, it differed significantly at 18 months age. The maximum value of nitrogen uptake at first stage (3 months) was recorded in *Acacia catechu* (8.98 mg) and minimum in *Albizia chinensis* (5.84 mg), while *Alnus nitida* reported 8.10 mg only. At the end of the experiment, the maximum nitrogen uptake was observed in *Alnus nitida* (5122.00 mg) followed by *Albizia chinensis* (1185.45 mg) and *Acacia catechu* (730.90 mg) as depicted in table 11.

Table 11. Nitrogen content of root, shoot and nodules and nitrogen fixed by various NFTs

Species Time of sampling	Total nitrogen %age of root, shoot and nodules					Nitrogen uptake by plant (mg)		Total nitrogen fixed (kg/ha/yr)* (Plant + Soil)	
	Total N% of root		Total N% of shoot		Total N% of nodules			Poly bags (dia=20.37 cm x length=45 cm)	3m
	T ₁	T ₃	T ₁	T ₃	T ₃	T ₁	T ₃		
<i>Acacia catechu</i>	1.34	2.11	1.96	2.51	3.54	8.98	730.90	124.28	7.41
<i>Albizia chinensis</i>	0.95	1.66	1.29	2.75	3.37	5.84	1185.45	198.40	8.84
<i>Alnus nitida</i>	1.29	1.32	2.02	2.87	3.25	8.10	5122.00	833.10	14.10
Mean	1.19	1.70	1.76	2.70	3.39	7.64	2346.12		
	SE_m	CD_{0.05}	SE_m	CD_{0.05}	SE_m	CD_{0.05}	SE_m	CD_{0.05}	
Species at each stage	0.001	0.03	0.07	0.20	0.006	0.018	14.72	42.25	
Timings	0.007	0.02	0.05	0.14			10.41	29.88	

T₁, T₂ and T₃ indicate times of sampling i.e. after 3 months, 9 months and 18 months, respectively

* By difference method

4.7.3 Nitrogen Fixed

After calculating the total nitrogen fixed by the Nitrogen Fixing Tree species as sum of soil enrichment and plant uptake during 18 months of age, it has been found that *Alnus nitida* fixed the maximum quantity of nitrogen (14.10 kg/ha/yr) followed by *Albizia chinensis* (8.84 kg/ha/yr) and *Acacia catechu* (7.41 kg/ha/yr) if the plants to be planted at 3 m x 3m spacing (Table 11).

4.8 EFFECT ON SOIL PROPERTIES

The effect of various NFTs at 18 months age on soil properties were observed after studying the physical properties of soil like porosity, bulk density, water stable aggregates, mean weight diameter, soil strength and chemical properties of soil like pH, electrical conductivities, organic carbon contents and available nutrient contents (nitrogen, phosphorus and potassium). The results of the soil properties obtained after analyses are presented in Table 12.

4.8.1 Physical Properties

4.8.1.1 Porosity and bulk density

The porosity and bulk density of the soil under the species studied marked a marginal change upon the control, with a trend reverse to each other. The maximum porosity (46.31%) and minimum bulk density (1.25 g cm⁻³) were attributed with the soil at the vicinity of *Alnus nitida* while, *Acacia catechu* affected the least, to reduce the bulk density (from 1.28 g cm⁻³ to 1.26 g cm⁻³) and to increase the porosity (from 45.24% to 45.75%).

4.8.1.2 Water stable aggregates and mean weight diameter

There was significantly better aggregation of soil observed under *Alnus nitida* followed by *Albizia chinensis* and *Acacia catechu* than the control. The above trend was maintained for both water stable aggregates and mean weight diameter for which the maximum values were observed to be 72.12 per cent and 1.15 mm

Table 12. Soil physico-chemical status under 1.5 years old NFTs

Species Parameters	Porosity (%)	Bulk density (g cm ⁻³)	Water stable aggregates (%) > 0.25mm	Mean weight diameter (mm)	Soil strength (lb inch ⁻²)	Electrical conductivity (dsm ⁻¹)	pH	Organic carbon (%)	Available nutrients (kg ha ⁻¹)		
									N	P	K
<i>Acacia catechu</i>	45.75	1.26	70.38	1.10	26.84	0.38	7.09	1.70	456.87	45.94	329.76
<i>Albizia chinensis</i>	45.87	1.26	71.09	1.12	27.23	0.39	7.07	1.76	458.24	45.66	330.46
<i>Alnus nitida</i>	46.13	1.25	72.12	1.15	27.54	0.38	7.06	1.88	461.17	45.03	328.84
Control	45.24	1.28	69.33	1.07	26.55	0.35	7.11	1.67	448.28	44.74	327.84
SE _m	0.47	0.02	0.24	0.01	0.61	0.02	0.03	0.01	0.87	0.73	1.36
CD _(0.05)	NS	NS	0.70	0.02	NS	NS	NS	0.03	2.55	NS	NS

while the minimum values were (under control) 69.33 per cent and 1.07 mm, respectively.

4.8.1.3 Soil strength

The soil strength (lbs inch⁻²) under various NFTs differed significantly with control. The pressure required to penetrate the soil surface was found to be maximum at the soil under *Alnus nitida* (28.07 lbs inch⁻²) and minimum was found in *Acacia catechu* soil i.e. 26.84 lbs inch⁻², whereas, *Albizia chinensis* soil had 27.23 lbs inch⁻². All the three species studied had shown marginal improvement upon the control, the value of which was 26.55 lbs inch⁻².

4.8.2 Chemical Properties

4.8.2.1 Electrical conductivity

The electrical conductivity of soil did not show any improvement and was found to be non-significant. Maximum value in dsm⁻¹ was observed in *Albizia chinensis* (0.39) which was followed by *Acacia catechu* and *Alnus nitida* both had shown similar value i.e. 0.38.

4.8.2.2 pH and Organic Carbon

There was no significant difference observed in the soil pH though, the species studied improved the organic carbon of soil significantly. The maximum percentage of organic carbon (1.88%) was observed under *Alnus nitida* followed by *Albizia chinensis* (1.76%) and *Acacia catechu* (1.70%) yet, they had shown a reverse trend for pH, which was maximum for control (7.11) and minimum for the soil at the vicinity of *Alnus nitida* (7.06).

4.8.2.3 Available nutrients (N, P and K)

The available nitrogen content in kg/ha was maximum under *Alnus nitida* (461.17) which was followed by *Albizia chinensis* (458.24) and *Acacia catechu*

(456.87), they differed significantly with the control value and among themselves except the similarity observed between *Acacia catechu* and *Albizia chinensis*.

Available phosphorus content in soil increased slightly by the three NFTs than the control value. However, the maximum phosphorus content was observed in the soil under *Acacia catechu* (45.94 kg/ha) which was closely followed by *Albizia chinensis* (45.66 kg/ha) and *Alnus nitida* (45.03 kg/ha).

As evident from Table 12, it has been found that the potassium content of soil has shown a marginal improvement upon control in all the three species studied. The maximum potassium content was reported in the rhizosphere of *Albizia chinensis* (330.45 kg/ha) which was preceeded by *Acacia catechu* (329.76 kg/ha), *Alnus nitida* (328.84 kg/ha) and then the control (327.84 kg/ha).

DISCUSSION

CHAPTER-5

DISCUSSION

The root is an important part of the plant, responsible for acquisition of soil based resources and regulation of many physiological and biochemical processes in the plant system (Went, 1938; Chibnall, 1939; Kende, 1965; Skene, 1967; Skene and Kerridge, 1967). They control the insufficient or excessive accumulation of most elements besides exploiting the deep underground zones both laterally and vertically for water and nutrients (van Noordwijk *et al.*, 1996). Ecologically, they constitute a major source of organic material for soil and thus affect its structure, aeration and biological activities. Fitter (1991) reported that the diversity of root systems are dependant on these functions to a greater extent. Their distribution through space and time is influenced by genetic characters of the plant and localized soil conditions (Huck, 1983; Fitter, 1985). During the present investigations, systematic studies were carried out on rooting and nodulation behaviour as well as their effect on soil properties and the results obtained are discussed as under :

5.1 ROOTING BEHAVIOUR

5.1.1 Length and Lateral Spread of Roots

The root length and length of primary, secondary and tertiary roots differed significantly among the species at 9 and 18 months of age. *Acacia catechu* showed maximum root length while *Alnus nitida* recorded minimum length during first 3 months though, they behaved differently during later stages. At the age of 9 months, *Alnus nitida* registered maximum vertical and horizontal spread as well as

length of lateral roots; but the maximum length of primary root was observed in *Acacia catechu*. *Albizia chinensis* showed maximum length of primary, secondary and tertiary roots during 18 months age. The results suggested that *Acacia catechu* had better root development during pre-monsoon sampling which may be attributed to its better adaptability to warm and dry conditions than other species (Habish, 1970). Maximum length during post-monsoon and early-winter samplings in case of *Alnus nitida* might be due to favourable conditions for its growth during monsoons; being a moisture loving species, besides its resistance to winter frost as compared to other two species. *Albizia chinensis* was however, most susceptible to frost and did not respond to growth during cold climate.

Variation among species at different growth stages as observed in the present investigations may be due to their genetic character (Atkinson, 1977; 1983) as well as the dynamics of the soil moistness. Similar variations have also been recorded in *Thuja heterophylla*, *Thuja plicata*, *Pseudotsuga menziesii* (Eis, 1974) and in red pine (Fayle, 1975a; 1975b).

The rate of expansion of root systems has often been ascribed to be increasing due to insufficient water and nutrient flow to them (Taylor *et al.*, 1972). Similar difference in growth rate of root systems with the time of observations has been reported in incense cedar (Wilcox, 1962).

5.1.2 Angle of Emergence

The root branch angles are key components of root system architecture in which lateral roots diverge from parent root at wider angles which increase the chances of their entry to unexploited horizons (Henderson *et al.*, 1983; Fitter, 1991). In general, the primary roots tend to be positively geotropic, secondary diageotropics and further branches to be ageotropic (Fitter, 1987). During the present studies the angles observed between primary-secondary roots and between secondary-tertiary roots varied significantly among the species. *Acacia catechu* had attributed maximum angle of emergence of secondary roots while *Albizia chinensis* registered the same for tertiary roots. The angle between

primary-secondary roots was greater than that of secondary-tertiary roots. Similar results have also been noticed on *Acacia mangium*, *Albizia lebbek* and *Leucaena leucocephala* (Kar and Patra, 1996).

The variation in angle among species shows their genetical characters as well as internal anatomies (Charlton, 1975; 1983).

5.1.3 Collar Diameter and Root Diameter Classification

Root diameter determines the length of root that a plant can produce for unit input of resources to the system. It increases due to secondary cambial growth and radial movement of water from soil into mature xylem elements (Baylis, 1975). The finer roots impose larger cost on plant due to their higher rate of turn over than coarse roots which exert greater forces on soil (Goss, 1977; Piersson, 1982). The diameter of various roots in each species differed significantly in the present studies after transfer from the tubes to the larger polybags. *Acacia catechu* registered maximum radial increment during pre-monsoon but minimum increment during post-monsoon sampling. The results are indicative of the better adaptability of *Acacia catechu* to higher temperatures which promoted root development during pre-monsoons, while, maximum moisture during post-monsoon period normally restricted its radial growth. *Alnus nitida* had recorded minimum basal area during 9 and 18 months which may be due to its higher nodule weight observed during these stages (Heilman and Ekuan, 1982). Minimum number of finer roots (<0.5mm dia.) were observed during pre-monsoon sampling, but these were proportionately larger than other two stages; which can be explained in terms of ion mobility status as well as volume of soil exploited (Baldwin, 1975; Robinson and Rorison, 1983).

5.1.4 Number of Primary, Secondary and Tertiary Roots

Seedlings generally produce one or several main roots directly from seed, which then give rise to laterals and subsequent laterals (Rose, 1983). Each of the three species had shown presence of single primary root i.e. a dominating tap-root system which is a principal feature of all dicotyledonous angiosperms (Dutta, 1980;

Rose, 1983; Klepper, 1991). Similar phenomena have also been observed in silver fir (*Abies alba*) and scots pine (*Pinus sylvestris*) by Kostler *et al.* (1968). Interestingly, prominent primary root was observed during pre and post-monsoons but it was indistinct during early winter. This may be due to better root penetration during summer and comparatively lesser growth of laterals during late monsoon months due to sufficient moisture in surface soil contributing to near anaerobic soil conditions thereby making the tap root indistinguishable (Drew and Lynch, 1980) which thereby indistinct primary root as observed during early-winter might be due to dying of main axis and better development of laterals to take over its function which changes its direction and rate of growth (Rose, 1983; Fitter, 1991). Besides, the present phenomenon also draws support from the findings of Klepper (1991) who reported that development of roots during early winter when shoot growth remains stunted.

The number of secondary, tertiary and total rootlets varied considerably among the species at each stage except at 3 months stage. Although, *Alnus nitida* showed minimum number of secondary roots during first stage, nevertheless it possessed the maximum during subsequent stages; for which minimum number of secondary roots was observed in case of *Albizia chinensis*. Numbers of tertiary and total rootlets were minimum in *Acacia catechu* irrespective of stage of sampling. The number of roots of each category recorded the maximum value in *Albizia chinensis* at initial sampling while *Alnus nitida* excelled its counterparts in each category during subsequent samplings. The varied trends in root branching pattern as observed from the present investigations may be related to various functional attributes. The variations marked can also be explained to be due to genetic behaviour and age of plants (Kostler *et al.*, 1968) as well as due to changes of physical conditions of soil with time of observation (Pomerleau and Lotie, 1962).

5.1.5 Length and Lateral Spread of Shoot

Significant variation among species about their shoot length and lateral branch spread was observed at 9 months and 18 months age. Maximum shoot development at 3 months was observed in *Acacia catechu*, but *Alnus nitida*

registered the maximum at 9 months and 18 months age. At 9 months, *Albizia chinensis* showed minimum development of shoot both vertically and horizontally. Minimum lateral branch spread and shoot length after 18 months were observed in *Acacia catechu* and *Albizia chinensis*, respectively. The poor development of *Albizia chinensis* during early winter may be due to its maximum susceptibility to the prevailing environmental conditions. Nevertheless, the higher nodulation in *Alnus nitida* might have contributed to better shoot growth (Schwintzer and Lancelle, 1983) of this species. The variation among the species, however, may be explained on the basis of their genetic behaviour with changing environmental conditions (space, food, light etc.) as reported by various workers (Brouwer and DeWit, 1968; Nimbakar *et al.*, 1986; Mohatkar and Relwani, 1987; Relwani *et al.*, 1987).

5.1.6 Biomass Accumulation in Root and Shoot

Although, the fresh and dry matter accumulation in root and shoot differed significantly among the species at 9 months and 18 months yet, they followed a similar trend. The pre-monsoon observation recorded maximum root biomass in *Albizia chinensis* and that of shoot in *Acacia catechu*; while *Alnus nitida* registered the minimum accumulation in case of both roots and shoots. However, *Alnus nitida* excelled the other two species during the successive stages of sampling. *Albizia chinensis* recorded minimum at 9 months and *Acacia catechu* at 18 months. The variation in root and shoot biomass accumulation has been generally reported to be due to variations in their hormonal regulation (Huck, 1983) which is dependent on changing environmental conditions (water, nutrients, light, CO₂ and O₂ concentration) of the soil (Brouwer, 1963) as well as the root architecture (Fitter, 1991). Further, the high nodulation in *Alnus nitida* may also explain its maximum dry matter accumulation during later stages (Robin *et al.*, 1984).

5.1.7 Root Shoot Ratio

Considerable differences were observed among the species with respect to their root-shoot ratio comprising the length and lateral spread at each stage as well as the fresh and dry biomass during pre and post-monsoon months.

Root to shoot length ratio recorded the highest value in *Albizia chinensis* and lowest in *Alnus nitida* at each stage which indicates that the genotype has more influence than environment to maintain the root-shoot length ratio. In general, maximum root-shoot ratio in respect of length was observed during early-winter while lower values were observed during post-monsoon sampling through high shoot and less root growth. The cessation of shoot growth but maintenance of root growth is of common occurrence in tree species during winter months. Drew and Lynch (1980) reported that with temporary saturation of soil by excess water, dissolved oxygen is depleted from the bulk soil solution which promotes lesser root growth. Similar, small root-shoot ratio has also been reported by Schuurman (1980).

The ratio between root and branch spread was observed to be maximum in *Alnus nitida* at each stage but minimum in *Albizia chinensis* and *Acacia catechu* during early-winter and pre as well as post-monsoon stages, respectively. Significantly higher ratio was observed at 3 months stage. Several workers have reported that various annual crops such as some grass species show higher root-shoot ratio during germination and plant establishment (Simanton and Jordan, 1986; Klepper, 1991) which lends support to the present findings. Besides, Huck *et al.* (1983) observed that root growth increased during moisture stress which also supports the present findings of higher root-shoot ratio during pre-monsoon months.

The significant variations in root-shoot fresh and dry weight ratios among the species at pre and post-monsoon samplings suggests their considerable dependence on moisture rather than temperature. The maximum ratio was observed in *Albizia chinensis* while minimum in *Acacia catechu* during initial stage and *Alnus nitida* during later stages. The root-shoot biomass ratio which was maximum at 9 months corresponding with early-winter, might be due to its inverse relationship with the starch content of leaves which is minimum in winter (Huber, 1983). Minimum ratio noticed during 3 months may be due to relatively higher shoot biomass accumulation than root during the stage after radicle emergence

(Brouwer, 1983). Although, the root-shoot ratio more or less constant for a particular species (Penka, 1965), nevertheless, the observed variations among the species with the time of sampling could also be attributed to their age which is in accordance with the findings of various researchers (Bray, 1963; Cannell and Willet, 1976).

5.2 NODULATION BEHAVIOUR

5.2.1 Nodulation Status

The root nodulation and nitrogen fixation activities of the tree species are influenced by both their genetic behaviour as well as climatic conditions (Hardy *et al.*, 1968; Gibson, 1976; Waughman, 1977; Gibson and Jordan, 1983; Pokhriyal *et al.*, 1996). During the present studies three months old seedlings of *Acacia catechu* and *Albizia chinensis* showed nodulation only on primary roots whereas *Alnus nitida* failed to nodulate. The delay in nodulation in *Alnus nitida* could be due to lack of sufficient number of competitive, efficient and effective *Frankia* to infect the grown seedlings. Furthermore, the low nodulation status/ activity during June was also observed by earlier workers (Pokhriyal *et al.*, 1996) which may be explained through the prevailing environmental conditions i.e. hot summer, water stress, root temperature (Kuo and Boersma, 1971; Sprent, 1972; Engine and Sprent, 1973) or due to low water potential which suppress the root hair infection (Worral and Roughley, 1976) or degenerate the nodule (Roughley, 1970; Pankhurst and Gibson, 1973). During 9 and 18 months, *Alnus nitida* registered maximum nodulation (80-85%) on primary, secondary as well as on tertiary roots, while *Acacia catechu* and *Albizia chinensis* manifested only 6 to 9 per cent of the total number of nodules formed by the three species. The profuse nodulation in *Alnus* spp. has also been reported by earlier workers (Ferguson and Bond, 1953; Heilman and Ekuan, 1982). Maximum nodulation was observed in secondary roots followed by tertiary and primary irrespective of number of rootlets nodulated. However, while considering nodulation per root, the maximum was observed in primary followed by secondary and tertiary roots. The lesser nodulation per rootlet than its parent root might be attributed to less surface area, infection sites and

lesser enzymatic activity. Nevertheless, the greater rate of turnover of finer root than coarser one may also explain the present findings (Fahey *et al.*, 1988).

5.2.2 Nodule Biomass

The results pertaining to nodule biomass revealed that both fresh and dry biomass of nodules maintained a similar trend but differed significantly among the species at 9 months and 18 months stages. Maximum nodulation was observed during post-monsoon sampling may be due to increased photosynthetic activity during rainy season which have a positive effect on nodulation (Gordon and Wheeler, 1978). The nodule biomass was observed to be directly proportional to number and size of nodules present on the primary, secondary and tertiary roots. Maximum nodule biomass was observed in secondary roots which was followed by primary and tertiary roots. *Alnus nitida* manifested maximum fresh and dry biomass which varied between 63 to 83 per cent at 9 months and 18 months. However, it varied between 9 to 26 and 7 to 10 per cent in *Albizia chinensis* and *Acacia catechu*, respectively. The maximum nodule biomass in *Alnus nitida* might be due to high nodulase activity of alder than leguminous species (Rodriguez, 1971).

5.2.3 Nitrogen Content

The importance of root distribution on ion mobility as well as assimilation of nutrients to rest of the plant have been well documented by earlier workers (Bray, 1954; Fitter, 1991). Nitrogen content of root and shoot varied among the species and increased significantly with time. The total nitrogen content in shoot was maximum in *Alnus nitida* and in root it was in *Acacia catechu*. High nitrogen content in *Alnus* shoot has also been reported by Daly (1966) which may be due to better uptake of nutrients through extensive root system (Barley, 1970; Nye and Tinker, 1977) besides its profused nodulation. During the pre-monsoon observation *Albizia chinensis* registered minimum nitrogen content in both root and shoot but during post-monsoon observation it was associated with *Alnus nitida* and *Acacia catechu*, respectively.

More nitrogen content in both root and shoot as observed during 18 months might be due to better nitrogen dynamics in plant through higher nodulation at that stage (Heilman and Ekuan, 1982; Beniwal *et al.*, 1995).

The total nitrogen content of nodules varied significantly among the species. *Acacia catechu* recorded maximum nodule nitrogen content although, it had registered the minimum nodule biomass. Similar relation was also observed earlier in *Dalbergia sericea* whose nodules comprised maximum nitrogen percentage but minimum fresh biomass as compared to those of *Dalbergia sissoo* and *Albizia chinensis* (Purohit *et al.*, 1997).

5.2.4 Nitrogen Uptake by Plant

Nitrogen uptake of the plant is a function of growth rate as well as the active-passive mechanism of the root surface and is influenced by the available nitrogen content as well as physico-chemical properties of soil besides the prevailing climatic conditions (Jain *et al.*, 1986). During the present investigations nitrogen uptake differed significantly among the species at 18 months stage. Although, the pre-monsoon observation recorded maximum uptake in *Acacia catechu* and minimum in *Albizia chinensis*, during post-monsoon, *Alnus nitida* accumulated significantly higher N than other two species while *Acacia catechu* gathered the lowest amount. At 18 months stage, *Alnus nitida* contributed 72.77 per cent of the total uptake by three species but *Acacia catechu* and *Albizia chinensis* claimed only 10.38 and 16.84 per cent, respectively. The nutrient uptake of plant is a function of its demand and supply from soil which is required for growth and survival, the maximum nitrogen uptake in *Alnus nitida* may be due to its high nitrogen content on the root-soil interface, maximum number of finer roots for absorption of nutrients (Gillespie, 1989). Moreover, better nitrogen dynamics activities of *Alnus nitida* than its leguminous counterparts as observed in the present studies also supports the present findings. The better performance of *Acacia* observed during June and *Albizia* during September may be due to increased nitrogenase activities of these species during these stages as observed

by earlier workers (Chaukiyal, 1994; Pokhriyal *et al.*, 1991a; 1991b; Pokhriyal *et al.*, 1996).

5.2.5 Nitrogen Fixed

The nitrogen fixed in soil as well as in plant was found to be maximum in *Alnus nitida* which was followed by *Albizia chinensis* and *Acacia catechu*. The higher nitrogen fixation rate by alder (*Alnus rubra* 350 kg/ha/yr and *Alnus nepalensis* 268.92 kg/ha/yr) has also been reported by earlier researchers (Newton *et al.*, 1964; Singh and Pokhriyal, 1998). Lesser nitrogen fixation by *Acacia* communities (Seizko, 1987; Sanginga *et al.*, 1990) also supports the present findings. Danso *et al.* (1992) observed the nitrogen fixation rate (50 kg/ha/yr in *Acacia* spp.) Singh and Pokhriyal (1998) noticed the nitrogen fixation rate of *Albizia chinensis* as 201.69 kg/ha/yr.

However, nitrogen fixation rate (expressed as kg/ha/yr) observed during the present investigations under field conditions was comparatively lesser than those observed earlier. This may be due to the fact that the present experiments were carried out in polybags and then worked out for field conditions. Besides this, it could be attributed to the age of the plant. Hence, further research is required to prove the potential as well as to find out the rate of nitrogen fixation of these species under field conditions.

5.3 SOIL PROPERTIES

Roots have been reported to induce changes in rhizosphere which differ genetically with respect to root exudation and physical and chemical constituents of the localized soil (Graham, 1984; Marschner, 1986; 1991). During the present investigations, it was observed that the physico-chemical characteristics of soil were affected by the root systems as well as the nodulation of the Nitrogen Fixing Tree species introduced in it.

5.3.1 Physical Properties

The maximum porosity and minimum bulk densities were recorded for soil in the vicinity of *Alnus nitida*, followed by *Albizia chinensis* and *Acacia catechu*

although it was nonsignificant in comparison to control. The increase in porosity or decrease in bulk density might be attributed to accumulation of organic matter and apertures created by the finer roots, which corroborate the findings of earlier workers (Volobuey, 1964; Liyanage and Jayasundara, 1987; Hosur and Dasog, 1995).

The aggregation of soil was maximum under *Alnus nitida* (Plates 10 & 11) which retained the maximum percentage of aggregates on the sieve of pore size 0.25 mm in addition to maximum mean weight diameter. Significant aggregation observed in soil over control may be due to the pressure exerted by the root system on the limited environment of the polybag. Besides, organic substances released from finer roots as well as those indigenous to soil interact with root system to bind the soil thus improving soil aggregation (Bhimaya *et al.*, 1956; Malik *et al.*, 1965; Kemper and Koch, 1966; Venkataraman and Thomas, 1978; Bhatia and Harisankar, 1980; Marschner, 1991). Since, *Alnus nitida* had maximum number and biomass of root system, hence, it exerted maximum pressure which provided better aggregation than *Albizia chinensis* and *Acacia catechu*.

Soil strength registered a similar trend as that of aggregation although it did not vary significantly from the control. The strengthening of soil by plant roots have been claimed to be dependent on their surface area, distribution, branching pattern, extent of mucigel production and nature of bond with soil as well as the nature of rhizosphere, mechanical characteristics of root and soil and also dependent on the density of root hairs (Volobuey, 1964; Coutts, 1983; Fitter, 1991).

5.3.2 Chemical Properties

The results of the present studies revealed that the three species also affected the soil chemical properties, of which the available nitrogen content and organic carbon differed significantly while marginal changes were observed in respect of pH, electrical conductivity, available phosphorus and potassium content.



Plate 10. Soil binding attained by the three species after water spray through thumb pressure for 3 minutes

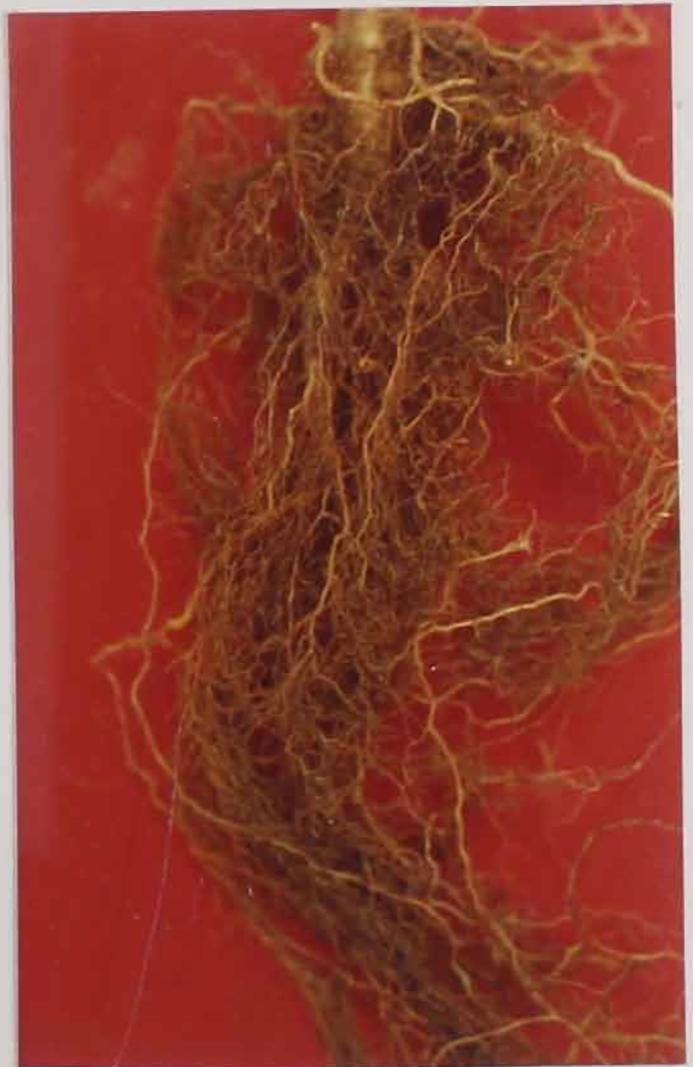


Plate 11. Fibrous roots developed in *Alnus nitida* during 9 months responsible for better binding of the soil

The variation in pH in the rhizosphere of various plant species have been suggested to be due to excretion of organic acids, protons and bicarbonates by the root systems or due to cation-anion exchange between root and soil (Marschner *et al.*, 1986; Marschner, 1991; Jungk, 1991).

Changes in electrical conductivity of soil by tree species has also been recorded by Mathew *et al.* (1997), which is indicative of the total soluble salts in the soil.

The species studied enriched organic carbon content of soil which was significantly higher with *Alnus nitida* followed by *Albizia chinensis* and *Acacia catechu*. Although, organic matter content is affected by leaf litter, high rate of turn over of minute rootlets, death and decomposition of roots and exudation of organic chemicals from them may also increase the organic carbon content of soil (Huck, 1983; Waisel *et al.*, 1991). Whipps and Lynch (1986) reported that competition between roots and rhizosphere micro-organisms induces a release of organic carbon (upto 30 per cent of the total plant dry weight) under conditions of oxygen stress which may also explain the present findings.

The available nitrogen content of soil in the vicinity of the Nitrogen Fixing Tree species was considerably higher than control. The higher nitrogen content in association with *Alnus nitida* followed by *Albizia chinensis* and *Acacia catechu* may be ascribed to varied nitrogen fixing capabilities of the three species. Better nitrogen transformation by *Alnus* communities have been reported by earlier workers (Bollen and Liu, 1968).

The available phosphorus and potassium content of soil did not differ significantly with the control although, there was a marginal increase in the soils under each species studied. The increase of phosphorus and potassium might be due to their mobilisation, phosphatase activity of proteoid roots (Marschner, 1991), or nutrient pump and scavenging mechanism of root systems (van Noordwijk *et al.*, 1996). The minimum phosphorus content observed under *Alnus nitida* may be due to higher utilization of this nutrient in the energy consuming process of nodulation and nitrogen fixation (Chung and Kim, 1965).

SUMMARY
AND
CONCLUSION

CHAPTER-6

SUMMARY AND CONCLUSION

The present investigations entitled "Studies on rooting behaviour, nodulation of various NFTs and their effect on soil properties" were carried out in the main campus of Dr. Y. S. Parmar University of Horticulture and Forestry, Nauni-Solan during the year 1997-98. The species studied were *Acacia catechu*, *Albizia chinensis* and *Alnus nitida* and the results obtained are summarised as under:

- All the species showed well developed root systems (both vertically and horizontally) which varied with time and species. Maximum root length was observed in *Acacia catechu* and minimum in *Alnus nitida* at 3 months. At 9 and 18 months maximum root length was observed in *Alnus nitida* while, the minimum was associated with *Albizia chinensis* and *Acacia catechu*, respectively. The lateral roots and branches spread as well as shoot length also showed a similar trend except for *Albizia chinensis* which registered minimum shoot length at 18 months.
 - The tap root was single and conspicuous during pre-monsoon (June) and post-monsoon (September) but indistinct during early-winter. Although, the length of primary root was maximum for *Acacia catechu* upto 9 months, *Albizia chinensis* recorded minimum length at or after 9 months stages.
 - The length as well as number of secondary and tertiary roots differed significantly among the species. Maximum number of primary, secondary and tertiary roots as well as their length were recorded in *Alnus nitida* for the age of 9 and 18 months old plants. Whereas, *Albizia chinensis* recorded minimum number of secondary roots and *Acacia catechu* for tertiary roots. Minimum root
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length of secondary and tertiary roots was also recorded in *Albizia chinensis* at 9 months age and in *Acacia catechu* at 18 months age.

- Collar diameter did not differ among the species at 3 months stage; but showed significant difference during subsequent stages. *Albizia chinensis* and *Acacia catechu* recorded minimum collar diameter after 9 months and 18 months, respectively while *Alnus nitida* had maximum.
- Wide variations were observed among the species for number of rootlets of each root system with respect to their diameter classes (0-0.5 mm, > 0.5-1 mm, > 1-2 mm, > 2-5 mm, > 5-10 mm, > 10-15 mm, > 15-20 mm, > 20-25 mm, > 25-30 mm and > 30-35 mm). The rootlets occupied diameter classes 0-0.05 mm and 1-2 mm during 3 months. Although, at 9 months stage, the uppermost class was recorded to be > 5-10 mm for *Albizia chinensis* and > 10-15 mm for other two species, yet, the former failed to exceed 20-25 mm at 18 months stage during which *Acacia catechu* and *Alnus nitida* exhibited maximum diameter classes (> 15-20 mm and > 30-35mm, respectively).
- The fresh and dry biomass of both root and shoot differed significantly among the species at 9 and 18 months age of which when minimum values were associated with *Albizia chinensis* and *Acacia catechu*, respectively; while, *Alnus nitida* registered the maximum irrespective of both stages.
- The root-shoot ratio obtained on the basis of length and lateral spread at each stage, and on the basis of biomass (fresh and dry) during pre and post-monsoon varied considerably among the species. The maximum ratio in respect of length and biomass was observed during December(early-winter) while during June (pre-monsoon) in respect of lateral spread. Conversely, the minimum ratio was recorded during September (post-monsoon) on the basis of length and lateral spread but during June for biomass.

- The root-shoot ratio comprising lateral spread was maximum for *Alnus nitida* irrespective of stage, while *Acacia catechu* during pre and post-monsoon and *Albizia chinensis* during early-winter recorded the minimum. In respect of length the maximum and minimum ratios were observed with *Albizia chinensis* and *Alnus nitida*, respectively at each stage of sampling. Further, the ratio pertaining to biomass was maximum in *Albizia chinensis* at each sampling while the minimum values were associated with *Alnus nitida* during early-winter as well as post-monsoon and *Acacia catechu* during pre-monsoon sampling.

The nodulation study of root systems revealed that at 3 months stage *Acacia catechu* and *Albizia chinensis* showed only a single nodule each, while *Alnus nitida* failed to nodulate. However, both maximum number as well as nodule biomass were observed in case of *Alnus nitida* during successive stages. Although, the species *Albizia chinensis* and *Acacia catechu* did not show considerable difference during 9 months, the former recorded minimum values for number as well as biomass of primary root nodules and number of tertiary root nodules. However, during 18 months, the number of nodules, observed on primary and secondary roots and the nodule biomass of each category were minimum in *Acacia catechu*.

Maximum nitrogen per cent of root as well as nodules were obtained in *Acacia catechu*. *Alnus nitida*, however, recorded maximum nitrogen percent of shoots but was minimum with respect to nodules. The percentage of nitrogen was greater during 18 months corresponding with the month September than that observed at 3 months stage during the month of June.

- Nitrogen uptake of plant was maximum in *Alnus nitida* and minimum in *Acacia catechu* at 18 months stage and the similar trend was also observed for rate of nitrogen fixation of the three species.
- The Nitrogen Fixing Trees species studied, affected the physical and chemical properties of soil of which porosity, strength, electrical conductivity, available

phosphorus and potassium contents showed a slightly increasing trend, while pH and bulk density decreased marginally. However, the water stable aggregates, mean weight diameter, organic carbon percentage and available nitrogen content improved significantly the maximum being recorded under *Alnus nitida* followed by *Albizia chinensis* and *Acacia catechu*.

CONCLUSION

The occurrence of species mixtures of widely differing habit and phenology are common particularly in agroforestry. However, lack of sufficient knowledge about roots and root behaviour becomes a cause of serious concern. Knowledge of location specific root adaptive characteristics of possible root complementarity or competitive attributes either in space or time and of the behaviour of root systems in relation to that of the aerial parts, soil fertility, effective crop mixtures etc. to be ascertained.

The three tree species showed varied rooting patterns and nodulating capacities, thereby, indicating their suitability over a wide range of agroforestry systems.

Acacia catechu demonstrated better development of lateral roots with high primary-secondary root angle and least branching pattern. The possibility of interference of their roots with surface feeders (crop) root system cannot be ruled out and hence its suitability in agri-silvicultural system may be questionable. Nevertheless, the potential of this species to change the orientation of roots under adverse soil and environmental conditions indicates its suitability for wastelands and silvo-pastoral systems.

Albizia chinensis, however, showed moderate fibrous rooting together with better vertical root development, least root angle and high branching patterns which hold a promise for incorporation of this species in agroforestry systems.

The profuse fibrous rooting system and high nodulating potential of *Alnus nitida* possibly ensure soil conservation as well as better rhizosphere interactions and hence may be exploited in marshy soils with clay contents.

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APPENDICES

APPENDIX-I

Meteorological data of the experimental site during the year 1997-98

Month	Mean monthly				Total rainfall (mm)
	Temperature (°C)		Relative humidity (%)	Sunshine hours	
	Maximum	Minimum			
1997					
March	22.6	9.5	55.0	6.20	36.8
April	24.5	12.5	55.0	8.20	128.6
May	29.0	16.1	46.0	9.00	52.6
June	29.4	19.0	64.0	5.40	104.2
July	29.2	21.3	78.0	4.30	69.4
August	26.7	20.2	84.0	4.10	425.0
September	27.3	18.1	75.0	6.60	43.6
October	22.5	10.3	71.0	5.90	45.6
November	20.5	6.6	70.0	6.50	59.2
December	17.0	2.9	67.0	5.20	85.2
1998					
January	17.5	2.1	60	6.63	15.1
February	18.7	4.7	89.5	6.10	87.1
March	20.8	6.1	56.3	6.80	125.5
April	28.2	11.2	50.9	-	46.6
May	23.2	15.4	46.3	-	63.0
June	31.5	17.9	57.5	-	185.1
July	29.3	20.3	80.0	-	206.4
August	28.2	20.2	79.0	-	100.8
September	27.3	17.8	81.0	-	193.7

APPENDIX-II

Analysis of variance for the parameters of rooting behaviour

Sources of variation	df	Mean sum of squares							Collar diameter
		Root length	Length of primary root	Length of secondary root	Length of tertiary root	Maximum lateral root spread	Angle of emergence		
							Angle between		
							Primary-Secondary	Secondary-Tertiary	
Species at 3 months (T ₁)	2	20.4108334	43.1284	0.3894	0.1281	7.63	16.8954	28.3082	0.11853
Species at 9 months (T ₂)	2	432.8877	333.9399	93.1646	14.4146	390.8541			157.7669
Species at 18 months (T ₃)	2	1026.8076	5795.5387	416.7809	133.00	694.0208			629.1691
Timings	2	31964.1231	33860.5869	5865.4036	2224.7617	2654.6359			2565.5133
Error	54	11.1909	0.9072	0.2268	0.1008	0.5887	1.0647	0.2268	0.0448

Sources of variation	df	Mean sum of squares							
		No. of rootlets under various diameter classes (mm)							
		0-0.5	0.5-1	1-2	2-5	5-10	10-15	15-20	20-25
Species at 3 months (T ₁)	2	259.00	0.0000	0.0000	-	-	-	-	-
Species at 9 months (T ₂)	2	10173184.0	889.00	427.00	156.3333	2.3333	2.3333	-	-
Species at 18 months (T ₃)	2	111826514.3	145322.333	45761.333	30102.3333	2942.3333	37.3333	2.333	2.3333
Timings	2	42769720.63	145576.83	18899.23	8666.68372	1511.23	112.00	12.3823	3.1423
Error	54	15.5407	2.7783	0.4032	0.8092	0.5103	0.0112	0.0028	0.2023

Contd....

APPENDIX-II continue ..

Source of variations	df	Mean sum of squares												
		No. of secondary roots	No. of tertiary roots	Total number of roots	Shoot length	Lateral branch spread	Fresh biomass		Dry biomass		Root- shoot ratio			
							Root	Shoot	Root	Shoot	Root length to shoot length	Max. lat. Root spread to lateral branch spread	Root to shoot (fresh wt.)	Root to shoot (dry wt.)
Species at 3 months (T ₁)	2	121.3333	44.3333	259.000	14.3508	20.8453	0.01003	0.0758	0.003033	0.003033	0.04083	0.01003	0.0301	0.0399
Species at 9 months (T ₂)	2	230064.33	7401809.333	10601227	2536.634	256.6837	1055.3545	1718.5016	251.6530	403.1587	0.731033	0.14163	0.003033	0.0028
Species at 18 months (T ₃)	2	717613.0	53332167.00	130075626	2853.85334	7257.6448	33811.3461	164470.1536	7983.6933	33988.46523	0.63583	0.04934	0.21863	0.20403
Timings	2	242437.8243	22923420.73	52019604	66502.0524	26223.3181	33048.0892	106698.0369	8247.066	22901.1748	0.6517	0.0175	0.8281	0.5929
Error	54	6.8607	57.6583	350.8848	7.2828	0.6727	1.6807	8.6247	0.28	0.5103	0.0063	0.000567	0.0063	0.001183

APPENDIX-III

Analysis of variance for the parameters of nodulation behaviour

Sources of variation	df	Mean sum of squares											
		No. of nodules on primary root	No. of nodules on secondary roots	No. of nodules on tertiary roots	Total number of nodules	Fresh biomass of primary root nodules	Fresh biomass of secondary root nodules	Fresh biomass of tertiary root nodules	Fresh biomass of total nodules	Dry biomass of primary root nodules	Dry biomass of secondary root nodules	Dry biomass of tertiary root nodules	Dry biomass of total nodules
Species at 3 months (T ₁)	2	2.33	0	0	2.3333	52.2097	0	0	52.2097	5.605833	0	0	5.6058
Species at 9 months (T ₂)	2	6190.33	11762.33	7588	75196.33	2955232.27	2778856.52	537041.143	15861165.9	304508.703	291859.33	53814.88	1661578.40
Species at 18 months (T ₃)	2	70651	2138101.33	152322.33	1250599	9705252.36	7118393.36	1675040.66	47905491.08	1126082.37	846240.663	216511.75	5888559.20
Timings	2	28870.5823	105379.245	3686.736	547543.282	5237768.53	12293962.51	2354103.87	53288369.68	549218.9619	1176444.07	225923.11	5167886.90
Error	54	8.6247	10.08	4.1503	5.67	11127.318	29949.2767	5606.23	118390.0	1543.6575	686.07	386.4343	13021.3787

APPENDIX-IV

Analysis of variance for nitrogen content

Sources of variation	df	Mean sum of squares			
		Total nitrogen percentage			Nitrogen uptake
		Root	Shoot	Nodule	
Species at 3 months (T ₁)	2	0.3152	1.149633		18.3652
Species at 18 months (T ₂)	2	1.0992	0.2352	0.148633	40815600
Timings	1	2.73105	9.4778		57419131.46
Error	36	0.00007	0.0343	0.000252	0.495

APPENDIX-V

Analysis of variance for the parameters of soil Physico-chemical properties

Sources of variation	df	Mean sum of squares										
		Porosity	Bulk density	Water stable aggregates	Mean wt. Diameter	Soil strength	Electrical conductivity	pH	Organic carbon content	Nitrogen	Phosphorus	Potassium
Treatment	3	0.977375	0.001108	9.6698	0.00793	1.321133	0.0021	0.00344	0.060375	214.721	2.14308	9.0484
Error	24	1.5663	0.0028	0.4032	0.000328	2.6047	0.0028	0.0063	0.0007	5.2983	3.7303	12.9472

CURRICULUM VITAE

Name : Ranjan Kumar Kar
Father's Name : Sh. Durga Ram Kar
Date of Birth : 28.06.1973
Sex : Male
Marital Status : Unmarried
Nationality : Indian

Educational Qualifications :

Certificate/ Degree	Class/ Grade	Board/University	Year
Matric	First	Board of Sec. Edu. Orissa	1988
10+2	Second	C.H.S.E. Orissa	1990
B.Sc. (Forestry)	First	O.U.A.T., Bhubaneswar	1996

Whether sponsored by some state/
Central Govt./Univ./SAARC : NGO (Asian Rural Life Development
Foundation) in collaboration with
Govt. of Orissa

Scholarship/ Stipend/ Fellowship, any : NA
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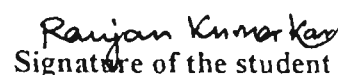
45687

Title of Thesis : Studies on rooting-behaviour, nodulation of various NFTs and their effect on soil properties.
 Name of the student : Ranjan Kumar Kar
 Admission number : F-96-9-M
 Year of award of degree : 1999
 Major Advisor : Dr. S.D. Kashyap,
 Deputy Director of Research,
 Dr. Y.S. Parmar University of Horticulture
 and Forestry, Solan (H.P.).
 Major Field : Agroforestry
 Minor Field (s) : Soil Science and Microbiology
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ABSTRACT

Three NFTs, *Acacia catechu*, *Albizia chinensis* and *Alnus nitida* were selected to explore their rooting-behaviour, nodulation and their effect on soil properties. The seedlings were grown on polythene tubes (5 cm x 11.5 cm), transferred to polybags (30 cm x 45 cm) and laid out through C.R.D. Root and nodulation parameters were studied at 3(pre-monsoon), 9(early-winter) and 18 months(post-monsoon), while nitrogen-dynamics was assessed at 3 and 18 months, whereas soil enrichment was studied during 18 months. 3 months sampling did not mark any remarkable difference among the species. During pre-monsoon, *Acacia catechu* recorded maximum root and shoot length alongwith their lateral spread for which *Alnus nitida* registered maximum during remaining samplings. Primary root was inconspicuous during early-winter but with maximum length in *Albizia chinensis*. Lateral roots were numerous in *Alnus nitida* during last two stages but longest only in early-winter. Minimum angle of secondary but maximum of tertiary roots were observed in *Albizia chinensis*. Although, initial sampling recorded maximum number of finer roots (<0.5 mm dia.) in *Albizia chinensis* yet, *Alnus nitida* possessed the maximum finer, coarser roots and collar dia. during succeeding samplings. *Albizia chinensis* for root and *Acacia catechu* for shoot biomass during 3 months while, *Alnus nitida* during 9 and 18 months reported maximum for both. Maximum root-shoot ratio in respect of length and biomass was associated with *Albizia chinensis* and early-winter while, in lateral-spread it was with *Alnus nitida* and pre-monsoon. Nodulation was observed maximum in *Alnus nitida* during 9 and 18 months but minimum in *Acacia catechu* (biomass) during post-monsoon and *Albizia chinensis* (number) in early-winter. All the species studied however, provided indeterminate nodule with more or less cylindrical, palmate-type and spherical shape in the three species, respectively. Maximum nitrogen (%) was observed in *Acacia catechu* for root and nodule but in *Alnus nitida* for shoot. The latter attributed maximum uptake and fixation (soil + plant) of nitrogen. There was marginal changes in soil properties in respect of porosity, B.D., strength, E.C., PH and avail-P and K while, W.S.A., M.W.D., avail-N, org-C improved significantly with maximum at the vicinity of *Alnus nitida*. The effect of root and nodulation on different soil properties were discussed.


 Major Advisor


 Signature of the student


 Countersigned

Professor and Head
 Department of Silviculture and Agroforestry