*Agric. Rev.*, 25 (3) : 157 - 172, 2004

# NUTRIENT CYCLING IN FOREST ECOSYSTEMS - A REVIEW

J.C. Sharma and Yogender Sharma

Department of Soil Science and Water Management,
Dr. Y. S. Parmar University of Horticulture and Forestry, Nauni, Solan (HP) - 173 230, India

## ABSTRACT

**Nutrient management has been well recognized since early times and has become highly relevant with the advent of various commercial forestry programmes. There is a need to understand the nutrient cycling and also budgeting in different forest ecosystems to know the amount of nutrients to be replenished to maintain the forest ecosystems in good health. The cycling of nutrients is important both in natural forests and man made protected plantations as considerable amount of nutrients are returned through litter fall, weathering of rocks, biological $N_2$ fixation, rainfall etc. and become available for reabsorption. Investigations carried out by various researchers with different forest species in India and abroad demonstrated considerable variations in the major components of nutrient cycle. Maximum amount of macronutrients (N, 33-57%; P, 13-38%; K, 40-48 %; Mg, 40-68%) in *Tectona grandis*, *Gmelina arborea* and *Eucalyptus* was accumulated in bole, while maximum Ca (57-75%) was held in bark. Though large amount of nutrients was accumulated in the biomass components of the standing crop, but the annual retention of N, P, K, Ca and Mg was much less than the quantity returned to the soil through litter fall. Harvesting of only utilizable biomass (148 t/ha) of *Tectona grandis* at the age of 30 years removed 247, 41, 170, 632 and 198 kg/ha N, P, K, Ca, and Mg, respectively. However, harvesting of utilizable biomass of *Eucalyptus grandis* (264 t/ha) at the age of 11 years removed comparatively higher amount i. e. 380, 50, 220, 650 and 220 kg/ha of N, P, K, Ca, and Mg, respectively. But, the total amount of these respective nutrients removed in the whole tree harvesting of *Eucalyptus hybrid* at the age of 10 years was comparatively less i.e. 341, 9, 199, 293 and 139 kg/ha, N, P, K, Ca and Mg, respectively. The harvesting of utilizable biomass in *Eucalyptus grandis* irrespective of age was more exhaustive. The removal, retention and release of nutrients varied with species, age, site and climate conditions etc. Fixation of atmospheric $N_2$ by microorganisms is probably the most important pathway for this element to enter the forest ecosystems.**

In natural forests and man made protected plantations, cycling of nutrients is an important aspect as significant amounts of nutrients are returned to the soil through litter fall and become available for cycling. Plants take up the nutrients from the soil and use them for various metabolic processes. Some of the plant parts such as leaves, branches, seeds fruits and roots are returned to the soil during the plant's growth. The litter or biomass so added decomposes through activities of soil microorganisms and the nutrients that had been bound in the plant parts are released to the soil where they again become available to plants. Nutrient dynamics in soil-plant system are studied under a common term called "nutrient cycling". It occurs to varying degrees in all land use systems and involves the continuous transfer of nutrients in, through and out of the different components of an ecosystem encompassing processes such as weathering of minerals, activities of soil biota and other transformations occurring in the biosphere, atmosphere, lithosphere and hydrosphere (Switzer and Nelson, 1972; Golley *et al.*, 1975; Jordhan, 1985). Other transformations mentioned in the definition includes the nutrients which may be brought into the system from atmosphere through rainfall, canopy wash, stem flow, biological nitrogen fixation while some other lost through crop harvest, forest fire, erosion etc. Thus, nutrient cycling in soil-plant systems is a dynamic and complex system of geological, chemical and biological cycling from which soil organic matter and nutrient supplies are replenished/maintained and thereby ensuring perpetual productivity of the site.

Investigations on litter production and

nutrient uptake, retention and return in natural forests as well as in protected plantations are important aspects of nutrient cycling. The plants periodically return various nutrient elements through litter fall of leaves, twigs, branches, flowers, fruits etc. The nature and amount of organic matter produced after decomposition of litter fall depend on the dominating tree species present and site characteristics of the area, which regulate the physical and physico-chemical properties of the soil. Thus, the percentage return of nutrients varies with species, site conditions, plant age, etc. (Sugar, 1989). A higher percentage of nutrients appear to be returned in vigorously growing stands than nutrient deficient stands.

The functioning of forest ecosystem is much influenced by the availability of nutrients and water and the biological cycle of nutrient affect the forest productivity. Thus, for proper management of these ecosystems, complete and up-to-date information on mineral budget and cycling of nutrient elements is very important. Hence, an attempt has been made to review work done in India and abroad, pertinent to bio-geo-chemical cycling under different forest ecosystems.

**Nutrient Cycling in a Forest Ecosystem Consists of two Pathways, Namely:**

(i) An internal biological cycle
(ii) An external geo-chemical cycle

In the process of internal biological cycle there are two important pathways: tree to soil: along this nutrients are transported to forest floor via leaf/litter fall, twig, fruits and flower drop etc. The other pathway is movement of nutrient elements from soil to tree through the activity of root systems. There are other minor routes like stem flow, crown/ canopy wash and through rainfall the nutrients dissolved in rains as atmospheric input into forest soil. The major component in nutrient cycle is retention, release and transfer in forest stand. The nutrients stored in the annual biomass increment of tree stands fall in the retention parameter. The different paths of the nutrient transfer are depicted in conceptual Figure 1.

The external geo-chemical cycle encompasses input of nutrient elements by various means such as precipitation, weathering of rocks, biological $N_2$ fixation, fertilization etc. and output of nutrients through harvest, forest fire, volatilization, leaching, drainage, erosion etc.

**Nutrient Cycle:** According to Remezov (1959) and Switzer and Nelson (1972) the different paths of nûtrient transfers in nutrient cycling can be recognized/studied as given below:

**1. Biological Cycle**

(i) Bio-chemical (within trees)
- Nutrient uptake, retention and release
- Internal transfer/distribution

(ii) Bio-geo-chemical (soil-plant relationships)

**2. Geo-chemical Cycle**

**(i) Inputs**
- Precipitation
- Weathering of parent rocks
- Biological $N_2$-foxation
- Dust
- Fertilization

**(ii) Outputs**
- Leaching
- Erosion/runoff losses
- Drainage water
- Volatile losses
- Removal in harvest

**Biological Nutrient Cycling:** Biological cycling involves the transfer of nutrients between forest floor and associated forest stand. The major routes within closed cycle include:
(i) Uptake (ii) Retention (iii) Restitution and (iv) Internal transfers.

The major components of nutrient cycle are retention, release and transfer fluxes

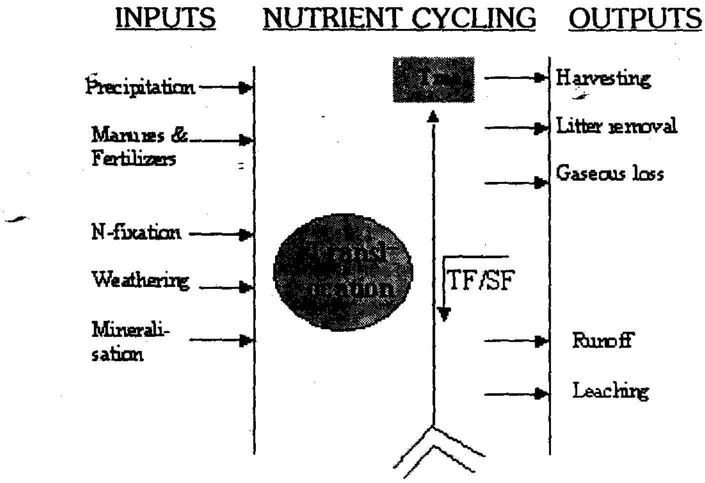


Fig. 1. Conceptual diagram of nutrient cycling

in the forest stand. The nutrients stored in the annual biomass increment of tree stands fall in the retention parameter. The release of nutrients is mainly identified as quantities of elements stored in litter fall. The uptake of elements is the sum of elemental storage in retention plus the release of nutrients in annual leaf fall. Transfer rates are expressed as kg/ha/yr in studies of nutrient cycling.

**Nutrient Uptake (Removal) and Retention:** Rannie (1955) probably for the first time has drawn attention that a considerable amount of nutrients immobilized in the crop and has questioned the ability of poorer soils to supply for a prolonged period, the nutrients required to maintain continuous timber production. The nutrient elements are lost from the site in number of ways, the greatest loss being through crop/tree removal.

The type and age of vegetation cover, soil and climatic conditions influence absorption of nutrient by tree. The nutrient content of the stock does not represent the gross uptake of nutrients by the tree since some trees have been died and some of the nutrients taken up by the surviving trees have been returned to the soil in various ways. Consequently, gross uptake of nutrients by the trees has been calculated from the estimates of total dry matter production (Ovington and Madgwick, 1959). The oldest stand of *Cedrus deodara* (60 years) forest in Kullu district of Himachal Pradesh had ân annual storage of 32.07, 27.79, 21.10, 8.47 and 1.28 kg/ha of K, Ca, N, Mg and P, respectively (Table 1). The accumulation of these nutrients followed the descending order: K > Ca > N > Mg > P (Sharma, 1977). The ranking of few species for nutrient storage studied by Ramam (1984) was as follows:

N: *Pinus* > *Tectona grandis*> *Shorea robusta* > Araucaria
K: *Pinus* > Araucaria > *Tectona grandis* > *Shorea robusta*
Ca: Araucaria > *Tectona grandis* > *Shorea robusta* > *Pinus*

Leaf litter of *T. grandis* and *S. robusta* stored lower amounts of P and Mg in contrast to the other species. Different forest species differed considerably in nutrient uptake and release e.g. *S. robusta* plantation was rated high in the uptake of Ca and N over *C. deodar* (Tables 1 and 2). The annual retention of N was maximum (29 kg/ha) followed by K (20

**Table 1.** Annual uptake of some nutrients by different tree species

| Species | Nutrient (kg/ha) | | | | | Reference |
|---|---|---|---|---|---|---|
| | N | P | K | Ca | Mg | |
| *Tectona grandis* (40 yrs) | 478 | 91 | - | 680 | - | Farugi (1972) |
| *Shorea robusta* | 339 | 37 | - | 380 | - | Farugi (1972) |
| *Eucalyptus hybrid* (10 yrs) | 59 | 11 | 43 | 169 | 16 | George, (1977) |
| *P. patula* (12 yrs) | 51 | 3 | 22 | 23 | 13 | Farugi (1972) |
| *Cedrus deodara* | 21 | 1.3 | 32 | 27 | 8.5 | Sharma, (1977) |
| *D. sisoo* (24 yrs) | 106 | 6 | 33 | 198 | 14 | Sharma *et al.* (1988) |
| *E. hybrid* (10 yrs) | 109 | 2 | 51 | 88 | 34 | Tandon *et al.* (1996) |

**Table 2.** Nutrient uptake, retained and returned in different species

| Species | Dry matter (t/ha) | | Nutrients (kg/ha) | | | | | Reference |
|---|---|---|---|---|---|---|---|---|
| | | | N | P | K | Ca | Mg | |
| Scot pine (mature) | - | Uptake | 50 | 4 | 4 | - | - | Duvigneaud and Denaeyer-DeSmet (1970) |
| | | Retained | 10 | 1 | 2 | | | |
| | | Returned | 35 | 3 | 4 | | | |
| European beech (mature) | - | Uptake | 50 | 12 | 14 | - | - | Duvigneaud and Denaeyer-DeSmet (1970) |
| | | Retained | 10 | 2 | 4 | | | |
| | | Returned | 40 | 10 | 10 | | | |
| Douglas-fir (37yrs) | - | Uptake | 39 | 7 | 29 | - | - | Gassel *et al.* (1973) |
| | | Retained | 24 | 6 | 14 | | | |
| | | Returned | 14 | 1 | 15 | | | |
| *E. hybrid* (10 yrs) | 142 | Uptake | 59 | 11 | 43 | - | - | George (1977) |
| | | Retained | 39 | 10 | 33 | | | |
| | | Returned | 20 | 1 | 10 | | | |
| *E. grandis* (27 yrs) | - | Uptake | 100 | 4.5 | 66.7 | - | - | Turner and Lambert (1983) |
| | | Retained | 29.6 | 1.1 | 30.6 | | | |
| | | Returned | 70.8 | 3.4 | 36.1 | | | |
| *Shorea robusta* (35 yrs) | 5.03 (litter fall) | Uptake | 178 | - | - | 152 | - | Ramam (1984) |
| | | Retained | 112 | | | 78 | | |
| | | Returned | 66 | | | 74 | | |
| *Cedrus deodara* (35 yrs) | 5.33 (litter fall) | Uptake | 130 | - | - | 108 | - | Ramam (1984) |
| | | Retained | 20 | | | 21 | | |
| | | keturned | 110 | | | 87 | | |
| *P. patula* (12 yrs) | - | Uptake | 51 | 2.9 | 22 | - | - | Bhartari (1986) |
| | | Retained | 29 | 2.7 | 15 | | | |
| | | Returned | 22 | 0.2 | 7 | | | |
| *D. sisoo* (24 yrs) | - | Uptake | 106 | 6 | 33 | - | - | Sharma *et al.* (1988) |
| | | Retained | 39 | 3 | 17 | | | |
| | | Returned | 67 | 3 | 16 | | | |
| *E. globulus* (10 yrs) | 90.66 | Uptake | 101 | 7 | 76 | - | - | George and Varghese (1991) |
| | | Retained | 43 | 3 | 36 | | | |
| | | Returned | 58 | 4 | 40 | | | |
| *Eucalyptus hybrid* (10 yrs) | 138 | Uptake | 109 | 2 | 51 | 88 | 34 | Tandon *et al.* (1996) |
| | | Retained | 34 | 1 | 20 | 29 | 14 | |
| | | Returned | 75 | 1 | 29 | 59 | 20 | |

kg/ha) and Mg (14 kg/ha) in plantation ecosystems of *Eucalyptus hybrid* in Haryana (Tandon *et al.*, 1996).

Storage of nutrients in the current litter of forest stand is influenced by magnitude of leaf fall and its elemental concentration. In general, the accumulation of nutrients was higher in leaves of younger plantations. But as the stand age increased, major portion of nutrients was stored in bole due to increase in non-photosynthetic biomass, while maximum calcium was held up in bark (Sharma, 1977; Negi and Sharma, 1984; Tandon *et al.*, 1996). Trees of identical biomass in different species were contrasted for storage of different elements and according the investigations carried out by Sharma (1977) the order for storage of nutrients in different components in two species was as like this:

| | | |
|---|---|---|
| *Tectona grandis* | : | Wood > branch > leaf |
| *Cedrus deodara* | : | Wood > branch for Ca only |
| | | Leaf > branch for P, K and N |

Net annual nutrient accumulation may be considered as the difference between total nutrient uptake and that returned to the soil in the form of litter fall and canopy washings. Since nutrient accumulation usually follows biomass expansion, it increases linearly or exponentially during periods of rapid early growth, and at diminishing rate as the stand reaches maturity. Total nutrient accumulation in rapidly growing species is rather large. Accumulation of nutrients increased manifolds with the increase in stand age from 4 years (young) to 10 years (mature plantation) in *Eucalyptus hybrid* (George, 1977; Tandon *et al.*, 1988, 1996), *E. globulus* (Negi and Sharma, 1984), *E. grandis* (Tandon *et al.*, 1991), *D. sisoo* (Sharma *et al.*, 1988) and *Populus deltoides* (Tandon *et al.*, 1991). Maximum amount of macronutrients (N, 33-57%; P, 13-38 %; K, 40-48%; Mg 40-68%) in different forest species (*Tectona grandis*, *Gmelina arborea* and *Eucalyptus*) was accumulated in bole and maximum Ca (57-75%) in bark (Negi and Sharma, 1984; Tandon *et al.*, 1988; George and Varghese, 1990a; Negi *et al.*, 1990, 1995). The pattern of annual mineral cycling (uptake, retention and release) varied at different ages in different forests species (Tables 1 and 2). Among the different nutrients, maximum accumulation was of N. Though large amount of nutrients were accumulated in the biomass components of the standing crop, but the annual retention of N, P, K, Ca and Mg was much less than the amount returned to the soil through litter fall. While in case of P, the retention and release was almost same (Negi and Sharma, 1984; Tandon *et al.*, 1996).

The estimates on the nutrient accumulation (N, P and K) in different components in standing biomass of different tree species showed that the maximum amount was accumulated in log wood and the lowest in leaves (Giri Rao *et al.*, 2000). Among the tree species studied, maximum amount of N and P was removed by *D. sisioo* (4,346 kg N $ha^{-1}$ and 234 kg P $ha^{-1}$). While in case of K, maximum removal occurred in *Leucaena leucocephala* (1,725 kg $ha^{-1}$) which showed high requirement for K. Nitrogen removal was maximum in *D. sisoo* followed by *L. leucocephala*, *A. auriculiformis* and *Eucalyptus camaldulensis*. Their study concluded that *D. sisoo* was highly exhaustive as compared to other species and when site has been used for it is to be reused further for crop production, it must be thoroughly checked for its fertility status and for replenishment of exhausted nutrients.

Location affected the nutrient accumulation and biomass production. Valley sal was found to be high in Ca than its counterpart in hill forests (Ramam, 1984). Of the total above ground biomass (76.9 t/ha), wood constituted 66 per cent, which removed 187, 15 and 187 kg/ha of N, P and K (40-48%), respectively. George (1984) reported that 120 t/ha of total biomass in *Eucalyptus* plantation constituted 69 per cent above ground biomass and accumulated 42, 50 and 35 per cent N, P and K of total uptake amounting to 168, 47 and 104 kg/ha, respectively. *A. mearnsii* plantation grown in Nilgiri South forest division showed that 56 per cent of total biomass (94 t/ha) was contributed by wood and accumulated 424, 21 and 143 kg/ha of N, P and K accounting for 41, 48 and 40 per cent of total uptake, respectively. In comparison to other species *E. globulus* removed comparatively lesser percentage of N than that removed either by *E. grandis*, *E. hybrid*, and *A. mearnsii*, but removed more K (George, 1984; George and Varghese, 1990a and b).

### Internal Transfer

Redistribution of nutrients in living biomass has its importance in biochemical cycling and hence in nutrient conservation within the standing crop. Retranslocation of nutrients before abscission of leaves depends upon many factors *viz.*, plant growth, species, and stature associated with age and site characteristics. Switzer and Nelson (1972) and Wells and Jorgensen (1975) reported that 25 to 39 per cent of the N requirement of 17 to 20 year old loblolly pine plantations was met by internal cycling. A similar portion of the K requirement was also met in this fashion, but internal transfer of Ca and Mg did not appear to play a major role in meeting the requirements for these elements. Switzer and Nelson reported that internal transfer met a major part of the requirement, but Wells and Jorgensen did not support this conclusion. Retention of all the nutrients was maximum in sal and minimum in pine (Table 2). Calcium had little possibility of back translocation prior to the leaf fall, being the structural element, so its retention was higher in all the species. There is a general translocation of nutrients from senescent organs to actively growing regions of the tree. Young leaves are always richer in N, P and K, but poorer in Ca, than mature leaves. During active growth N, P and K concentration steadily decreases, but remain constant once leaves are completely developed, until a decline during autumnal yellowing. The nutrient contents of standing crop differ considerably in various forest types according to the degree of uptake and tree biomass which in turn are affected by tree age, site quality etc. The nutrients accumulated in various components of tree varied considerably. Major portion of all the nutrients (N, P, K, Mg) was accumulated in bole followed by leaves/ needles, bark, least in twig, while maximum Ca was held up in bark (Tandon *et al.*, 1988, 1996; Negi *et al.*, 1990; Rawat and Tandon, 1993; Giri Rao *et al.*, 2000). Of all these nutrients, maximum accumulation was of Ca followed by K, N, Mg and least of P.

### Nutrient Returns

A major portion of the nutrients taken up annually by the above ground components of the trees is returned to the soil through litter fall and canopy wash (Table 3). The percentage restitution varies somewhat with species, site and stand age, for example a higher percentage of absorbed nutrients appear to be returned to the soil in vigorously growing stands than in nutrient deficient stands. Hardwoods like *Tectona grandis* and *Shorea robusta* generally known to return more nutrients than conifers. These returned 8-10 per cent total P and K absorbed by them through leaf fall and depleted the soil to the extent of 200 and 100 kg/ha respectively (Seth *et al.*, 1963). The nutrients accumulated in various tree components varied considerably. Conifers and deciduous trees differed in the storage of elements in their litter mass (Ramam, 1984).

**Nutrient Return by Litter Fall:** Plants return various mineral nutrients through leaf fall (litter fall), branches, twigs, flowers, fruits etc. The extent of nutrients returned to soil often forms a large proportion of nutrients extracted by the plants from the soil and relatively a small portion is retained in the growing biomass. The liter fall decomposes and

**Table 3.** Nutrient return by litter fall in different tree species

| Tree species | Litter (t/ha) | Nutrient (kg/ha) | | | | | Reference |
|---|---|---|---|---|---|---|---|
| | | N | P | K | Ca | Mg | |
| Pinus | 7.04 | 74 | 13 | 39 | 46 | 9 | Seth *et al.* (1963) |
| *Araucaria* | 5.90 | 33 | 16 | 25 | 168 | 17 | Seth *et al.* (1963) |
| *Gmelina arborea* | 9.94 | 64 | 6 | 24 | 64 | 10 | Negi *et al.* (1990) |
| *Eucalyptus hybrid* | 9.95 | 74.7 | 1.16 | 31.38 | 59.1 | 19.7 | Tandon *et al.* (1996) |
| *Tectona grandis* | 4.10 | 35.2 | 7.5 | 25.0 | 54.5 | 12.3 | Hosur *et al.* (1997) |
| *Dalbergia sisoo* | 6.29 | 110.5 | 10.2 | 118.0 | 169.3 | 9.3 | -do- |
| *Acacia catechu* | 5.86 | 52.6 | 7.8 | 72.0 | 94.3 | 7.9 | -do- |
| *Dendrocalamuc strictus* | 5.83 | 45.5 | 5.8 | 113.7 | 75.8 | 7.0 | -do- |
| *Eucalyptus tereticornis* | 8.31 | 66.3 | 5.6 | 87.0 | 78.3 | 19.8 | -do- |
| *Casuarina equisetifolia* | 5.51 | 53.6 | 8.7 | 30.8 | 73.8 | 17.9 | -do- |
| *Quercus incana* | 4.93 | 46.43 | 6.41 | 35.53 | - | - | Singh and Bhatnagar (1997) |
| *Populus deltoides* | 1.10 | 11.9 | 2.5 | 7.9 | 21.3 | 8.9 | Sharma *et al.* (2000) |

is reused by the growing trees. The age of forest stand and tree species hold considerable influence on quantity of nutrient accumulated in litter mass in forest. The per cent return of nutrients through litter fall varied with age of the plant, site, climate, plant parts etc. The storage figure for Ca in the litter mass ranged 26 kg/ha in 16-year plantation to 66 kg/ha in 35-year-old sal plantation. Maximum amount of N (74 kg/ha) was found in the current year's litter of 35 year old plantation (Narayana, 1972).

Tables 1 and 2 give a comparative account of nutrient uptake, retained and returned in various plantation ecosystems. Substantial amount of nutrient elements was accumulated in the biomass components and the annual retention within the biomass components was less than that returned to the soil. Greater fraction of annual uptake in *Eucalyptus hybrid* ranging from 50 to 69 per cent was returned to the soil annually through litter fall indicating that its annual needs were less as compared to the returning percentage. Conifers and deciduous differed considerably in the release of nutrients e.g. release of Ca and N in *Cedrus* stand was 110 kg/ha and 87, respectively, but lower amounts of these were retained in the annual retention. In contrast, *Shorea* released lower amounts of Ca and N via leaf fall but immobilization of these in tree biomass amounted to 112 and 78 kg/ha/yr, respectively (Ramam, 1984). The return of nutrients in various forest species was more than retention (Table 2). Leaf litter returned maximum amount of nutrients to the soil and the maximum return was observed for N followed by K, and P (Singh, 1968, 1969; Srivastava *et al* 1972; George, 1977; Turner and Lambert, 1983; Bhartari, 1986; Sharma *et al.*, 1988; Tandon *et al.*, 1996).

On an annual basis, 58, 4.6 and 40 kg/ha of N, P and K, respectively were returned in *E. globulus* to the soil through litter fall. The maximum amount (57% each N and P and 53%, K) was returned through litter and lowest through bark (George and Varghese, 1990a and b and 1991). The return of nutrients in various forest spp. was more than the retention (Table 2). Turner and Lambert (1983) reorded that of the total uptake of 100.4, 4.5, and 66.7 kg/ha/yr of N, P and K, respectively 70, 75 and 59 per cent of these respective nutrients were returned to the soil. But, this also included the nutrients returned by the understorey vegetation and the return of nutrients was more than that retained. The analytical results of leaf litter showed that the quantity of nutrients added into the soil decreased in the order Ca > N> Mg > K >P (Tandon *et al*, 1991; Sharma *et al.*, 2000).

An evaluation of nutrient returns through litter fall under different tree species is important to understand the dynamics of soil fertility. Leaf litter not only affects the nutrient reserves of soils but also brings out many important changes in physical, chemical and biological characteristics of soils. Trees take up large quantities of nutrients and substantive portion of the removed nutrient was returned back to the soil through litter fall (Table 3). Seth *et al.* (1963) and Srivastava *et al.*, (1972) demonstrated that leaf litter of forest species returned substantial amount of various nutrient elements. Similarly, the litter fall and return of nutrients was also more in younger plantation possibly due to faster growth of canopy. Out of the total litter produced in *Eucalyptus hybrid*, leaf constituted 82 per cent at the age of 4 years, which decreased to 73 per cent at the age of 10 years. Whereas in *Populus deltoides*, it was 85.2 per cent in young stand and decreased to 69.5 per cent at the age of 9 years. (Tandon *et al.*, 1991 and 1996). Among the various components of litter in 13-15 years old plantations of *Tectona grandis*, *D. sisoo* and *A. catechu*, leaf litter contributed maximum i.e. 97, 89 and 76 per cent of total litter fall of 6.3, 5.8 and 4.1 t/ha, respectively. The amounts of N, P, K, Ca and Mg returned under the respective species were 35, 7.2, 23.9, 63.7 and 11.9; 103.8, 9.5, 112.3, 112.3 and 6.7 and 32.4, 6.2, 42.2, 80.0 and 5.3 kg/ha, respectively (Hosur and Dasog, 1995).

The biological cycle of nutrients in an ecosystem is one of the principal processes that support organic matter production. Trees take up a large quantity of nutrients and much of it returned to the soil through litter fall (Tiwari, 1993). The nature and amount of organic matter produced in the process of biological cycling after decomposition of litter fall depends on dominating tree species present and the site characteristics of the area, which regulate the physico-chemical and biological properties of the soils. The percentage return of nutrients varied with species, site conditions, plant age etc. (Sugar, 1989). The available N, P and K increased from 14.87 to 24.61, 1.51 to 5.59 and 10.0 to 30.58 kg/ha/yr, respectively with the increase in age of *Populus deltoides* stand. Maximum amount of the nutrient contents was found in the upper layer (0-15 cm) in seven years old plantation in four different aged plantations (2, 3, 6 and 7 years) (Fiaz Moshin *et al.*, 1996).

Hosur *et al.* (1997) conducted study on the litter production and nutrient return in different tree species and observed that contribution of leaf litter to the total litter fall was more than other plant parts. Different plants parts showed variations in nutrient concentrations and the concentration of Ca, K and N were comparatively higher that other nutrients. *Dalbergia sisoo* returned highest N, P, K and Ca among six plantations studied. The nutrient return followed the order: Ca >K > N in *D. sisoo* and *A. catechu*, Ca > N> K in *Tectona grandis* and *Casuarina* and K > Ca > N in bamboo and *Eucalyptus*. The return of P and Mg was lower in all the cases.

A higher percentage of nutrient uptakes appear to be returned in vigorously growing stands than nutrient deficient stands. Differences in nutrient status of the soils receiving litters from pine (*Pinus roxburghii*) deodar (*Cedrus deodara*) and oak (*Quercus incana*) indicated that total additions of macronutrients (N, P and K) by the litter of these species was 53.46, 62.85 and 88.32 kg/ha, respectively (Singh and Bhatnagar, 1997). The ranking of these species for the addition of these nutrients exhibited the order: oak > deodar > pine. This indicated the superiority of oak litter over pine and deodar in terms making more nutrients available to the soil. The deciduous trees contributed more *to the forest soil fertility* than conifers (Vogt *et al.*, 1986). It has been found that *E. globulus* returned 58, 4.6 and 40 kg/ha of N, P and K, respectively. The maximum amount (48% of N, 63% P and 50% of K) was returned through litter fall, followed twigs (20-35%) and minimum by bark (Singh, 1968, 1969; Srivastava *et al.*, 1972; George and Varghese, 1990a; Negi *et al.*, 1990). The return of Ca was highest followed by Mg and least return was of P (Kaul *et al.*, 1979; Negi *et al.*, 1990). A study by Shanmughavel (1993) on the nutrient return through litter fall in bamboosa recorded highest concentration on N, P, Ca, and Mg in leaf litter. On the annual basis, the total return on N was 141 kg/ha followed by 121 kg/ha P, 79 kg/ha Mg, 72 kg/ha of Ca and 131 kg/ha K. Maximum amount of all the nutrients was returned through leaf.

**Geo-chemical Cycling:** The geo-chemical nutrient cycle involves the import of nutrient from sources such as dust, precipitation, weathering of parent rock, biological nitrogen fixation and fertilization; while outputs includes leaching and erosional losses through drainage and runoff water, volatile losses, removal in tree harvest, leaf litter etc. The amount of nutrients gained or lost by an ecosystem are influenced by factors such as soil properties, climatic conditions, location of ecosystem in relation to the sea and industrial areas, type of vegetation etc. These fluxes tend to reach to equilibrium in a mature forest, unless disturbed by man or acts of nature.

**Nutrient Inputs (Gains):** Input of nutrients is through dust, precipitation, weathering of parent rock, biological nitrogen fixation and fertilization.

**Precipitation (Atmospheric Inputs):** Some quantity of nutrient elements essential for plant growth is also added into the soil through precipitation and dust and addition vary with location as well as season of the year, depending largely on dust load, lightening activity etc. Quantity added through precipitation at some locations in the world is depicted in Table 4. Among various nutrients, maximum amount added through precipitation was of Ca followed by N, K Mg and minimum of Pand the order was Ca>N>K>Mg>P. The average input for nitrogen at all sites was about 8.8 kg/ha/yr. The inputs for P, K, Ca and Mg averaged about 0.3, 5.7, 10.4 and 3.7 kg/ha/yr., respectively. These values are in line with other reports on precipitation inputs summarized by Woodwell and Whittaker (1967) and Weetman and Webber (1972). The atmosphere is an important source of nitrogen. Through electrical discharge, molecular nitrogen is converted to ammonium, nitrate or various oxides of nitrogen and those dissolve in atmosphere in high humidity conditions reach the soil through precipitation. Large quantities of nitrogen and sulfur are introduced to atmosphere by industrial pollution and automobile exhaust, which also enter the soil through precipitation. The average annual nutrient inputs from atmospheric sources may not appear large, but when taken in the context of lifetime of a forest, they can be significant.

**Nutrient Return by Rainfall and Canopy Washes:** The chemical composition of rainwater has received much attention in the past and the chemical impurities in rain water is the result of contamination by atmospheric particles (or aerosols) which may act as condensation nuclei or which may be removed from the atmosphere (washout) by falling raindrops. The origins of these particles are oceanic, terrestrial, or extra terrestrial as a result of air pollution from the combustion of fuel, and biogenic or volcanic. Aerosols and dust may adhere to leaves, branches, stems etc. and these may add significantly to the chemical concentration through fall and stem

**Table 4.** Input of nutrients in precipitation

| Location | Precipitation (mm/yr) | Nutrients (kg/ha/yr) | | | | | Reference |
|---|---|---|---|---|---|---|---|
| | | N | P | K | Ca | Mg | |
| Great Britain | 1717 | 8.7 | 0.3 | 2.8 | 6.7 | 6.1 | Boyle and Ek (1972) |
| Germany | 624 | 20 | 0.1 | 4.6 | 19.0 | — | Neumann (1966) |
| Nigeria | 1850 | 14 | 0.4 | 17.5 | 12.7 | 11.3 | Nye (1961) |
| Mississippi | 1270 | 13.3 | 0.3 | 4.0 | 5.0 | 1.0 | Switzer and Nelson (1972) |
| USSR | 204 | 5.6 | 0.5 | 7.7 | 15.4 | 2.5 | Remezov and Pogrebnyak (1969) |
| Sweden | 420-468 | 1.4-5.2 | - | 0.6-3.7 | 2.6-13.9 | 0.6-2.6 | Tamm (1958) |
| N. Carolina | 1169 | 3.5 | 0.3 | 0.9 | 3.4 | 0.7 | Wells *et al.* (1972) |
| Tasmania | 993 | 2.4 | 0.5 | 4.5 | 12.5 | 2.6 | Adams and Attiwill (1991) |

flow. Intensity of rain, leaf composition, weight of leaves, branches etc. are some of the important overriding factors in determining the nutrient return by rain. An assessment of the amount of plant nutrients added to a site through rainfall is of importance in a study of the nutrient cycling/balance of a site. When a forest association occupies a site, such an assessment is complicated because the chemical composition of rainwater is altered as the rainfalls onto and through the canopy of the forest.

The litter fall is the major pathway of nutrient flow to the soil from standing biomass, but nutrients are also returned to the soil through rainfall, canopy washes and stem flow. Appreciable quantities of K and Mg were added through rainfall (Table 4). Considerable amounts of N, K, Ca and Mg were leached from the tree canopy and returned to the soil through stem flow and canopy washes (Tables 5 and 6). However, the amount of nutrients returned through stem flow was comparatively lesser than through fall, as greater amount of rainfall passes through canopy then stem flow (Cole *et al.*, 1967; Wells and Jorgensen, 1975; George, 1978). The return of K in mature *Eucalyptus obliqua* in Australia was more than that returned through litter fall while Mg was more or less the same. With regard to other elements (N, P and Ca), the major portion was returned through litter fall. The greatest increase in ionic concentration (equivalent) due to canopy was in the order: Na > K > Ca > Mg (Table 6) (Attiwil, 1966). He concluded that concentration of nutrients were highest in summer and lowest in winter both under canopy and at the open plot. Concentrations were in rainwater sampled under the forest canopy than in rainwater sampled above the forest canopy or at the open site. Generally, nutrients found associated with organic molecules move more slowly from the forest canopy than those found in ionic form (K).

**Biological $N_2$ Fixation:** Fixation of atmospheric $N_2$ by different tree species through symbiotic and non-symbiotic relationships is probably the most important pathway for this element to enter the forest ecosystems. Many forest tree species has ability to add nitrogen to the soil through the process of biological fixation of atmospheric nitrogen (Table 7). But it is very difficult to estimate the exact amount of $N_2$ fixed by the trees and shrubs, which is actually used or potentially available to the associated crop during the various periods of time.

Symbiotic fixation occurs through the association of plant roots with nitrogen fixing microorganisms and many legumes form an association with bacteria *Rhizobium*. Nonsymbiotic fixation is effected by free living bacteria (*Clostridium*, *Azotobacter* and *Beijerinkia* species) and blue green algae, and

**Table 5.** Nutrient return through rain (kg/ha) in *Eucalyptus* plantation

| Source | N | P | K | Ca | Mg | Ecosystem | Reference |
|---|---|---|---|---|---|---|---|
| Stem flow | 0.2 | 0.1 | 3.9 | 3.8 | 0.2 | *Eucalyptus* | George (1986) |
| Through fall | 2.0 | 0.1 | 9.4 | 8.8 | 2.0 | | |
| Total | 2.2 | 0.2 | 13.3 | 12.6 | 2.2 | | |
| Rainwater | 1.7 | 0.2 | 5.2 | 5.9 | 2.5 | | |
| Litter fall | 13.6 | 0.2 | 2.7 | 11.1 | - | Douglas-fir | Cole *et al* (1967) |
| Through fall | 1.5 | 0.3 | 10.7 | 3.5 | - | | |
| Stem flow | 0.2 | 0.1 | 1.6 | 1.1 | - | | |
| Through fall + Stem flow | 9.6 | 0.5 | 12.3 | 6.0 | 2.0 | Loblolly pine | Wells and Jorgensen (1957) |
| Litter fall | 58.2 | 7.8 | 16.0 | 29.2 | 6.9 | | |

**Table 6.** Concentration (ppm) of nutrients in rainwater in mature *Eucalyptus obliqua* forest

| Rain | Nutrients (ppm) | | | | | | | | Annual rainfall (inches) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | K | | Ca | | Mg | | Na | | | | | |
| | O* | UC | O | UC | O | UC | O | UC | | Sept. 1960-Sept 61 | Sept. 1961-Sept 62 | Mean |
| Spring 1960 | 0.18 | 1.96 | 0.34 | 1.13 | 0.46 | 1.96 | 1.74 | 2.91 | OF | 44.19, | 33.10 | 30.67 |
| Summer 1960/61 | 0.36 | 4.58 | 0.46 | 2.16 | 0.60 | 1.96 | 2.18 | 5.49 | AC | 40.89, | 30.69 | 35.79 |
| | | | | | | | | | UC | 29.82, | 21.24 | 25.43 |
| | | | | | | | | | TF(%) | 72.9, | 69.20 | 71.3 |
| Summer 1961/62 | 0.35 | 4.95 | 0.50 | 3.02 | 0.64 | 2.09 | 2.24 | 6.62 | AC | 44.06, | 33.06 | 35.56 |
| | | | | | | | | | UC | 32.01, | 25.16 | 28.63 |
| | | | | | | | | | TF(%) | 72.9, | 76.10 | 74.2 |
| Mean | 0.20 | 2.14 | 0.28 | 1.38 | 0.54 | 1.26 | 1.71 | 4.05 | | 29.82, | 21.24 | 25.53 |

Attiwil (1966)

* OF = Open forest, UC = Under canopy, OF = Open forest, AC = Above canopy, UC = Under canopy, TF = Through fall.

can be a significant factor in natural ecosystems, which have relatively lesser nitrogen requirements from outside systems. It is not believed to be much and account only for few kilogram of N/ha/yr in most forest soils (Brady, 2000). However, nonsymbiotic $N_2$ fixation is of minor importance in agricultural systems that have far greater demands of nitrogen. Symbiotic $N_2$ fixation in non-legumes is carried out by *Rhizobium* in association with members of the family *Leguminosae* and *Frankia*, a genus of *Actinomycetes*. A large number of leguminous species were believed to occur naturally in forests. Some legumes have been successfully introduced into problem areas as a source of N in preparation of site for afforestation (Gadgil, 1971). Symbiotic N-fixation by *actinorhizal* plants made significant contributions of N in many forest ecosystems. Presumably, this type of biological nitrogen fixation varies according to the species, organic matter content, climate, soil type, microbial activity, management practices etc. Various workers have estimated biological $N_2$ fixation by many tree species in different areas and studies carried out by Hognberg and Kvarnstorm (1982) on this aspect showed that *L. leucocephala* could fix higher amount of N i.e. 100-500 kg/ha (Table 7). Sanginga *et al.* (1995) in their review also cited $N_2$ fixation levels of 100-300 kg N/ha/yr and some times up to 500 kg N/ha/yr. Such estimates are subject to a number of variables such as soil,

**Table 7.** Estimates of symbiotic (by *Rhizobium and Frankia*) and non symbiotic $N_2$ fixation in some woody species

| Species | $N_2$-fixation (kg/ha/yr) | Reference |
|---|---|---|
| **Symbiotic $N_2$- fixation** | | |
| *Acacia mersnsii* | 200 | Dommergues, 1987 |
| *Casuarina equisetifolia* | 60-110 | Dommergues, 1987 |
| *Rethrina peoppigiana* | 60 | Escalanati, 1984 |
| *Acacia albidia* | 20 | Nair, 1984 |
| *Gliricidia sepium* | 13 | Szott *et al* 1991 |
| *Inga jinicuil* | 35-40 | Roskoski, 1982 |
| *Leucaena leucocephala* | 100-500 | Hognberg, 1982 |
| *Sesbenia rostrata* | 83-109 | People and Herridge, 1990 |
| *Alnus* spp. | 60-209 | Tarrant, 1990 |
| **Non-symbiotic $N_2$- fixation** | | |
| *Aztobacter* spp. | 20-25 | Brady, 2000 |
| *Clostridium spp.* | 5-20 | Brady, 2000 |

climate and plant management conditions. Among the 650 woody species belonging to nine families that are capable of fixing atmospheric $N_2$, 515 belong to the family *Leguminosae* (320 in *Mimosoideae*, 170 in *Paplionoideae* and 25 in *Caesalpinoideae*) (Nair *et al.*, 1998).

**Weathering of Parent Rock:** The geological weathering of parent material is thought to be one of the most important means of replenishing nutrient reserves in most forest ecosystems. Among factors, which influence the rate of input from this source is the nature of the weatherable rock, climatic conditions, topography, vegetation, microorganisms, etc? Most forest soils contain sufficient primary and secondary minerals as components of the parent material to ensure an adequate cycle of cations through normal weathering processes. The soil developed over two different parent material i.e dolerite and gneiss having similar forest cover, climate and topography showed that cations such as $Ca^{2+}$, $Na^{+}$ and $K^{+}$ except $Mg^{2+}$ were present in higher amounts in Dolerite than in gneiss (Singh and Singh, 1991).

**Fertilizers Contribution to Nutrient Cycling:** The application of commercial fertilizers is an accepted mean of increasing rates of nutrient cycling and tree growth in nutrient deficient stands. Where one or more nutrient is in limited supply, trees are unable to fix energy at a satisfactory rate, nor utilize other nutrient elements to the extent that they are needed. Nitrogen may become a limiting factor to tree growth in boreal and other forest ecosystems, because this element is largely immobilized in the material accumulated on the forest floor. A study by Cromer and Williams (1982) on biomass production and nutrient accumulation in a fertilizer experiment in *E. Globulus* (age 9.6 years) showed maximum accumulation of N and minimum for P. The addition of fertilizer might hastened the decomposition of organic matter and accelerated the nutrient cycling. Banerjee *et al.* (1998) showed that effect of various fertilizer treatments on *D. sisoo* and found that N status was higher with lower dose of N and for other nutrients with higher dose. Low N status was due to the fact that *D. sisoo* is a nitrogen-fixing tree.

**Nutrient Outputs (Losses):** Nutrient output from a forest ecosystem occurs through various ways such as leaching and surface runoff, removal of leaf litter, crop harvesting, shifting cultivation, volatilization and human interference.

N, P, Ca, and Mg, respectively. When whole *Eucalyptus hybrid* tree was harvested at the age of 10 years which is its rotation age about 341, 9, 199, 293 and 139 kg/ha of N, P, K, Ca, and Mg, were removed, respectively which is a considerable amount (Tandon *et al.*, 1996). The increase in nutrient content of standing crop with stand age has a direct bearing on the total biomass production and nutrient accumulation. As such the nutrient accumulation in various components varies considerably. The total amount of nutrients removed in harvest varied with species and also with the age. The harvesting of only utilizable biomass (148 t/ha) in *Tectona grandis* at the age of 30 years removed 247, 41, 170, 632 and 198 kg/ha N, P, Ca, and Mg, respectively (Negi *et al* 1995). Nine year old *E. globulus* plantation produced 139 t/ha of dry matter of which wood contributed 68 per cent of total biomass and retained 58, 56 and 37 per cent N, P and K of total uptake amounting to 539, 28 and 113 kg/ha, respectively (Negi *et al.*, 1984). However, a study by George and Varghese (1990b) on annual uptake, retention and return of various nutrients in a 10 year old *E. globulus* plantation reported lower values and indicated the effect of locality factors on biomass production and consequently on nutrient accumulation.

Human activities such as shifting cultivation, lopping of trees, removal of leaf litter for fuel, safety material in packing cases, animal bedding, deliberate forest fire and illegal felling have been serious causes of upsetting nutrient cycle of natural forest ecosystems. It is therefore necessary to take necessary safe guards to protect the forest stands from biotic interferences and suitable measures should be taken to maintain continued productivity of scarce forest resources.

## CONCLUSION

The information on nutrient cycling under forest ecosystems is essential for better understanding of forest and soil productivity, conservation of nutrients in the management of commercial short rotation forestry on a perpetual basis and to protect the ecosystems form degradation. Because of the conservative nature of nutrient cycling, mature forest stands make only minimal demands on soil nutrients. Although the annual uptake of nutrients by a vigorous stand of tree approached that of an agricultural crop on an area basis and a large percentage of the absorbed nutrients were returned to the forest floor through litter fall. The inputs of nutrients from atmospheric sources, biological $N_2$ fixation and weathering of parent rocks is sufficiently rapid to meet most of the nutrient demands. There were wide variations in the amount of nutrient inputs to the soil through geo-chemical and biological cycles among ecosystems. The crop harvesting and removal of litter drained a large amount of nutrients. However, in short rotation commercial forestry where major emphasis is to increase biomass production and removal besides maintaining fertility, removal of nutrients in crop harvesting can not be ruled out. Hence for the sustained productivity on sustainable basis, nutrients removed in harvest must be replenished to avoid the deleterious effects on the ecosystems. Necessary safe guards should also be taken to prevent the human interferences and also to maintain the nutrient status of the forest soils. Thus, better understanding of mineral budget and cycling of nutrient elements are crucial to maintain the productivity of forests and forest soils for the effective management of different forest ecosystems.

## REFERENCES


Adams, M.A. and Attiwill, P.M. (1991). *For. Ecol. Mgmt.*, **44**: 93-114.

Attiwil, P.M. (1966). *Pl. Soil*, **24**: 390-406.

Banerjee, S.K. *et al.* (1998). *Adv. Forestry Res. India*, **19**: 98-118.

Bhartari, S.K. (1986). *Indian For.*, **112**: 187-201.

Boyle, J.R. and Ek, A.R. (1972). *Can. J. For. Res.*, **2**: 407-412.

Brady, N.C. (2000). The Nature and Properties of Soils. Prentice Hall of India, New Delhi, pp. 332-333.

Carlisle, A. *et al.* (1967). *J. Ecol.*, **55**: 615-627.

Cole, D.W. *et al.* (1967). In: Primary Productivity and Mineral Cycling in Natural Ecosystems. (Young, H.E. ed.). Univ. Maine Press, Orono.

Cromer, R.N. and Williams, E.R. (1982). *Indian For.*, **112**: 187-201.

Dommergues, Y.R. (1987). In: Agroforestry: A Decade of Development. (Steppler, H.A. and Niar, K.P.R. ed.) pp 245-271, ICRAF, Nairobi, Kenya.

Duvigneaued, P. and Denaeyer-DeSmet (1970). In: In Analysis of Temperate Forest Ecosystems. (Reichle, D.E. ed.) Springer-Verlag, New York.

Ehwald, E. (1957). Uber den Nahrstoffkreislauf des Waledes. Deutsche Akd. Landw Wiss. Berlin. Sitz. Ber.6.1.56 p.

Escalanti, G. *et al.* (1984). *Pesquisa Agropecuaria Brasileira*, **19**: 223-230.

Farugi, C. (1972). Ph. D. Thesis, Banaras Hindu University, Varanasi, India.

Fiaz Mohsin *et al.* (1996). *Indian J. For.*, **19**: 302-310.

Gadgil, R.L. (1971). *Pl. Soil*, **34**: 357-367.

Gassel, S.P. and Cole, D.W. (1965). *Soil Sci. Soc. Am. Proc.*, **20**: 97-100.

Gassel, S.P. *et al.* (1973). *Soil Boil.*, **5**: 19-39.

George, M. (1977). Ph. D. Thesis, Meerut Univ. Meerut (UP) India.

George, M. (1978). *Indian For.*, **104**: 719-726.

George, M. (1984). *Indian For.*, **110**: 61-67.

George, M. (1986). *Myforest*, **22**: 19-26.

George, M. and Varghese, G. (1990a). *Indian For.*, **116**: 42-48.

George, M. and Varghese, G. (1990b). *Indian For.*, **116**: 962-968.

George, M. and Varghese, G. (1991). *Indian For.*, **115**: 110-116.

Giri Rao, L.G. *et al.* (2000). *Indian For.*, **126**: 772-781.

Golley, F.B. *et al.* (1975). Mineral Cycling in a Moist Forest Ecosystems, Univ. Georgia Press, Athens, 248 p.

Hognberg, P. and Kvarnstorm, M. (1982). *Pl. Soil*, **66**: 21-28.

Hosur, G.C. and Dasog, G.S. (1995). *J. Indian Soc. Soil Sci.*, **43**: 256-259.

Hosur, G.C. *et al.* (1997). *Indian J. For.*, **20**: 231-235.

Jordan, C.F. (1985). Nutrient Cycling in Tropical Forest Ecosystems. John Wiley, New York, USA.

Kaul, O.N. *et al.* (1979). *Indian For.*, **105**: 171-179.

Kaushal, R.K. *et al.* (1996). *Indian J. For.*, **19**: 258-263.

Nair, K.P.R. (1984). Introduction to Agroforestry. Kluwer Academic Publishers, Netherlands. pp. 307-322.

Nair, P.K.R. *et al.* (1998). In: Agroforestry in Sustainable Agricultural Systems. (Buck, L.E. *et al.* ed.) Lewis Publishers CRC Press, New York. pp 1-31.

Narayana, D.S. (1972). Ph. D. Thesis, Botany, Banaras Hindu University, Varanasi, India.

Negi, J.D.S. *et al.* (1984). *Indian For.*, **110**: 802-813.

Negi, J.D.S. and Sharma, D.C. (1984). *Indian For.*, **110**: 944-953.

Negi, J.D.S. *et al.* (1990). *Indian For.*, **116**: 681-686.

Negi, S.S. *et al.* (1995). *Indian For.*, **121**: 455-464.

Neumann, E.E. (1966). *Arch Forester*, **15**: 1115-1138.

Nye, P.H. (1961). Pl. Soil, **13**: 333-346.

Ovington, J.D. and Madgwick, H.A. (1959). *Pl. Soil*, **10**: 389-400.

People, M.B. and Herridge, D.F. (1990). *Advances in Agronomy*, **44**: 155-223.

Ramam, S.S. (1984). *Indian J. For.*, **7**: 93-102.

Rawat, J.K. and Tandon, V.N. (1993). *Indian For.*, 977-985.

Remezov, N.P. (1959). *Pochvovedenie*, **1**: 71-79.

Remezov, N.P. and Pogrebnyak, P.S. (1969). Forest Soil Science. USDA, Natn. Sci. Found., Washington, D.C. 261p.

Rennie, P.J. (1955). *Pl. Soil*, **7**: 49-95.

Roskoski, J.P. (1982). In: Nitrogen Cycling in Ecosystems of Latin America and the Carribbean. (Roberstson, G.P. *et al.*, ed.) Martinus Nijhoff, The Hague, The Netherlands. pp 283-292.
Roskoski, J.P. et al. (1982). In: Biological Nitirgen Fixation Technology for Tropical Agriculture. (Graham, P.H. ed.) CIAT, Cali, Colombia. pp 447-454.
Sanginga, N. *et al.* (1986). In: Biological Nitrogen Fixation in South Africa. (Sali, H. and Keya, S O. ed.) MIRCEN, Nairobi, Kenya.
Sanginga, N.K. *et al.* (1995). *Pl. Soil.* **174**: 119.
Seth, S.K. *et al.* (1963). *Indian For.*, **89**: 90-98.
Shanmughavel, P. (1993). *Myforest*, **29**: 249-252.
Sharma, B.M. (1977). Ph. D. Thesis, Banaras Hindu University, Varanasi, India.
Sharma, D.C. *et al.* (1988). *Indian For.*, **114**: 261-268.
Sharma, I.P. *et al.* (2001). *Indian J. Soil Cons.*, **28**: 91-97.
Sharma, N.K. *et al.* (2000). *Indian J. Soil Cons.*, : 295-299.
Singh, A.K. and Singh, B. (1991). *Indian J. For.*, 14: 196-201.
Singh, K.P. (1968). Proc. Symp. Recent Adsv. Tro. Ecol. (Misra, R. and Gopal. G. ed.) pp. 665.
Singh, K.P. (1969). *Trop. Ecol.*, **10**: 83-95.
Singh, R.D. and Bhatnagar, V.K. (1997). *Indian J. For.*, **20**: 147-149.
Srivastava, P.B.I. *et al.* (1972). Proc. Symp. Man-Made Forests in India. Soc. Indian For.
Sugar, G.V. (1989). *Myforest*, **25**: 43.
Switzer, G.L. and Nelson, L.E. (1972). *Soil Sci. Soc. Am. Proc.*, **36**: 143-147.
Szott, L.T. *et al.* (1991). In: Agroforestry: Principle and Practices. (Javis, P.G. ed.) Elsevier, Amsterdam, The Netherlands. pp 127-152.
Tamm, C.O. (1958). In: *Encycl. Plant Physiol.*, **4**: 233-242.
Tandon, V.N. *et al.* (1988). *Indian For.*, **114**: 184-199.
Tandon, V.N. *et al.* (1991). *Indian For.*, **117**: 596-608.
Tandon, V.N. *et al.* (1996). *Indian For.*, 122: 31-38.
Tarrant, R.F. (1990). In: Biology of Alder. Pacific Northwest Forest and Range Experiment Satation, Portland, pp. 193.
Tiwari, D.N. (1993). Poplar. Surya Publications, Dehradun, India.
Turner, J. and Lambert, N. (1983). *For. Ecol. Mgmt.*, **6**: 155-168.
Vogt, K.A. *et al.* (1986). *Adv. Ecol. Res.*, **15**: 303-377.
Weetman, G.F. and Webber, B. (1972). *Can. J. For. Res.*, **2**: 351-369.
Wells, C.G and Jorgensen, J.R. (1975). In: Forest Soils and Forest Land Management. (Bernier, B and Winget, C.H. ed.) Lavai Univ. Press Quebec.
Wells, C.G. *et al.* (1972). *Sci. Soc.*, **88**: 66-78.
Woodwell, G.M. and Whittaker, R.H. (1967). In: Symposium on Primary Productivity and Mineral Cycling in Natural Ecosystems. (Young, H.E. ed.) Univ. Maine Press, Orono. pp 151-166.