SOIL PRODUCTIVITY CHANGES UNDER SELECTED EXOTIC FOREST TREE SPECIES WITH SPECIAL REFERENCE TO BENEFICIAL MICROFLORA

By

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THESIS

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DECLARATION

I hereby declare that this thesis entitled **"Soil productivity changes under selected exotic forest tree species with special reference to beneficial microflora"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

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Introduction

INTRODUCTION

Microbial communities are important components of soil food webs that regulate the cycling of materials, energy and nutrients. The diversity of microorganisms in soil seem to be critical to the maintenance of soil health and quality, as they strongly influence the soil fertility attributes. The two major drivers of soil microbial community structure, i.e., plant type and soil type, are thought to exert their role in a complex manner. Many factors including physico-chemical properties of the soil, temperature and vegetation type generally influence the type of microflora present in the soil. Microbial growth in soil is primarily carbon limited and therefore, the presence of organic matter significantly influence on microbial population.

Soil bacteria and fungi play a pivotal role in various biogeochemical cycles and are responsible for the cycling of organic compounds. Certain microorganisms fix atmospheric nitrogen in the root nodule of trees by establishing a symbiotic relationship. Nitrogen mineralization, the key process that ensure plant available nitrogen and their by the soil fertility, is strongly influence by soil microbial activity, rhizobia, nitrobacter, nitrosomonas. When the mineralization rate is slowed down or inhibited, N_2 fixation will continue. N_2-fixing trees improve the N status of soils (Dommergues 1995). Microorganisms enhance the P availability to plants by mineralizing organic P in soil and by solubilizing precipitated phosphates. Phosphorus solubilizing bacteria play an important role in phosphorus nutrition by enhancing its availability to plants through release from inorganic and organic soil P pools by solubilisation and mineralization. Microorganisms play a key role in the natural K cycle also. Some species of *Rhizobacteria* are capable of mobilizing potassium in available form in soils.

Wooded ecosystems contribute substantially to enrich their soil microbial population. Apart from the enumerable ecosystem services they offer, they harbour enumerable beneficial microbes that influence the soil health. For instance N-fixing trees help to enrich the soil available N pool considerably. Large number of indigenous and exotic tree species have been identified to enrich the soil microbial

activity. The relevance of exotic tree species owing to their fast growth and multiple uses are well established. In this context, the multiple uses of *Acacia auriculiformis* has recently generated a greater interest due to its teak–like grain, used in joinery and furniture making as cheap substitute for teak. Yet another factor that endear the species for polyculture integration is its N-fixing ability and thereby improving soil fertility. *Acacia mangium* is another important species used in plantation forestry programs due to its fast growth and wider utility. *Swietenia macrophylla* is a promising structured timber species that was introduced to Indian sub-continents long back. The biomass and nutrient accumulation in exotics like *Swietenia macrophylla* has greater acclimation capacity to enhance the photosynthetic plasticity under full sun. *Casuarina equisetifolia* is yet another fast growing multipurpose actinorhizal tree capable of fixing atmospheric nitrogen by virtue of a symbiotic relationship between the plant roots and *Frankia.*

Soil biological health is an important indicator of soil quality. Hence it is necessary to evaluate biological indices in afforested soils to understand the soil quality improvement by the afforestation. The influence of tree species on soil properties has been of interest for decades initially with respect to site degradation and amelioration through planting different tree species and more recently to distinguish among the factors that control nutrient availability.

In this context, understanding the diversity and dynamics of microflora population will throw light into various aspects of possible soil productivity changes over time due to long occupancy of exotic tree species. Moreover, the possible effect of different tree species on the soil microflora will give valuable information to the overall micro site enrichment potential of these exotic trees. However, the information on the potential for soil productivity improvement in relation to the microbial diversity are scarce from these exotic species. Hence, the present study was undertaken with the specific objective to study the variations in soil productivity due to long term occupancy of selected exotic tree species with special reference to the quantity and quality of the soil microflora.

Review of literature

REVIEW OF LITERATURE

The literature pertaining to the study entitled "soil productivity changes under selected exotic forest tree species with special reference to beneficial microflora" have been consulted thoroughly and presented under the following titles.

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2.1 "Soil microflora" – ecological and productivity implications

Soil ecosystem services need to monitor soil quality in terms of soil functions. This in turn requires functional indicators. Microbial functional diversity offers an indirect and effective means to characterize soil quality and changes happening to it (Sassi *et al.*, 2012).

The abundance and activities of soil microorganisms are influenced by various edaphic (e.g. soil type, nutrient status, pH, moisture) as well as plant factors (e.g. species, age). The soil pH can influence the relative numbers of fungi and bacteria (Rousk *et al.*, 2009). Microbial growth in soil is carbon limited and, therefore, the presence of organic matter has the greatest influence on microbial

populations (Wardle, 1992). Soil microbial communities are extremely diverse in their composition and play an important role in nutrient cycling functions such as organic matter decomposition and mineralization, nutrient mobilization and carbon sequestration (Strickland and Rousk, 2010).

In most of the soil microbial communities, fungi play a crucial role in organic matter decomposition and nutrient cycling in soil by decomposing complex substrates. (Buyer *et al.*, 2001; Oren and Steinberger, 2008). Soil microorganisms, such as bacteria and fungi, play central roles in soil fertility and promoting plant health. (Jennifer *et al.*, 2004). Changes in the relative numbers of fungi and bacteria may have significant effects on the soil ecosystem, such as carbon sequestration in agroecosystems (Strickland and Rousk, 2010).

Soil bacteria and fungi play a pivotal roles in various biogeochemical cycles also (Wall and Virginia, 1999). They are responsible for the cycling of organic compounds. Soil microorganisms also influence above-ground ecosystems by contributing to plant nutrition (George *et al.*, 1995; Timonen *et al.*, 1996), plant health (Filion *et al.*, 1999; Smith and Goodman, 1999), soil structure (Wright and Upadhyaya, 1998) and soil fertility (Yao *et al.*, 2000; O'Donnell *et al.*, 2001). Bacterial and fungal diversity increases soil quality by affecting soil agglomeration and increasing soil fertility. They are both important in nutrient cycling and in enhancing plant health through direct or indirect means. In addition, a healthy rhizosphere population can help plants deal with biotic and abiotic stresses such as pathogens, drought and soil contamination (Jennifer *et al.*, 2004).

There is increasing evidence that distinct microbial communities inhabit soils of different forest types. Microbial community composition has been shown to differ where microbial biomass was similar among forest types within a climatic region (Myers *et al.*, 2001; Leckie *et al.*, 2004). It has long been thought that bacteria rather than fungi mediate processes in soils of higher fertility (Wardle, 2002).

The type of organic compounds released by plants has been postulated to be a key factor influencing the diversity of microorganisms in the rhizosphere of different plant species (Bowen and Rovira, 1991). *Acacia auriculiformis* plantation establishment might cause soil acidification in strongly weathered soils in the wet tropics because the base cations in the soil are translocated rapidly to plant biomass during *Acacia* growth. Yamashita, *et al.* (2008) examined whether soils under an *acacia* plantation were acidified, as well as the factors causing soil acidification. *Acacia auriculiformis* act as a major source of Organic Matter (OM), hence increasing organic carbon and nitrogen content and decreasing the C/N ratio. The increased OM content suggests that humification processes are the main cause of the significant decrease in pH. Total exchangeable cations initially increased slowly but doubled (topsoil 0–25 cm) after 10 years (Kasongo *et al.*, 2009). *Acacia mangium* has high nitrogen-fixing ability by symbioses with nodule forming bacteria and produces leaves that are more nitrogen-rich than native tropical leguminous trees (Tilki and Fisher, 1998). *Casuarina equisetifolia* is a fast growing multipurpose actinorhizal tree capable of fixing atmospheric nitrogen by virtue of a symbiotic relationship between the plant roots and *Frankia* (Rajendran and Devraj, 2004).

The influence of tree species on soil properties has been of interest for decades (Binkley 1994; Hobbie, 1992), initially with respect to site degradation and amelioration through planting different tree species (Dimbleby, 1952), and more recently to distinguish among the factors that control nutrient availability (Binkley and Giardina, 1998). Several investigations have demonstrated distinct differences among tree species in characteristics of the forest floor and soil, including humus form, nutrient content, base status, and rates of mineralisation of C, N and P, nitrification and denitrification (Binkley and Valentine, 1991; Gower and Son 1992; Fyles and Cote, 1994; Priha and Smolander, 1999; Thomas and Prescott, 2000). The effects are attributed to species differences in litter quality, root exudates, herbivory, and nutrient uptake (Hobbie, 1992). Tree species influences on soil processes are likely to be mediated through their effects on soil microorganisms, and soil microbial biomass and activity are influenced by tree species (Turner *et al.*,

1993; Bauhus *et al.*, 1998; Priha *et al.*, 2001). Data for 1-year, 5-year, 10-year and 20-year old secondary successional forests showed that the age of the fallows had little effect on the soil microbial populations (Deka and Mishra, 1984).

Microbial communities in litter and soil are the functional link through which the tree species occupying a site may alter rates of soil processes fundamental to nutrient cycling and carbon flux. There is evidence that distinct microbial communities develop on decomposing leaf litters of different tree species (Prescott and Grayston, 2013). Distinct microbial communities have been reported in forest floors under different tree species; differences are most pronounced in the F layer. Distinctions in microbial communities in mineral soil under different tree species have been determined in several common garden experiments. The main factors associated with differences in microbial communities in litter, forest floors and soil are the pH and base cation content of the litter and whether the trees are broadleaf or coniferous.

As the principal drivers of soil nutrient cycling processes, soil micro-organisms are the critical link between shifts in the composition of the dominant vegetation and fundamental shifts in ecosystem functioning. Characteristics (or functional traits) of the vegetation on a site could influence the composition and functioning of the soil microbial community through alteration of microclimate (through shading, frost protection, throughfall and uptake/transpiration of soil water), production of litter (both aboveground and roots), interactions with herbivores (both above and belowground), production of root exudates, and interactions with root symbiotic organisms such as mycorrhizal fungi. Recent studies of the biogeography of soil microorganisms have demonstrated strong relationships between the soil microbial community and factors such as pH, texture, organic matter content and C:N ratio of the soil (Fierer and Jackson, 2006; Fierer *et al.*, 2009; Rousk *et al.*, 2010; Brockett *et al.*, 2012).

Soil microorganisms are important drivers of soil processes, and they play a key role in the decomposition of recent plant material (Bardgett *et al.*, 2005). Because they rely on organic carbon (OC) for growth, they are affected by any

change in C input or C loss in soils (Zak *et al.*, 2003). In forest ecosystems, C input is derived primarily from the decomposition of organic matter, such as leaf and root litter, plant exudates, woody plant debris and animal remains. The contribution of these components varies substantially depending on the tree species present (Gleixner *et al.*, 2005), and root exudates, in particular, vary in quality and quantity among tree species (Grayston *et al.*, 1997; Calvaruso *et al.*, 2011). Additionally, litter quality measures, such as the amount of nutrients and tissue structure, as well as the relative proportions of C and N compounds of different decomposability, such as protein and lignin, vary between broadleaf tree species (Jacob *et al.*, 2009; Gessner *et al.*, 2010).

Little is known about the link between the aboveground tree species diversity and the soil microbial diversity in mixed-species forests (Gleixner *et al.*, 2005). In general, the distribution and abundance of the soil microbial communities is a function of abiotic (physical and chemical) conditions and biotic factors (interactions among species/food supply) (Scherer-Lorenzen *et al.*, 2005). In forest soils, the vertical and horizontal distribution of soil microorganisms can differ extremely but microbes are generally most abundant in the upper surface soil layer E in particular, within the first few centimeters of the topsoil (Fierer *et al.*, 2003; Steenwerth *et al.*, 2008). The large food supply through decomposition of plant litter and plant residues supports a high microbial abundance at the topsoil's surface. Evidently, the decomposer community is affected by plant litter characteristics (Wardle *et al.*, 2006) such as the provision of microhabitats (Ettema, 1998; Hansen, 2000) and the chemical composition of the foliage (Ricklefs and Matthew, 1982; Hättenschwiler *et al.*, 2008).

From the voluminous literature on rhizosphere, it is known that the microbial community is not only influenced by root exudates and nutrient uptake but also by the plant species (Grayston *et al.*, 1998; Smalla *et al.*, 2001; Wieland *et al.*, 2001), phenology (Dunfield and Germida, 2003; van Elsas *et al.*, 2008), the background soil characteristics (Marschner *et al.*, 2001; Buckley and Schmidt, 2003; Girvan *et al.*, 2003; Johnson *et al.*, 2003), and the developmental stage of the

plants (DiCello *et al.*, 1997). Notably, not only does the plant influence its own rhizosphere microbial community, but also the microorganisms play important roles in the growth of their plant host and its ecological fitness. For example, bacterial communities in the rhizosphere may affect the plant by altering the supply of inorganic nutrients (Uroz *et al.*, 2007), nitrogen fixation (Cocking, 2003), producing plant growth hormones (Nieto and Frankenberger, 1989), and repressing plant pathogens (Hamdan *et al.*, 1991; Berg *et al.*, 2005). In the tropics vesicular-arbuscular mycorrhizae seem to play a major role in the growth of trees and crop plants (Diem *et al.*, 1981).

Rahman *et al.* (2000) examined the host ranges of nodulating *Rhizobia* (*Bradyrhizobium sp.* and *Rhizobium sp.*) strains on *Acacia* species, by inoculating seedlings hydroponically cultured in test tubes with *Rhizobial* strains. Each *Rhizobial* strain showed a different spectrum of host range over four provenances of *A. mangium* and four other species (*A. ampliceps, A. auriculiformis, A. nilotica* and *A. oswaldii*). They observed that the host range of some *Rhizobia*l bacteria is strictly defined even to provenance level.

2.2 Nutrient dynamics in the forest ecosystem

Nutrient cycling in forest ecosystems is driven primarily by transfer processes through which nutrients and carbon move into (inputs) and out of (outputs) the various ecosystem components or compartments. Therefore an ecosystem model provides a useful conceptual background for understanding the flow of elements in forests and the effects of nutrient flows on productivity. Such a model visualizes a forest ecosystem as a complex of interacting compartments, for example, the various plant components – foliage and twigs, wood, bark, coarse roots, fine roots; the litter and humus layers of the forest floor; soil organic matter; the soil solution; and the sorptive surfaces of soil minerals. Various processes link the different compartments by transferring nutrients between them. Nutrient fluxes of interest include inputs (precipitation and interception, fertilizer additions, atmospheric fixation), outputs (leaching, harvesting, fire, denitrification), nutrient

release and retention in soil (mineralization, immobilization, cation exchange and anion retention, mineral dissolution and retention), plant uptake, and litterfall. Nutrient fluxes are also affected by factors such as changes in microclimatic conditions (temperature and moisture) and the rate of litter decomposition (Khanna, 1998). The effects of land use change on soil carbon stocks are of concern in the context of international policy agendas on greenhouse gas emissions mitigation. Guo and Gifford (2002) reviews the literature for the influence of land use changes on soil C stocks and reported the results of a meta-analysis of these data from 74 publications. The meta analysis indicates that soil C stocks decline after land use changes from pasture to plantation (−10%), native forest to plantation (−13%), native forest to crop (−42%), and pasture to crop (−59%). Soil C stocks increase after land use changes from native forest to pasture (+ 8%), crop to pasture (+ 19%), crop to plantation (+ 18%), and crop to secondary forest (+ 53%). Wherever one of the land use changes decreased soil C, the reverse process usually increased soil carbon and *vice versa.*

Chavan *et al.* (1995) determined the effect of forest tree species on properties of lateritic soil. They observed that the forest tree species (*Tectona grandis, Terminalia tomentosa, Pongamia pinnata, Gmelina arborea, Eucalyptus, Acacia auriculiformis,* and *Casuarina equisetifolia*) in ten-year-old plantations at Wakawali [Maharashtra], did not change the soil physical properties under the canopy, but there were marked effects on the soil chemical properties compared with natural forest soils. Organic carbon, available nitrogen, phosphorus and potassium increased significantly in the surface layer. In general, the soils under the forest cover showed higher nutrient status.

Available nutrient status of soil in 4 different plantations: *Acacia auriculiformis* (10 years), *A. mangium* (8 years), *Casuarina equisetifolia* (10 years), and *Tectona grandis* (11 years), situated in Karnataka has been examined by Rathod and Devar (2004).They found that among the 4 species, available nitrogen content in soils under *A. auriculiformis* (10 years) and *C. equisetifolia* was higher compared to soil under *T. grandis* and *A. mangium.* The depletion of nitrogen was observed

in both the layers of soil under *A. auriculiformis* and *T. grandis*. They also found that available phosphorus content decreased in soils under the plantations compared to control sites. Available potassium content increased in surface soils under *C. equisetifolia* which may be due to biocycling from deeper layers and addition to the surface. However, there was an increase of potassium content in subsurface soil under layers of *T.grandis* and *A. auriculiformis*as compared to the control sites.

2.3 Microorganism associated with forest tree species

Fungi are a major component of the biodiversity in forest ecosystems and play crucial roles in decomposition processes, facilitating nutrient recycling and humus formation (Cooke and Rayner 1984). Fungi can serve as indicators of environmental changes resulting from natural or anthropogenic causes, such as global warming and elevated carbon dioxide levels (Frankland *et al.* 1995; Treseder 2005). Understanding the distribution of fungi associated with leaf litter decompositionin relation to climactic patterns is crucial, as it will provide useful insights into the future changes of biodiversity and functioning of forest ecosystems in response to global warming.

Generally, the abundance of fungi and protozoa decline with increasing soil depth (Ekelund *et al.*, 2001; Taylor *et al.*, 2002; Fierer *et al.*, 2003), and those of actinomycetes increase (Federle *et al.*, 1986; Fritze *et al.*, 2000). Natural infection by Claveria sp. (fungus) was observed in seedlings, saplings and 2-3 yr old plantations of *Acacia mangium* in the Philippines (Anino 1992).

Bakarr and Janos (1996) found that VAM fungi was present in association with *A. auriculiformis, A. mangium, A. leptocarpa.* Dhar and Mridha (2006) also observed arbuscular colonization in three plants. The highest arbuscular colonization was in *A. mangium* (72%) and the lowest was in *S. macrophylla* (17%). The highest AM fungal spore population was in *A. auriculiformis* (714) and the lowest was in *D. sissoo* (102).

Jamaluddin and Chandra (1997) reported that barren bauxite mine overburden soil was deficient in VAM fungi but the forest plantations (*Acacia*

auriculiformis) enhanced the VAM population. VAM colonization and spore density (and tree growth) varied with species and with age for the same species. They found that population of VAM fungi was more in the plantation in the degraded forest area than in plantations on the overburden.

Kumar *et al.* (1999) observed that ectomycorrhizal fungi like *Pisolithus tinctorius, Scleroderma sp.* and *Thelephora ramarioides* were present in association with different tree species like *A. auriculiformis, A. holosericea, A. mangium, E. camaldulensis* and *E. tereticornis.*

Among soil organisms, bacteria and fungi actively participate in organic matter decomposition liberating chemical nutrients and furthering plant growth. Microorganism numbers vary in and between different soil types and conditions, with bacteria being the most prominent. Bacterial counts in different soils ranged from 4×10^6 to 2×10^9 g^{-1} dry soil (Whitman *et al.*, 1998). Growth of microbial populations and their action on soils are dependent on the interaction between plant species and soil (Grayston *et al.*, 1998). The composition of the bacterial populations seems to be profoundly influenced by the plant (Dilly *et al.*, 2000).

Fast growing rhizobium spp. and slow growing bradyrhizobium spp. of *Acacia mangium* were isolated from different agro-climatic regions of Kerala by Dhaneshkumar *et al.* (2001). They revealed that five Rhizobium isolates from *A. mangium* plantations of the State of Kerala and a commercial culture for mangium performed better while the isolates and commercial culture of *A. auriculiformis* showed poor nodulation on mangium.

Oyun *et al.* (2006) reported that acacia litter have a single phase of decomposition. Bacteria population increased linearly with nutrient content, while fungal population varied more with litter type than with different phases of decomposition. They also found that the bacteria population isolated from Acacia-Gliricidia mixture was highest, followed by *Gliricidia sepium* alone while it is lowest in *Acacia auriculiformis*, however more fungal population were isolated

from *Acacia auriculiformis* litter than *Gliricidia sepium* litter in all the phases of decomposition.

The effects of the decomposition of the leaf litter of 8 tree species on soil microorganisms were determined by CunYu (2006). The results revealed that the number of fungi in the treatment with decomposing leaves was more than those in the control treatment, indicating that fungi might be an important decomposer of leaf litter. During the initial period of decomposition, the number of bacteria was more than that of fungi and actinomycetes. But in the middle and later period of decomposition, bacterial count decreased, while the population of fungi and actinomycetes increased. It is also found that the soil affected by the decomposition of the leaf litter of *Albizia falcataria*, *Acacia auriculiformis*, *Acacia mangium* and *Schima superba* had higher microbial biomass, more microbial diversity species and higher population of bacteria. On the other hand, the soil influenced by the decomposition of the leaf litter of *Pinus elliottii* and *Pinus massoniana* showed an opposite trend.

In contrast to numerous elaborations concerning actinomycetes of cultivated soils, little is known about their occurrence in forest soils. The main factor limiting actinomycete development in forest soils is believed to be the low pH, as the development of most actinomycetes is facilitated by a neutral or alkaline soil reaction. However, these microorganisms have also been isolated from strongly acidic soils also (Golińska and Dahm 2011).

2.3.1 Biological nitrogen fixation

Trees can increase nutrient inputs and reduce nutrient losses through a variety of processes. Biological nitrogen fixation is prominent among these as it is the only truly renewable source of nutrients in agroforestry or agriculture as a whole. Symbiotic nitrogen N_2 fixation occurs with a wide variety of trees. The endosymbionts in legume trees and in the non-legume genus *Parasponia* (Ulmaceae) are *Rhizobia* (Sprent and Parsons, 2000). Many of the trees used in agroforestry are legumes as the ability to fix nitrogen allows them to grow rapidly

in nitrogen depleted soils. Thus one of the principal roles of nitrogen-fixing trees is to improve soil fertility, athough many legume trees have multiple uses for fodder, fuelwood, fruits and timber. Legume trees are thus found in almost all types of agroforestry systems: as shade trees in perennial crops, in improved fallows, in hedgerow intercropping systems, as erosion barriers, live fences, isolated trees in parklands and fodder trees.

All environmental limitations that adversely affect plant growth and vigour also decrease amounts of nitrogen fixation in legumes, although the symbiosis is sometimes more sensitive to such constraints than other aspects of plant growth (Giller, 2001). Nitrogen fixation is sensitive to nutrient deficiencies, in particular phosphorus deficiency, which may restrict nodule formation if acute. Molybdenum deficiency influences nitrogen fixation directly as molybdenum is a component of the nitrogenase enzyme. Nitrogen fixation is thought to be more sensitive to drought stress than other processes, such as photosynthesis, although the evidence is somewhat equivocal (Sprent, 1984).

Slow-growing *Rhizobia* are all members of a single genus, *Bradyrhizobium*, whereas the fast-growing *Rhizobia* have been split into several genera. Five genera of fast-growing *Rhizobia* are currently recognized: *Rhizobium, Azorhizobium, Sinorhizobium, Mesorhizobium* and *Allorhizobium*, although this field is changing rapidly. Some trees are reported to nodulate only with slow-growing *Rhizobia* (Dreyfus and Dommergues, 1981) but the vast majority examined nodulate with fast-growing *rhizobia.* Recent studies of *rhizobia* that nodulate legume trees have resulted in the description of the new species *Sinorhizobium terangae* and *Sinorhizobium saheli* from nodules of Sesbania and *Acacia spp.* in Senegal (Lajudie *et al.*, 1994) and *Mesorhizobium plurifarium* (Lajudie *et al.*, 1998), *Sinorhizobium arboris* and *Sinorhizobium kostiense* (Nick *et al.*, 1999) from nodules of *Prosopis* and *Acacia* spp. in Sudan and Kenya. The success of many of the fast-growing legume trees in agroforestry has undoubtedly been due to their ability to nodulate and fix nitrogen in soils across the tropics.

Nitrogen-fixing symbioses are also formed between non-legume trees and actinomycetes (*Frankia spp.*), which are termed actinorhizal symbioses (Giller, 2001). The most important of these are the *Casuarina spp.* from Australasia, which are used for soil stabilization, as windbreaks and for poles and fuelwood throughout the tropics. It has been estimated that *Frankia* fixes atmospheric nitrogen up to 362 kg N/ha/year, which is an essential nutrient for all plant metabolic activities and growth (Shantharam and Mattoo 1997). Reddell *et al.* (1988) also reported that the increase in growth and biomass of casuarinas due to inoculation of *Frankia* might be strongly correlated with improved accumulation of nitrogen due to *Frankia.*

Three main approaches are appropriate to increase N2 fixation: clonal selection of trees combined with vegetative propagation, inoculation with effective rhizobium or *Frankia* strains, and proper fertilization (especially P) (Dommergues 1995).

The annual N2-fixing potential (i.e. the amount of fixed N2 in a constraint-free environment) can be higher than 30-50 g N2 fixed per tree in the most active species, be they leguminous trees or actinorhizal trees such as *Casuarina equisetifolia* (Dommergues 1995). Gauthier *et al.* (1985) concluded that *Casuarina equisetifolia* can fix about 40-60 kg N2 per hectare per year at normal densities of 10 000 trees ha-1.

Nodule efficiency as expressed by the ratio of N2 fixed to nodule dry weight appeared to be higher in *A. auriculiformis* (0.44–0.81) than in *A. mangium* (0.23–0.55) (Galiana *et al.*, 1990). Galiana, (1991) found that *Bradyrhizobium* strains from Australian *Acacia mangium* were more effective in nitrogen fixation than strains from other origins [Hawaii (USA) and Senegal] or other tree species(*Albizia lebbeck, Leucaena leucocephala* and *Prosopis juliflora*).

On a seasonal average basis, maximum nodule biomass and nitrogen fixation activity was observed during the summer season followed by the rainy season and winter season (Chaukiyal *et al.*, 1999). Wahab (1980) found that active nitrogen fixation in *Casuarina equisetifolia* occurred throughout all seasons of the

year, except during the late summer months. Fixation was higher at night than during the day or afternoon.

Ganry and Dommergues (1995) prepared a list of high nitrogen-fixing tree species such as *Leucaena leucocephala, Calliandra spp., Casuarina spp., Acacia mangium, A. mearnsii, A. seyal, Gliricidia sepium, Sesbania spp.*, average nitrogen-fixing tree species such as *Prosopis juliflora, A. saligna* and low nitrogen-fixing tree species such as *A. raddiana, A. senegal, A. cyclops, Faidherbia albida.* Turk and Keyser (1992) reported that *Acacia mangium* is specific for nodulation and effective in N2 fixing when inoculated with *Rhizobia* and *Bradyrhizobiun.*

Singh *et al.* (1994) reported that nitrogen enrichment of the soil was best and similar in *A.* nilotica and *A. auriculiformis* (which also had a higher nitrogen status in their roots than their stems), and least in *A. catechu.* Hu and Chang (1983) reported that *Rhizobium sp.* isolated from nodules of *A. auriculiformis* successfully formed nodules of similar morphology to those occurring naturally, on host seedlings growing in yeast extract mannitol agar medium in sterilized test tubes. The number of nodules in *Acacia auriculiformis* and *A. mangium* at two different sites ranged between 3 and 30 per gram rhizosphere soil (Selvi *et al.*, 2008). *Acacia mangium, Leucaena leucocephala* can fix 200 to 300 kg N/ha annually, whereas others (e.g. *Acacia* albida, *A. senegal*) may fix less than 20 kg N/ha annually (Bowen *et al.*, 1990). Galiana *et al.* (1998) observed that nitrogen derived from atmospheric N_2 fixed symbiotically by *A. mangium* was 50% in the whole trial and up to 90% in plots with less fertile soils when the trees were inoculated with an efficient strain (*Bradyrhizobium*). Sanginga *et al.* (1995) reported that some tree species such as *Leucaena leucocephala, Gliricidia sepium* and *Acacia mangium* can derive between 100 and 300 kg N ha^{-1} yr^{-1} from atmospheric N_2, while species such as *Faidherbia albida* and *Acacia senegal* might fix less than 20 kg N ha^{-1} yr^{-1}.

The actinorhizal plants that exhibit the highest N2-fixing potential belong to two genera: *Alnus* and *Casuarina.* N_2-fixing potential of 2-year old *Casuarina equisetifolia* is 116 kg N2/ha per year, which is fairly high. Actinorhizal plants are ideal for many systems of land use like production forestry, agroforestry, protective

forestry, reclamation forestry, urban forestry and amenity plantations (Dommergues, 1996).

Certain microorganisms fix atmospheric nitrogen in the root nodule of trees by establishing a symbiotic relationship. Rhizobium usually infects legume trees for nodulation while *Frankia* is an actinomycete, which is known for actinorhizal symbiosis with nonlegumes. However, Azospirillium is an associative symbiotic nitrogen-fixing organism. *Vesicular Arbuscular Mycorrhizal* (VAM) fungi help plants absorb phosphorous (Shah *et al.*, 2006).

A fairly high N-fixing potential has been recorded for *Acacia mangium* (Gueye and Ndoye *et al.*, 1998). Inagaki and Ishizuka (2011) observed that *A. mangium* plantation can accumulate large quantities of N and returned to the forest floor, while its P resorption capacity was efficient. Such large N cycling and restricted P cycling in wide areas of monoculture *A. mangium* plantations may alter N and P cycling and their balance in the organic layer and soil on a stand level.

2.3.2 Phosphate solubilizing microbes

Phosphorus (P) is one of the major essential macronutrients for biological growth and development (Ehrlich, 1990) and unlike the case for nitrogen, there is no large atmospheric source that can be made biologically available (Ezawa *et al.*, 2002). Soil phosphorus (P) cycling and availability is controlled by a combination of biological processes (mineralization-immobilization) and chemical processes (adsorption-desorption and dissolution-precipitation) (Frossard *et al.*, 2000). Microbial inoculants are in use for improving soil fertility and for increasing growth of trees.

Microorganisms enhance the P availability to plants by mineralizing organic P in soil and by solubilizing precipitated phosphates (Chen *et al.*, 2006; Kang *et al.*, 2002; Pradhan and Sukla, 2005). It is present at levels of 400–1200 $mg \cdot kg^{-1}$ of soil. Its cycle in the biosphere can be described as 'open' or 'sedimentary', because there is no interchange with the atmosphere (Begon *et al.*, 1990). Microorganisms play a central role in the natural phosphorus cycle. This cycle occurs by means of the

cyclic oxidation and reduction of phosphorus compounds, where electron transfer reactions between oxidation stages range from phosphine (-3) to phosphate (+5). The genetic and biochemical mechanisms of these transformations are not yet completely understood (Ohtake *et al.*, 1996).

Evidence of naturally occurring rhizospheric Phosphorus Solubilizing Microorganism (PSM) dates back to 1903 (Khan *et al.*, 2007). Bacteria are more effective in phosphorus solubilization than fungi (Alam *et al.*, 2002). Among the whole microbial population in soil, PSB constitute 1 to 50 %, while Phosphorus Solubilizing Fungi (PSF) are only 0.1 to 0.5 % in P solubilization potential (Chen *et al.*, 2006).

Several reports have examined the ability of different bacterial species to solubilize insoluble inorganic phosphate compounds, such as tricalcium phosphate, dicalcium phosphate, hydroxyapatite, and rock phosphate (Goldstein, 1986). Among the bacterial genera with this capacity are *Pseudomonas, Bacillus, Rhizobium, Burkholderia, Achromobacter, Agrobacterium, Micrococcus, Aereobacter, Flavobacterium* and *Erwinia.* Among the soil bacterial communities, ectorhizospheric strains from *Pseudomonas* and *Bacilli,* and endosymbiotic *Rhizobia* have been described as effective phosphate solubilizers (Igual *et al.*, 2001). Strains from bacterial genera *Pseudomonas, Bacillus, Rhizobium* and *Enterobacter* along with *Penicillium* and *Aspergillus* fungi are the most powerful P solubilizers (Whitelaw, 2000). *Bacillus megaterium, B. circulans, B. subtilis, B. polymyxa, B. sircalmous, Pseudomonas striata,* and *Enterobacter* could be referred as the most important strains (Subbarao, 1988; Kucey *et al.*, 1989). A nematofungus *Arthrobotrys oligospora* also has the ability to solubilize the phosphate rocks (Duponnois *et al.*, 2006).

There are considerable populations of phosphate-solubilizing bacteria in soil and in plant rhizospheres (Sperberg, 1958; Katznelson *et al.*, 1962; Raghu and MacRae, 1966; Alexander, 1977). These include both aerobic and anaerobic strains, with a prevalence of aerobic strains in submerged soils (Raghu and MacRae, 1966). A considerably higher concentration of phosphate solubilizing bacteria is

commonly found in the rhizosphere in comparison with non rhizosphere soil (Katznelson *et al.*, 1962; Raghu and MacRae, 1966).

Principal mechanism in soil for mineral phosphate solubilization is lowering of soil pH by microbial production of organic acids and mineralization of organic P by acid phosphatases. Use of phosphorus solubilizing bacteria as inoculants increases P uptake (Khan *et al.*, 2009). Strains from the genera Pseudomonas, Bacillus and Rhizobium are among the most powerful phosphate solubilizers (Rodriguez and Fraga 1999).

Seasonal changes in soil phosphorus and associated microbial properties under adjacent grassland and forest in New Zealand examined by Chen *et al.* (2003). They observed that the seasonal changes in environment conditions (rainfall, soil moisture, and temperature) influenced microbial process involved in P cycling. Microbial biomass plays a pivotal role in P cycling. Annual release of P through microbial biomass was higher in the forest soil (16.1 kg ha^{-1}) than in the grassland soil (13.9 kg ha^{-1}). The turnover rate of biomass P was also higher in the forest soil (1.28 per year) than in the grassland soil (0.80 per year). In addition, abundant C and P (particularly labile forms) and high microbial and enzyme activities found in the forest floor highlight the importance of the forest floor in P cycling.

The use of phosphate solubilizing bacteria as inoculants simultaneously increases P uptake by the plant and crop yield. Phosphorus solubilizing bacteria play role in phosphorus nutrition by enhancing its availability to plants through release from inorganic and organic soil P pools by solubilization and mineralization (Khan *et al.*, 2009).

Phosphorus solubilizing bacteria mainly Bacillus, Pseudomonas and Enterobacter are very effective for increasing the plant available P in soil as well as the growth and yield of crops. So, exploitation of phosphate solubilizing bacteria through biofertilization has enormous potential for making use of ever increasing fixed P in the soil, and natural reserves of phosphate rocks (Khan *et al.*, 2009).

2.3.3 Potassium solubilizing microbes

Potassium is one of the essential macronutrient and the most abundantly absorbed cation in higher plants. Potassium plays an important role in the growth and development of plants. It activates enzymes, maintains cell turgor, enhances photosynthesis, reduces respiration, helps in transport of sugars and starches, helps in nitrogen uptake and is essential for protein synthesis. Potassium is the fourth most abundant nutrient constituting about 2.5 per cent of the lithosphere. However, actual soil concentrations of this nutrient vary widely ranging from 0.04- 3.00 per cent (Sparks and Huang, 1985).

Microorganisms play a key role in the natural K cycle. Some species of rhizobacteria are capable of mobilizing potassium in accessible form in soils. There are considerable population of K solubilizing bacteria in soil and rhizosphere (Sperberg, 1958). Silicate bacteria were found to dissolve potassium, silicon and aluminium from insoluble minerals (Aleksandrov *et al.*, 1967). It has been reported that most of potassium in soil exists in the form of silicate minerals. The potassium is made available to plants when the minerals are slowly weathered or solubilized (Bertsch *et al.*, 1985). Microbial inoculants that are able to dissolve potassium from mineral and rocks, have influence on plant growth and have both economic and environmental advantage. The first evidence of microbial involvement in soluiblization of rock potassium (Muntz, 1890). Silicate bacteria were found to resolve potassium, silicon and aluminum from insoluble minerals (Alexander, 1977). Certain bacteria are capable of decomposing alumino silicate minerals and releasing a portion of the potassium contained therein (Biswas and Basak, 2009).

2.4. Microbial population and the tree species

The population of soil organisms (both density and composition) and how well that population thrives is dependent on many soil factors, including moisture, aeration, temperature, organic matter, acidity and nutrient supply (Prichett 1979).

Root soil of the analyzed trees contained more microorganisms than soil outside the range of the roots (Golińska and Dahm 2011). The number of microorganisms in the soil and their diversity depend on many factors, both biotic and abiotic ones (Schlegel, 2000; Saadoun and Gharaibeh 2003). Among biotic factors plants are of great importance. Their root system can liberate various chemical compounds into soil.

Effect of afforestation and deforestation on forest floor microbial activities has been examined by Bhat, (1990). Differences in the microbial population (bacteria and fungi) and soil respiration (evolution of CO_2) were reported in soil samples taken at 0-10 and 10-20 cm depth from a newly established forest [species not stated] and from bare clearcut soil (in a deforested area) in the district of Kupwara, Kashmir. They observed that all the parameters measured were higher in the afforested area, except for the fungal count in the subsoil, which was slightly lower. They also observed that the largest differences were in the topsoil, where bacterial counts were nearly twice as high, and fungal counts and CO_2 evolution nearly 4× as high in the afforested area as in the deforested area.

Microorganisms, soil respiration, and available N, Ca, Mg, Na, K, and P contents were determined in five different forest soils (Cambisols) collected in spring, summer, autumn, and winter from a humid temperate zone of Galicia, Spain by Diaz-Ravina *et al.* (1993). They observed that microorganisms and soil respiration were positively correlated and showed a clear seasonal trend. The soils exhibited high microbial population values in spring and autumn and low values in summer and winter; total respiration values were largely higher in autumn than in the other seasons. They also observed that the seasonal variations in available Ca, Na, and K contents were much more marked than those found for available N, Mg, and P. Available N and K and the microbial population showed similar trends whereas available Ca, Mg, Na, and P did not exhibit a distinguishable and uniform seasonal pattern. The quantities of available nutrients in soils followed the order Ca > K = Na > Mg > P > N. Soils developed over basic rocks showed higher values of both microbial density and microbial activity developed over acid rocks. All

variables analysed were related to the type of soil but varied with the date of sampling; a significant seasonal effect on the microbial population, microbial activity and available nutrients was detected in all the soils studied.

ChaoMei *et al.* (1998) observed that mean annual amounts of soil microbes (bacteria, fungi and actinomycetes) under forests are in order mixed forest > pure *Acacia* forest > pure Eucalyptus forest > barren and waste land in Huaxian county near Guangzhou, China. They found that soil respiration intensity was high in *Acacia mangium* forest and in its mixed forest, and was low in Eucalyptus forest. Five years after forestation with tree species mentioned above on barren and waste land, the soil microenvironment was greatly improved, which resulted in the increments of soil microbes underground and of biomasses above ground.

Soil microbial diversity and fungi involved in litter decomposition were studied for a period of two years in the shola forests of Munnar and Wayanad, Kerala, by Florence *et al.* (2001). The sholas selected were Mannavan shola, Pambadam Shola and Manthan shola in Munnar Forest Division and Meppadi shola and Brahmagiri shola in Wayanad Forest Division. They found that the density of fungal population varied between sholas. The population of fungi was highest in Pambadam shola and lowest in Manthan shola. Both in Pambadam and Manthan sholas the bacterial population was higher at a soil depth of 0-10 cm. The actinomycete population was also high in Manthan shola at 0-10 cm and 10-20 cm depth. In Manthan shola, the fungal density of fully decomposed leaf was low. Aspergillus, Penicillium, Trichoderma, Verticillium and Pestalotiopsis were the common dominant genera identified from all sholas. Among the Actinomycetes, the genus Streptomyces dominated in all sholas.

Soil microflora of the sholas of Eravikulam National Park, Idukki District has been studied by Sankaran and Balasundaran (2001). Soil samples were collected at periodic intervals from three sampling sites: Rajamalai shola, shola near Eravikulam hut and Vattachirambu shola and grasslands adjacent to them. Three composite soil samples were collected from each of the shola and grassland during November to December each year for three consecutive years (1994-96). Their

Results showed that the density of fungal propagules in the shola forests ranged between 10.23 - 28.78 × 10^3 per gram of soil. The 220 isolates of fungi from soils of the shola forests yielded 68 identified species belonging to 28 genera. The fungi isolated from grassland soils ranged between 14.26 - 42.04 × 10^3 per gram of dry soil. The 286 fungal isolates belonged to 25 genera and 69 species. Shola forests and the adjoining grasslands contained floristically dissimilar communities of soil fungi indicating the difference in the environmental conditions of these two ecosystems. The species diversity of soil fungal and actinomycete flora of Eravikulam was lower compared to that of low elevation areas in Kerala.

The microflora under 20-year old *Enterolobium cyclocarpum, Peltophorum pterocarpum* and *Acacia auriculiformis* stands revealed that the tree stands harboured more bacterial (from 3.6 to 5.8 × 10^6 per g of soil), actinomycetes (from 18 to 21 × 10^5 per g of soil) and fungal (19.6 to 22.4 × 10^4 per g of soil) population than the barren soil (Buvaneswaran *et al.*, 2003).

Microbial population of spruce soil in Tatachia mountain of Taiwan has been determined by ShangShyng *et al.* (2003). They observed that about 45.5-90.9% of topsoil samples had higher microbial population than those of subsoil especially in actinomycetes, cellulolytic and phosphate-solubilizing microorganisms. Although rhizosphere of Spruce had higher total organic carbon and total nitrogen content than non-rhizosphere and dwarf bamboo areas, the microbial population had no significant difference among them.

The study microbial population and diversity as influenced by soil pH and organic matter in different forest ecosystems has been conducted by Adekunle *et al.* (2005). Microbial populations were isolated and counted in agar-plated composite soil samples collected from stands of three different species and an adjacent natural forest in Akure forest reserve. The plantations were mature and unthinned stands of *Nauclea didderrichi, Gmelina arborea* and *Tectona grandis.* They revealed that the soil samples consisted 33 species of bacteria and 23 species of fungi. The population of bacteria ranged between 26.14 × 10^6 and 360 × 10^6 MPN g^{-1} dried soil while that of fungi ranged between 2.50 × 10^6 and 23.34 ×

10^6 MPN g^{-1} dried soil. Highest species diversity and population of the microbes were isolated in soil samples from the natural forest and the least from *Tectona grandis* stand. The correlation and regression results show that microbial diversity and abundance is highly influenced by soil pH and organic matter. There was no significant difference in organic matter and pH values of the samples from the different forest ecosystem ($p=0.05$) but significant difference was discovered to exist in bacterial and fungal population ($p=0.05$). The number and species diversity obtained for bacteria were more than that of fungi but there was close association in the abundance of the microbes obtained for all the soil samples.

Microbial community analyses based on CLPP and PLFA profiles showed distinct differences in forest floors under different tree species and among sites of differing fertility (Grayston and Prescott 2005).

The study relationships between culturable soil microbial populations and gross nitrogen transformation processes in a clay loam soil across ecosystems has been conducted by Silva *et al.* (2005). The objectives of this study were to examine the relationship between gross N transformation rates and microbial populations and to investigate the role that Soil Organic Matter (SOM) plays in these factors. They found that culturable microbial and actinomycete populations were positively correlated with gross mineralization and ammonium ($NH4^+$) consumption rates over time in both ecosystems. These correlations provide evidence that microbial plate counts could be a good representation of all microbes responsible for gross mineralization and gross $NH4^+$ consumption. They also found that rates of gross mineralization, nitrification and $NH4^+$ consumption were significantly greater in forest soil than old-field soil. These greater rates in forest soil could be due to the presence of higher levels of readily transferable substrates in SOM. They observed that microbial populations were significantly ($p<0.01$) greater in forest soil than in old-field soil, which could also be related to the higher level of SOM in the forest soil.

The influence of different media and incubation temperatures on the quantification of microbial populations in *sorghum, Eucalyptus* and forest soils was

evaluated by Vieira and Nahas (2005). Microbial growth was compared by using complex (tryptone soyabean agar, TSA, casein-starch, CS, and Martin) and saline (Thorton, M3, Czapeck) media and incubation temperatures of 25 and 30°C. They observed that higher numbers of total bacterial and fungal Colony Forming Units (CFU) were in sorghum soils, and of spore-forming and Gram-negative bacteria in forest soils than other soils. Actinomycetes counts were highest in forest soil when using CS medium at 30°C and in sorghum soil at 25°C in M3 medium. They also observed that microorganism counts were dependent on the media and incubation temperatures. The counts at temperatures of 30°C were significantly higher than at 25°C. Microbial quantification was best when using TSA medium for total and spore-forming bacteria, Thorton for Gram-negative bacteria, M3 for actinomycetes, and Martin for fungi.

The study, effect of different leaf fall decomposition on soil microorganisms has been conducted by CunYu (2006). They observed that the number of fungi in the treatment with decomposing leaves was more than those in the control treatment, indicating that fungi might be an important decomposer of leaf litter. During the initial period of decomposition, the number of bacteria was more than that of fungi and actinomycetes. During the middle and latter period of decomposition, bacterial count decreased, while the population of fungi and actinomycetes increased. They also observed that the soil affected by the decomposition of the leaf litter of *Albizia falcate* [*Falcataria moluccana*], *Acacia auriculiformis*, *Acacia mangium* and *Schima superba* [*S. wallichii*] had higher microbial biomass, higher population of bacteria and more abundant microbial species. Results indicate that the effect of soil microbes was better in the former soil than in the latter soil.

ShangShyng *et al.* (2006) investigated the role of microorganisms in the ecology and nutrient transformation of forest soil in Taiwan. The soil temperatures were between 5.5 and 15.6°C and the soil pH ranged from 3.3 to 4.4. Total organic carbon and total nitrogen contents ranged from 2.3 to 37.1% and from 0.3 to 1.7%, respectively. The carbon/nitrogen ratio was between 8.2 and 24.4. They found that

in topsoil, each gram of soil contained 10^5-10^7 Colony Forming Units (CFU) culturable bacteria, 10^2-10^5 CFU actinomycetes, 10^3-10^5 CFU fungi, 10^4-10^6 CFU cellulolytic microbes, 10^4-10^6 CFU phosphate-solubilizing microbes, and 10^3-10^6 CFU nitrogen-fixing microbes. Microbial populations were higher in topsoil compared with subsoil, but lower in topsoil than in organic layer. Microbial populations also decreased with the depth of soil. Microbial populations at 1E horizon were 0.6% to 9.4% of those at O horizon. They also found that summer season had higher microbial populations, biomass and organic content than winter season, but the differences were not significant. They concluded that heavy coverage of organic matter was found in hemlock and spruce soil and was associated with acidic pH. Microbial populations decreased with increasing soil depth. Microbes play a very important role in organic matter decomposition and nutrition transformation in hemlock soil.

Acacia auriculiformis mixed with *Gliricidia sepium* (50:50) had an initial phase of rapid decomposition followed by a second phase of comparatively lower decomposition rate. *Acacia* litter showed only a single phase of decomposition. Bacteria population increased linearly with nutrient content that was immobilized during decomposition, while fungal population varied more with litter type than with different phases of decomposition. Generally, the bacteria population isolated from *Acacia-Gliricidia* mixture was highest, followed by *Gliricidia* while it is lowest in *Acacia*, however more fungal population were isolated from *Acacia* litter than *Gliricidia* litter in all the phases of decomposition (Oyun *et al.*, 2006).

The relationship between soil microbial population and soil fertility under different vegetation restoration in loess regions in China has been determined by Hong *et al.* (2007). They found that soil fertility and soil microbial population improved remarkably after 30 years of restoration, with increase in soil organic matter, total and available nitrogen, available potassium content and microorganisms. They also found that the number of bacteria and fungi increased at first then decreased, and eventually increased again after 40 years of restoration of forest soils. There was no significant change in the number of actinomycetes.

Correlation analyses showed that there was a significant correlation between the number of bacteria and soil properties (e.g. soil organic matter, total N, available P and available K), and between the number of fungi and soil organic matter and total N. But there was no significant correlation between the number of actinomycetes and soil properties. Principal component analysis showed total microbial population can be used as an index to evaluate vegetation restoration process and soil quality.

In terms of microbial abundance, Kara and Bolat (2009) found that burned forest soils had the most bacteria and fungi.

An attempt has been made by Sharma *et al.* (2009) to study the soil bacteria, fungi and actinomycetes population in Seabuckthorn stand soil at different altitudinal zones in different seasons. They observed that among different altitudinal zones greater microbial population size was in Seabuckthorn stand soil of middle elevation zone (altitude 2400-2700 m asl) followed by lower elevation zone (altitude 1800-2400 m asl) and lower was found in upper elevation zone (2700-3200 m asl). They also observed that bacterial, fungal and actinomycetes population was comparatively more in rhizospheric region of Seabuckthorn plant than non-rhizospheric soil. Non-Seabuckthorn site soil always harboured less population of bacteria, fungi and actinomycetes compared to Seabuckthorn stand site soil (Sharma *et al.*, 2009). The study effect of soil properties on the distribution of AM fungi in *Acacia* ecosystems has been conducted by Tamilsselvi *et al.* (2010). They found that the soil was acidic with moderate amounts of macronutrient and with no appreciable variation in micronutrient under *Acacia mangium*. They also found that spore population of *Arbuscular Mycorrhial* fungi was highest during the month of October and lowest during January. Spore abundance increased from May to October, whereas highest percent colonization was recorded during the month of January and lowest in April.

Schiavo *et al.* (2009) reported that the population of microorganisms was higher in the *A. mangium* area compare to Eucalyptus. The population of microorganisms was higher in in the summer, where it was observed a positively correlation with total carbon.

Tangjang *et al.* (2009) observed that bacterial population was highest during spring and that of fungi during autumn. Nonetheless, the highest microbial counts were recorded in the topsoil (0-10 cm) layer except during the rainy season when the population was greater in the subsurface (10-20 cm) layer.

Changes in soil properties and microbial indices across various management sites in the mountain environments of Azad Jammu and Kashmir has been determined by Abbasi *et al.* 2010). They examined the changes in soil properties over the course of a year (spring, summer, autumn, winter) for forest, grassland, and arable (cultivated land) soils in a typical hilly and mountainous region of Azad Jammu and Kashmir, Pakistan. The natural forest served as a control against which changes in soil properties resulting from removal of natural vegetation and cultivation of soil were assessed. Soil samples were collected from depths of 0-15 and 15-30 cm six times during the year. They found significant differences in soil temperature, soil moisture, Fe, Mn, Cu, Zn, and number of bacteria, actinomycetes, and fungi among the three land-cover types. Soil under cultivation had 4-5°C higher temperature and 3-6% lower moisture than the adjacent soils under grassland and forest. Populations of bacteria, actinomycetes, and fungi in the forest were 22.3 (10^5), 8.2 (10^5), and 2.5 (10^3), respectively, while arable land exhibited 8.2 (10^5), 3.2 (10^5), and 0.87 (10^3). Season (temperature) and depth showed significant effects on microbial activity and nutrient concentration, and both decreased significantly in winter and in the subsurface layer of 15-30 cm. Different contents of the parameters among arable, grassland, and forest soils indicated an extractive effect of cultivation and agricultural practices on soil. Natural vegetation appeared to be a main contributor to soil quality as it maintained the moisture content and increased the nutrient status and microbial growth of soil. Therefore, it is important to sustain high-altitude ecosystems and reinstate the degraded lands in the mountain region.

Maximum population density of soil microfungal was observed in the rainy season followed by winter and lastly summer under monoculture plantation of *Casuarina equisetifolia* L. plantations in coastal sand dunes, Orissa. Larger

microbial populations were encountered in plantation soil compared to barren sand, corresponding with the fluctuation of prevailing temperature, moisture and total organic carbon content. Rates of litter loss and carbon dioxide output followed the same trends as the population density. The annual K value was 0.41. The diversity index varied from 2.87 to 3.71 (Shannon) and 0.356 to 0.885 (Simpson). The similarity index showed that Highly Decomposed Litter (HDL) is more similar to Soil A (barren sand dune) than Soil B (sand dune with monoculture plantation of *Casuarina*) (Panda 2010).

Royer-Tardif *et al.* (2010) reported that plant diversity and site productivity are important drivers of forest floor microbial stability in the southern boreal forest of eastern Canada.

Sarkar (2010) found that size of symbiotic *Rhizobial* population is varied in different season; the size is greater in early winter than summer whereas top soil (0-15 cm) contained more *Rhizobial* population than subsurface (15-30 cm) soil.

XinTao *et al.* (2010) found that the species of dominant populations and quantities of soil microbial in forest land soil were different following seasons vary and forest types. The quantities of bacteria in middle-aged forest was significantly higher than that in near-matured forest and plantation, and it changed greatly as seasons change, while the change in near-matured forest and plantation were relatively gentle. The dominant bacterial population was the highest in the winter (near-matured forest > plantation > middle-aged forest). The dominant fungi species in the soil of the three forest types had the highest proportion in the autumn, and followed the order of plantation > near-matured forest > middle-aged forest.

Quantitative microbial population variability associated with the microclimate conditions observed in tropical rainforest soil by Rodrigues *et al.* (2011). The found that the fungi developed better during the dry season and bacteria during rainy season, and their populations decrease with depth, except in a changed environment.

The highest fungal counts were found in the top soil layer in all seasons except during the rainy season when the population was greater in the subsoil. It was found that their number decreased with increasing depth of the soil i.e. from 0-100 cm soil depth. Fungal population was the highest during autumn (2.1×10^4/g at top soil at undisturbed stand) and lowest during summer (0.8×10^4/g at top soil at undisturbed stand). Aspergillus and Penicillium were the most dominant genera at the two stands and at different depths. Soil organic carbon (1.40 % at top soil and 1.25 % at 100 cm depth at undisturbed stand) and total nitrogen percentage decreased with increasing depth of the soil (Barbaruah and Baruah 2012).

Microbial ecosystem in sunderban mangrove forest sediment, north-east coast of Bay of Bengal has been studied by Das *et al.* (2012). This was the first documentation of seasonal and spatial fluctuation of the culturable microbial population collected from different zones in the sediment of the Sunderban mangrove forest. They revealed that the population of cellulose degrading bacteria, [mean value of CFU $6.189 \pm 1.025 \times 10^6$ (g dry weight of sediment)$^{-1}$] was maximum during post monsoon in the deep forest region, whereas, the fungal population [mean value of CFU $3.424 \pm 0.886 \times 10^6$ (g dry weight of sediment)$^{-1}$] maximum during pre-monsoon in the rooted region. The abundances of microbes, in decreasing order, studied from different zones are nitrifying bacteria [mean value of CFU $1.125 \pm 0.359 \times 10^6$ (g dry weight of sediment)$^{-1}$], Phosphorous Solubilizing Bacteria (PSB) [mean value of CFU $0.805 \pm 0.322 \times 10^6$ (g dry weight of sediment)$^{-1}$], free living nitrogen fixing bacteria [mean value of CFU $0.417 \pm 0.120 \times 10^6$ (g dry weight of sediment)$^{-1}$] and Sulfur Reducing Bacteria (SRB) [mean value of CFU $0.356 \pm 0.125 \times 10^6$(g dry weight of sediment)$^{-1}$]. They also revealed that the content of organic carbon in the soil decreased from the deep forest region to the rooted and unrooted region but a reverse profile was found for soil salinity and soil silicate concentration. The results from this study indicated that the monsoon cycle has a pronounced effect on the microbially dominated biogeochemistry in the sediment and consequently on the ecology of the Sundarban mangrove forest.

An increasing interest has emerged with respect to the importance of microbial diversity in soil habitats. The extent of the diversity of microorganisms in soil is seen to be critical to the maintenance of soil health and quality, as a wide range of microorganisms is involved in important soil functions. The two main drivers of soil microbial community structure, i.e., plant type and soil type, are thought to exert their function in a complex manner (Meliani *et al.*, 2012).

Ming *et al.* (2012) suggest that fungal community was more sensitive than the bacterial community in characterizing the differences in plant cover impacts on the microbial flora in natural pine and planted forests in subtropical region of China.

The colony forming units of fungi range was high in the rhizosphere of *B. balcooa* than *A. auriculiformis*. Shannon diversity index for fungi diversity was high in the month of May in both the species. Evenness was high in the month of March in *A. auriculiformis* and in the month of May for *B. balcooa* (Das *et al.*, 2013).

Seasonal differences in tree species influence on soil microbial communities examined by Thoms and Gleixner (2013). Their results showed that the soil microbial community differed more markedly between the tree diversity levels in early summer than in autumn. The acidifying character of the decaying beech litter strongly influenced the soil pH values and structured the soil microbial community indirectly in early summer as it had in autumn. However, the measured differences in the microbial composition in early summer could be attributed primarily to litter quality. This direct influence of plant traits appeared to be eclipsed in autumn because of the high nutrient supply from fresh litter input. Following litter decomposition in the topsoil, however, litter-based plant traits emerged as a factor structuring the soil microbial community in early summer. Their results also indicate that a dense root network in association with arbuscular mycorrhizal fungi strongly supported microbial growth in the more diverse forest stands. They concluded that microbial communities are strongly influenced by abiotic controls. However, seasonal differences in litter decomposition rates and root activity should

be considered in the analysis of the effects of tree diversity or species on soil microbial communities.

2.5 Growth of trees as affected by bio fertilizers

A biofertilizer (also bio-fertilizer) is a substance which contains living microorganisms which, when applied to seed, plant surfaces, or soil, colonizes the rhizosphere or the interior of the plant and promotes growth by increasing the supply or availability of primary nutrients to the host plant.(Vessey, 2003). Bio-fertilizers add nutrients through the natural processes of nitrogen fixation, solubilizing phosphorus, and stimulating plant growth through the synthesis of growth-promoting substances. Bio-fertilizers can be expected to reduce the use of chemical fertilizers and pesticides. The microorganisms in bio-fertilizers restore the soil's natural nutrient cycle and build soil organic matter. Through the use of bio-fertilizers, healthy plants can be grown, while enhancing the sustainability and the health of the soil. Since they play several roles, a preferred scientific term for such beneficial bacteria is "Plant-Growth Promoting Rhizobacteria" (PGPR). Therefore, they are extremely advantageous in enriching soil fertility and fulfilling plant nutrient requirements by supplying the organic nutrients through microorganism and their by-products. Hence, bio-fertilizers do not contain any chemicals which are harmful to the living soil. Rhizobium inoculation induce the early establishment of nitrogen fixation in rooted stem cuttings of *A. auriculiformis* and improve the growth, biomass and nutrient uptake (Karthikeyan *et al.*, 2013b).

Chang *et al.* (1986) reported that seedlings of *Acacia auriculiformis* A. Cunn. ex Benth inoculated with only Rhizobium had greater root and shoot dry wt. and N uptake than control plant. Inoculation with both Rhizobium and G. fasciculatum resulted in the greatest number of nodules, seedling wt and uptake of N and P, and C_2H_2 reduction. Osonubi and Mulongoy (1991) found that inoculation with *Boletus suillus* increased drought resistance of *A. auriculiformis* but did not improve drought resistance of *A. mangium*.

Study done by El-Lakany (1987) on *C. equisetifolia, C. cunninghamiana* and *C. glauca* in tree nurseries and plantations showed that nodulation varied between species, and between sites within species. Trees on sandy soils had more nodules than those on heavy clay soils, and trees on well-irrigated, non-water logged soils produced more nodules than trees under other soil moisture conditions. Cross-inoculation tests showed that inoculation was possible between C. glauca plants and *C. equisetifolia* nodules and vice versa.

Cruz *et al.* (1988) reported that *Glomus fasciculatum* + *Rhizobium* and *Gigaspora margarita* + *Rhizobium* were most effective for promoting growth of *Acacia mangium* and *Albizia falcataria* in a P-deficient soil. They also reported that *Scutellospora persica* + *Rhizobium, Gigaspora margarita* + *Rhizobium* and *Glomus fasciculatum* + *Rhizobium* were most effective for promoting growth of *Acacia auriculiformis* in a P-deficient soil.

Brunck *et al.* (1990) observed positive effects of inoculation with *Rhizobium* or *Bradyrhizobium* on the growth of *Acacia mangium, A. ampliceps* and *A. senegal* in W. Africa and Cook Islands. They also observed positive effects of inoculation with *Frankia* on the growth of *Casuarina equisetifolia* in Senegal, and *Alnus nepalensis, A. acuminata* and *A. jorullensis* [*A. acuminata*] in Burundi.

Inoculated seedlings of *Casuarina equisetifolia* with the nitrogen fixing actinomycete *Frankia* had higher survival rates and grew more rapidly than uninoculated seedlings. Three years after planting, wood production by inoculated trees was up to 200% higher than that of uninoculated N-fertilized trees (Reddell, 1990).

Mixed inoculations with P-solubilizing bacteria and mycorrhizal fungi (*Glomus spp.*) promoted growth of *Acacia confusa* (14 to 63%), *A. mangium* (7 to 88%), and *Liquidambar formosana* (24 to 280%) in Taiwan (Young, 1990).

Successful nursery inoculation of seedlings of *Acacia mangium* and *A. auriculiformis* is reported using crushed nodules of *Rhizobium* from 1-yr-old (outplanted) trees of the same species, which had themselves been inoculated as

nursery seedlings with *Rhizobium*. Growth response in the nursery was good and survival was also high after planting in the field (Nga, 1994).

Mycorrhizal species was an important factor determining growth of *Casuarina* seedlings. Height growth of *Casuarina* seedlings was significantly increased by dual inoculation with a mycorrhizal fungus and a *Frankia* isolate. Phosphorus application rates influenced the effect of mycorrhizal inoculation (ChongLu *et al.*, 1995).

Inoculation with VAM fungi was found to benefit the growth and biomass production of *Acacia auriculiformis*, *Casuarina equisetifolia* and *Pterocarpus marsupium*. A significant increase in total P content was also observed in the inoculated plants. Significant differences were also observed between treatments (VAM, N2 fixing symbionts and fertilizer) in height and diameter of field planted 1-year-old *A. auriculiformis*. The percentage increase in growth (height and diameter) with fertilizer addition was more in symbiont-inoculated plants than non-inoculated controls. Symbiont inoculation alone did not increase growth. Maximum percentage increase in height was 57.4 (*G. calidonius* + fertilizer) and 56.2 (*G. calidonius* + *Rhizobium* + fertilizer) whereas for diameter growth the maximum increase was 84.5% (*Glomus intraradices* + *Rhizobium* + fertilizer), followed by 70.0% (*G. calidonius* + fertilizer). In control treatments the increase in height and diameter growth was 11.5 and 41.4% (Sharma *et al.* 1996).

The response of biofertilizer application revealed that all biofertilizer treatments showed a higher growth rate. However, the highest biomass of 11.6, 6.0 and 8.5 g were recorded, respectively, in *Casuarina equisetifolia*, *Acacia nilotica* and *Eucalyptus tereticornis* when they were co-inoculated with *Frankia* + *VAM*, *Rhizobium* + *VAM* and *Azospirillum* + *VAM*, respectively (Balasubramanian and Ravichandran, 1997).

Significant improvement was observed 90 days after inoculation with the *Frankia* strains in *Casuarina equisetifolia*. *Frankia* inoculated clones recorded average improvements of 93, 51 and 116% in shoot and root length and biomass

production, respectively at 90 days after inoculation, with a 220% increase in nodulation (Kumar and Gurumurthi, 1999).

The growth of *Casuarina equisetifolia* seedlings can be enhanced significantly through inoculation with suitable strain of *Frankia* and also with a host specific *VAM* (Vesicular Arbuscular Mycorrhizal) fungus. Dual inoculated plants grew better than sole inoculated plants, and significantly better than uninoculated controls 105 days after inoculation; shoot and root length by was 49 and 88% more, respectively, in dual than uninoculated plants. The root volume, mycorrhizal infection percentage and nodulation characteristics (nodule numbers, nodule dry weight and nodule nitrogenase activity) of dual inoculated seedlings were also significantly higher than in the uninoculated controls (Ravichandran and Balasubramanian, 1999).

Maximum height, girth at breast height (gbh) and total biomass of *Casuarina equisetifolia* were obtained in the combined application of *Azospirillum, Phosphobacterium, VAM* and *Frankia.* The combination of *VAM* + *Frankia* among double inoculation, and the combination of *Azospirillum, VAM* and *Frankia* in triple inoculation also proved to be the best treatment in promoting the significant total height, gbh and total biomass production (Rajendran *et al.*, 2000).

Inoculation of either *Frankia* or *G. fasciculatum* on *Casuarina equisetifolia* increased the biomass by 70% in over control. For nodulation, a 5-fold increase in nodule number was recorded with the inoculation of *Frankia* strains. Inoculation of *Frankia* produced an average of 0.467 nodules/plant during the study period as against uninoculated control (0.068 nodules/plant). *Frankia* and *G. fasciculatum* recorded the maximum colonization of 65.6% at 120 days after inoculation (DAI), against the inoculation of *G. fasciculatum* alone (58.5%). Nitrogen uptake of dually colonized plants ranging from 23.2-48.72 mg N/plant as maximum compared to 14.6 mg N/plant in uninoculated control at 120 DAI. Phosphorus uptake was also higher in dually colonized plants (Sempavalan *et al.*, 2001).

Kayode and Franco (2002) found that *Acacia mangium* inoculated with *rhizobia* strains and three *AMF*, *Glomus clarum*, *Gigaspora margarita* and *Scutellospora heterogama*, grew better than seeds planted without *Rhizobia* and *AMF* inoculate.

Giri *et al.* (2004) reported that under field conditions, AM colonization of *A. auriculiformis* enhanced tree survival rates (85%) after transplantation. Arbuscular mycorrhiza-colonized plants showed significant increase in height, biomass production, and girth as compared to nonmycorrhizal plants. In general, all growth parameters were higher on dual inoculation of *G. fasciculatum* and *G. macrocarpum* as compared to uninoculated plants under both nursery and field conditions.

Valdes *et al.* (2004) observed significant effects of the microorganisms on *Casuarina equisetifolia* growth. Volume of the plants inoculated with the *Frankia* + *G. intraradices* combination showed a significant growth and synergistic increase, single inoculation had a 750% increase compared with the uninoculated plants and a 1093% increase in co-inoculation. A significant increase in numbers, biomass and nitrogenase activity (ARA) of nodules resulted with the same treatment; total N content of the plants was also increased.

The highest biomass of 11.59, 6.03 and 8.47 gm per seedling were recorded respectively in *C. equisetifolia*, *A. nilotica* and *E. tereticornis* over control, when they were co-inoculated with *Frankia+VAM*, *Rhizobium+VAM* and *Azospirillum+VAM*, respectively. Indeed, it is interesting to note that single inoculation of biofertilizers brought about little biomass improvement than their combined inoculation with VAM in all the species tested. In nodulating nitrogen fixing species like *C. equisetifolia* and *A. nilotica* the combined inoculation effected higher nodule weight 0.85 gm (*Casuarina*) and 122.69 gm (*Acacia*), when compared to control (Balasubramanian and Ravichardran 2005).

Diouf *et al.* (2005) reported that, compared with controls, both *Rhizobial* and mycorrhizal inoculation improved the growth of the salt-stressed plants (*Acacia*

auriculiformis A. Cunn. ex Benth. and *Acacia mangium* Willd.), while inoculation with the ectomycorrhizal fungus strain appeared to have a small effect on their groth and mineral nutrition levels. Inoculation with both *Rhizobial* and *Mycorrhizal* gave the trees better tolerance to salt stress and suggested that the use of this dual inoculum might be beneficial for inoculation of both *Acacia* species in soils with moderate salt constraints.

Shah *et al.* (2006) found that *C. equisetifolia* and *A. nilotica* developed more nodules with higher nodule dry mass and high nodule nitrogenase activity compared to control. The inoculation resulted in high biomass built up over control. They also reported that the dual inoculation namely *Frankia+VAM*, *Rhizobium+VAM*, and *Azosprillum+VAM* showed higher productivity than single inoculation in all the above three tree species.

Zhang *et al.* (2010) observed that *Glomus* had high mycorrhizal colonization (88.5-96.0%) with *Casuarina equisetifolia* seedlings. Seedlings were subjected to drought stress without watering for 7 days and survival of the seedlings inoculated with *Glomus caledonium*, *G. versiforme* and *G. caledonium* increased by 36.6, 23.3 and 16.6%, respectively compared with uninoculated seedlings. Limited influence of AMF on seedling height growth was found, but the effects of AMF on total biomass increment were very significant; the increment ranged from 25.7 to 118.9% compared with uninoculated treatment, and it was noted that AMF exerted more influences on root biomass than shoot biomass.

Chong *et al.* (2012) found that Inoculated with mycorrhizal fungi could significantly promote the growth of *C. equisetifolia* seedlings.

The growth and biomass of *C. equisetifolia* rooted stem cuttings inoculated with *Frankia* showed 3 times higher growth and biomass than uninoculated control (Karthikeyan *et al.*, 2013a).

2.6 Forest soil productivity and beneficial microflora

Soil productivity is defined as the capacity of soil, in its normal environment, to support plant growth. Soil productivity is reflected in the growth of forest vegetation or the volume of organic matter produced on a site. Soil is the fundamental resource of the forest. Without it or its productive capacity, the other resources of the forest are diminished. Soil characteristics such as physical, chemical and biological aspects are closely interrelated, and impacts on one aspects may influence others. The physical properties of soil include such factors as soil texture, structure, porosity, soil density, drainage and surface hydrology. The chemical properties of soil include nutrient status (input and outputs) and pH. It is known that without biological activity soil is death. The biological characteristics of soil include the population of plants and animals that thrive in a particular soil, including microflora (bacteria, fungi, actinomycetes, N-fixing microbes and P and K solubilizing microorganism) and microfauna (worms, arthropods, protozoa). Forest soil contain a multitude of microorganisms that perform many complex tasks relating to soil formation, slash and litter disposal, nutrient availability and recycling, and tree metabolism and growth. Generally the number of organisms are greatest in the forest floor and the area directly associated with plant roots (Pritchett, 1979).

Glomus fasciculatum and *Scutellospora calospora* colonized the roots of this fast growing fuelwood tree (*Casuarina equisetifolia* L). These VAM fungi can be used successfully when this species is planted, especially in degraded soils (Sidhu *et al.*, 1990).

Young (1990) reported that soil property is a significant factor in the modification of the response of *Acacia* confusa, *A. mangium* and Liquidambar formosana to bacterial and fungal inoculations. The beneficial effect of P-solubilizing bacteria was demonstrated in soils with a high content of available P (95 μg/g soil).

The study, effect of forest tree species on properties of lateritic soil has been conducted by Chavan *et al.* (1995). They observed that forest tree species (*Tectona grandis, Terminalia tomentosa, Pongamia pinnata, Gmelina arborea, Eucalyptus, Acacia auriculiformis*, and *Casuarina equisetifolia*) in ten-year-old plantations at Wakawali [Maharashtra], India, did not change the soil physical properties under the canopy, but there were marked effects on the soil chemical properties compared with natural forest soils. They also observed that organic carbon, available nitrogen, phosphorus and potassium increased significantly in the surface layer. The CEC and exchangeable cations also increased due to the decomposition of organic matter added through leaf litter. Calcium was the dominant cation. In general, the soils under the forest cover showed higher nutrient status. Tiwari (1998) concluded that the *Frankia*-VAM-Casuarina association can be exploited to help raise Casuarina plantations on poor and abandoned soils.

Banerjee *et al.* (2004) observed that after eight years of planting, *Acacia mangium* performed very well in respect to all the growth parameters followed by A. holoserecia, Dalbergia sissoo, Albizia procera, Pithecellobium dulce, *Acacia auriculiformis* and Gmelina arborea in coal mine overburden spoils of Bisrampur colliery at Surguja district, Chattisgarh, India in 1993. The number of natural colonisers increased with increasing age of the planted species. Nutrient status of the spoils also increased gradually with the increase in age of the plants. Organic carbon increased greatly and, as a result, activities of bacteria, actinomycetes and fungi accelerated.

Lixia *et al.* (2004) observed that the total amount of microbes, especially of the number and percentage of bacteria was increased under artificial forests and most obvious result was found in soil under afforestation by *A. mangium*. They also suggest that the soil properties under artificial forests were improved because of microbes.

Biofertilizer inoculation can improve the soil nutrient status under both N and P deficient condition. Jayakumar and Tan (2005) reported that total dry matter production, and N and P contents were significantly higher in seedlings that

received dual inoculation with N2-fixing Bradyrhizobium sp. and P-solubilizing ectomycorrhizal Pisolithus tinctorius than in uninoculated control seedlings of *Acacia mangium* under both N and P deficient conditions.

Many evidences are found that the forest tree species can improve soil productivity. Schiavo *et al.* (2009) observed that in the Eucalyptus area, the P contents increased linearly with planting time. However, only at the twelfth year, differences between Eucalyptus and B. mutica areas have occurred. In the *A. mangium* area, such differences in the P content occurred at the third year with increment of 43%, at the 0-10 cm layer, in relation to B. mutica. Also, at the 0-10 cm layer, the total carbon contents were 98%, 78%, 70% and 40% higher than those found in Eucalyptus with three, five, twelve years of age and in the B. mutica area, respectively. The use of *A. mangium* led to improvements in the chemical and microbiological soil attributes in the substrate.

Soil organic C, total N and available P decreased with increasing soil depth. Soil organic C and total N concentration had correlation with the microbial colony forming units. It was noticed that plant residues, added organic matter, vegetation, plant species composition and soil mineral nutrients altered the microbial population as well as their species composition under traditional agroforestry system (Tangjang *et al.*, 2009).

FaMing *et al.* (2010) estimated that effects of nitrogen-fixing and non-nitrogen-fixing tree species on soil properties and nitrogen transformation during forest restoration in southern China. They observed that the N-fixing forests had 40-50% higher soil organic matter and 20-50% higher total nitrogen concentration in the 0-5 cm soils than the non-N-fixing forests. Soil inorganic N was highest under the secondary shrubland. They also observed that the N-fixing *Acacia auriculiformis* plantation had the highest soil available P. There were no significant differences in soil N mineralization and nitrification among the forest types, but seasonal variation in these N processes was highly significant. In the rainy season, the rates of N mineralization (7.41-11.3 kg N ha-1 month-1) were similar to values found in regional climax forests, indicating that soil N availability has been well

recovered in these forest types. Their results suggested that N-fixing species, particularly *Acacia mangium*, are more efficient in re-establishing the C and N cycling processes in degraded land in southern China. Moreover, the N-fixing species *A. auriculiformis* performed better than other species in improving soil P availability.

Combalicer *et al.* (2011) found that Aboveground Net Primary Productivity (*ANPP*), and nitrogen productivity were higher in the 20-year-old *A. auriculiformis* (6.28 tons ha^{-1} yr^{-1} and 267.23 kg kg^{-1} yr^{-1}, respectively) and *A. mangium* (6.43 tons ha^{-1} yr^{-1} and 221.72 kg kg^{-1} yr^{-1}, respectively) than *Pterocarpus indicus* Willd. stands. *Acacia mangium* and *A. auriculiformis* were attributed to their higher values of litterfall and aboveground biomass and carbon. Also, Specific Leaf Weight (*SLW*) was much higher in the 10- and 20-year-old *A. auriculiformis* (244 and 245 cm^2g^{-1}, respectively) and 20-year-old *A. mangium* (255 cm^2g^{-1}) than *P. indicus* stands. They reported that the *Acacia mangium* and *A. auriculiformis* are very important in the initial establishment of the plantation and could be considered as priority species to lessen the vast degraded areas in the country.

Bento *et al.* (2012) observed that the ability of the plants to decrease the soil concentration of total petroleum hydrocarbons is not directly related to its growth and adaptation to conditions of contamination, but the success of the association between plants and its symbionts that seem to play a critical role on remediation efficiency.

YongKwon and SuYoung (2012) reported that planting *Acacia mangium* and *Acacia auriculiformis* improved site qualities (litter fall, decomposition, and net mineralization) and microclimate factors (air temperature, soil temperature, and relative humidity) and decreased the variation rate of these factors in the study sites. Therefore, this study suggests that this type of plantation is efficient in improving site qualities.

Karthikeyan *et al.* (2013a) found that the soil nutrients, particularly soil N, was highly increased after planting of *C. equisetifolia* rooted stem cuttings inoculated with *Frankia.*

Singh *et al.* (2013) found that rehabilitation activities do help increase the level of microbial community in the soils. Deforestation activities decrease soil biological activities; however, proper forest management and rehabilitation activities are able to restore the condition of degraded forest land to its original state.

Materials and methods

MATERIALS AND METHODS

The present study entitled "Soil productivity changes under selected exotic forest tree species with special reference to beneficial microflora" was carried out during May - 2013 to May - 2014. The details of the materials used and the methodologies employed in the experiments during the course of investigation are described in this chapter.

3.1 Experimental site

The proposed study was conducted in an existing provenance trial plot of selected exotic tree species located in the sub-centre of Kerala Forest Research Institute, at Nilambur. The site is located in Malappuram district of Kerala State at 11°16'37"N latitude and 76°13'33"E longitude. The area has an elevation of 41 m above mean sea level. The temperature varies between 17° C and 37° C and the mean annual rainfall ranges from 2500 to 3500 mm. The study was conducted for a period of one year (May 2013 to May2014).

3.2 Experimental material

The following four fast growing exotic tree species were selected for the study

Acacia auriculiformis, Casuarina equisetifolia and *Swietenia macrophylla* were planted during 1982 and *Acacia mangium* was planted during 1984 with a spacing of 2m × 2m.

Acacia auriculiformis is native to Savannas of Papua New Guinea, islands of the Torres Straight and the northern areas of Australia. It is a medium sized evergreen tree, attaining a height of 10 m, rarely upto 30 m, and 60 cm diameter in about 30 years, which is its normal length of life. It has been planted extensively in the tropical countries. The reason ascribed for its extensive spread are due to its hardiness, vigorous growth, suitability for production of fuelwood, pulpwood, round wood and reclamation of wastelands.

Acacia mangium is another promising fast growing, evergreen leguminous tree, native to tropical rainforests of Australia, Papua New Guinea and Indonesia. In 14 years it grows up to 30 m height and 40 cm in diameter (DBH). This species is able to grow even in acidic soils with pH as low as 4.2. The trees are useful for shade, ornamental purpose, demarcating boundaries and wind breaks as well as for use in agro-forestry and erosion control.

Casuarina equisetifolia is indigenous to nort-east Australia, the Pacific Islands, the Malay Archipelago and Peninsula, Chittagong, Tenasserian, the Andamans and Nicobars. Its native habitat extends between 22°S and 22°N but today it is cultivated throughout the tropics especially in the coastal and semi-arid regions. It is generally found at elevations 0-1400 m above sea level. It is a moderate to large-sized tree, attaining a height of 30-35 m and a maximum DBH of 100 cm under favourable conditions.

Swietenia macrophylla is naturally distributed between 20°N and 18°S, extending from eastern Mexico across Central America, Columbia, and Venezuela to the western Amazonian lowlands in Ecuador, Peru, Brazil and Bolivia, from the sea level to 1500 m; however, it is most frequently found between sea level to 450 m elevation. It naturally thrives in evergreen moist forests (Amazonia), in deciduous moist forests (the seasonal forests, of the plains of western Venezuela) and in riparian forests. It is a large, evergreen to briefly deciduous tree, usually attaining a height of 40-45 m and DBH of 100-200 cm, but under most favourable localities it can attain 60 m height and 300 m DBH.

3.3 Collection of Soil samples

The soil samples for microbial analysis were collected from the rhizosphere, within a radius of 30 cm distance from the tree and from depth of 0-30cm layer of the top soil. Three replicate soil samples were collected from the plots of all the four tree species. The samples were collected at quarterly interval for a period of one year. At each sampling, 15 samples were collected (4 tree species + tree less

open area x 3 replications). Thus a total of 75 samples (5 treatments x 3 replications x 5 sampling) were collected for soil microflora analysis.

For analysing physico-chemical properties, the soil samples were collected at the start and again at the end of the study. The samples were analysed for pH, organic carbon, total and available nitrogen, available phosphorus and exchangeable potassium using standard procedures. Also, representative triplicate soil samples were collected from contiguous treeless open area as control. The soil samples were air dried and passed through 2 mm sieve. The sieve samples are then stored in a polythene bag for further physic-chemical analysis in the laboratory.

3.4 Physico-chemical properties of soil

The soil samples were analysed for the physico-chemical properties of soil such as soil moisture, bulk density, soil pH, organic carbon, total nitrogen, available nitrogen, available phosphorus and exchangeable potassium. The detailed methods are given as under.

3.4.1 Soil moisture

Soil moisture content was determined by weight loss after drying fresh soil at 100-110°C for 24 hour using the formula.

$$Soil\ moisture\ content\ (\%) = \frac{Wet\ soil\ (g) - Dry\ Soil\ (g)}{\text{Dry soil (g)}} \times 100$$

3.4.2 Bulk density

Soil samples for bulk density measurements were taken using a steel cylinder (Jackson, 1958). Bulk density was estimated by taking out a core of undisturbed soil by using steel cylinder. The soil was oven dried and weight was determined. The volume of soil was calculated by measuring the volume of cylinder ($\pi r^2 h$). The bulk density was calculated by dividing the oven dry weight of soil samples (g) by volume of the soil.

3.4.3 Soil pH

The pH of soil was determined using an aqueous suspension of soil (soil and water in 1:2.5 ratio) using an Elico pH analyser (Model Li 614).

3.4.4 Organic carbon

Organic carbon content of the soil was determined by wet digestion method (Walkley and Black, 1934). Soil organic matter was determined by multiplying the value of organic carbon by 1.334 (Van Bemmelen factor).

3.4.5 Total nitrogen

Total nitrogen content in soil samples was determined by Skalar method.

Sulphuric acid and Se powder mixture – 3.5 g selenium powder was weighed. 1 litre of conc. H_2SO_4 was carefully and slowly poured into a two litre beaker. Se powder was then dissolved into the H_2SO_4 by heating the beaker for 4 to 5 hours at 300^0 C. The black colour of the solution changed to deep blue colour and then light yellow. The solution was then cooled.

Digestion mixture – 10.8 g salicylic acid was weighed and added to 150 ml of H_2S and selenium mixture.

Procedure

From soil sample 0.4 g of soil was weighed into the digestion tube. 2.5 ml of the digestion mixture was poured into the digestion tube. The tube was then swirled well and allowed to stand for 2 hours or overnight. It was then inserted into the digestion block and heated at 100^0C for 2 hours. After cooling the tubes were removed from the block and 1 ml of 30% H_2O_2 was added and again after reaction 1 ml of 30% H_2O_2 was added. After the reaction ceased, they were again placed in the digestion block and heated at 330^0C for 2 hours. When the digest turned colourless, the digestion was completed. The digest was made upto 75 ml in a

equisetifolia and treeless control plot. *A. auriculiformis* and *A. mangium* were found to have significant effect on available phosphorus. Available phosphorus was highest in *A. auriculiformis* (4.16 kg ha^{-1}) and lowest in treeless control plot (3.88 kg ha^{-1}). Available phosphorus in *A. mangium* was at par with *C. equisetifolia* and in *C. equisetifolia* was at par with *S. macrophylla* and treeless control plot. Exchangeable potassium was highest in *S. macrophylla* (94.27 kg ha^{-1}) and lowest in treeless control plot (61.41 kg ha^{-1}). Exchangeable potassium in *S. macrophylla* was at par with *C. equisetifolia, A. mangium, A. auriculiformis* and treeless control plot.

4.1.2 Physico-chemical properties of final soil sample at thirty two years age of exotic forest tree species (May, 2014)

Soil physico-chemical properties were influenced by tree species. Data presented in the Table 2 reveal that, there was no significant difference in soil moisture in the tree plots. Soil moisture was highest in *S. macrophylla* (10.88 %) and lowest in treeless control plot (9.91 %). However, the tree plantations were found to have significant effect on bulk density of soil. Bulk density was high in treeless control plot (1.47) compared to tree plots. Bulk density was lowest in *A. auriculiformis* (1.16) and it was at par with *S. macrophylla.* Bulk density in *S. macrophylla* was at par with *C. equisetifolia* and *A. mangium.* Soil pH was highest in treeless control plot (5.47) and lowest in *A. auriculiformis* (5.00). Soil pH in *A. auriculiformis* was at par with *A. mangium* and *C. equisetifolia.* Soil pH in *C. equisetifolia* was at par with *S. macrophylla.* Soil pH in *S. macrophylla* was higher and was at par with treeless control plot.

Organic carbon was significantly higher in *S. macrophylla* (2.15 %) and lowest in treeless control plot (1.38 %). Organic carbon in treeless control plot was at par with *A. mangium, A. auriculiformis* and *C. equisetifolia.* Tree species were found to have significant effect on available nitrogen. Available nitrogen was significantly higher in plantations compared to treeless control plot. Available nitrogen was highest in *A. mangium* (71.60 kg ha^{-1}) and lowest in treeless control

3.4.3 Soil pH

The pH of soil was determined using an aqueous suspension of soil (soil and water in 1:2.5 ratio) using an Elico pH analyser (Model Li 614).

3.4.4 Organic carbon

Organic carbon content of the soil was determined by wet digestion method (Walkley and Black, 1934). Soil organic matter was determined by multiplying the value of organic carbon by 1.334 (Van Bemmelen factor).

3.4.5 Total nitrogen

Total nitrogen content in soil samples was determined by Skalar method.

Sulphuric acid and Se powder mixture – 3.5 g selenium powder was weighed. 1 litre of conc. H_2SO_4 was carefully and slowly poured into a two litre beaker. Se powder was then dissolved into the H_2SO_4 by heating the beaker for 4 to 5 hours at 300^0 C. The black colour of the solution changed to deep blue colour and then light yellow. The solution was then cooled.

Digestion mixture – 10.8 g salicylic acid was weighed and added to 150 ml of H_2S and selenium mixture.

Procedure

From soil sample 0.4 g of soil was weighed into the digestion tube. 2.5 ml of the digestion mixture was poured into the digestion tube. The tube was then swirled well and allowed to stand for 2 hours or overnight. It was then inserted into the digestion block and heated at 100^0C for 2 hours. After cooling the tubes were removed from the block and 1 ml of 30% H_2O_2 was added and again after reaction 1 ml of 30% H_2O_2 was added. After the reaction ceased, they were again placed in the digestion block and heated at 330^0C for 2 hours. When the digest turned colourless, the digestion was completed. The digest was made upto 75 ml in a

standard flask. The readings were then taken from the Skalar directly using the reagents.

3.4.6 Available nitrogen and Available phosphorus

Available nitrogen and available phosphorus content in soil samples were determined by Skalar method.

Forty gram of the soil sample was weighed in a polyethylene shaking bottle. Than 200 ml of distilled water was poured into it and shaken for 60 minutes. After shaking the soil sample was filtered through filter paper. The readings were then taken directly from the Skalar continuous flow analyser.

3.4.7 Exchangeable potassium

Exchangeable potassium in the soil samples were extracted using 1N neutral ammonium acetate and estimated using flame photometry (Jackson, 1958).

3.5 Isolation and enumeration of total soil microflora

The rhizosphere soils were collected from four exotic tree species plots namely *Acacia auriculiformis, Acacia mangium, Casuarina equisetifolia and Swietenia macrophylla.* Total bacteria, fungi, actinomycetes, nitrogen fixers, phosphate solubilizers, and potassium solubilizing bacteria were isolated and enumerated.

Quantitative estimation of bacteria, fungi, actinomycetes, N-fixer, phosphorus solubilizers and potassium solubilizing bacteria from different soil samples were carried out on Nutrient Agar medium, Rose Bengal Agar medium, Kenknights medium (Johnson and Curl, 1972), Jensen's Broth, Pikovskaya Agar medium (Rao and Sinha, 1963), and Glucose Yeast Extract Agar medium respectively by using serial dilution method. For that soil samples were collected and analysed at quarterly interval for a period of one year (May 2013 to May 2014).

3.5.1 Isolation and enumeration of microorganisms from soil by the serial dilution-agar plating method (or viable plate count method)

The serial dilution-agar plating method or viable plate count method is one of the commonly used procedures for the isolation and enumeration of fungi, bacteria and actinomycetes which are the most prevalent microorganisms. This method is based on upon the principle that when material containing microorganisms is cultured each viable microorganisms will develop into a colony, Hence the number of colonies appearing on the plates represent the number of living organisms present in the sample.

Different dilutions were used for isolation of different microflora. The dilution of 10^{-2} was selected for fungi and nitrogen fixing bacteria, 10^{-3} for actinomycetes, phosphate solubilizing microorganism and potash solubilizing bacteria and 10^{-4} for bacteria.

3.5.2 Pour plate techniques

The forerunner of the present pour-plate method was developed in the laboratory of the famous bacteriologist, Robert Koch. In this technique, successive dilutions of the inoculum (serially diluting the original specimen) were added into sterile petri plates to which was poured method and cooled (42-45°C) agar medium and thoroughly mixed by rotating the plates which is then allowed to solidify. For quantification of bacteria, fungi, actinomycetes, nitrogen fixers, phosphate solubilizer one ml from the required dilution was poured aseptically into sterile petri dishes to which cooled molten media was poured and gently rotated. The inoculated petri dishes were incubated at room temperature. Number of colony forming units from each sample was recorded.

3.5.3 Spread-plate techniques

The spread-plate technique was used for the separation of a dilute, mixed population of microorganisms so that individual colonies could be isolated. In this technique microorganisms were spread over the solidified agar medium with a

sterile L-shaped glass rod while the Petri dish is spun on a turntable. The theory behind this technique is that as the petri dish spins, at some stage, single cells will be deposited with the bent glass rod on to the agar surface. Some of these cells will be separated from each other by a distance sufficient to allow the colonies that develop to be free from each other. This technique was used for isolation and enumeration of potassium solubilizing bacteria.

The number of colonies appearing on dilution plates were counted and multiplied by the dilution factor to find the number of cells per gram of soil.

$$\text{No. of cells/ g} = \frac{Number\ of\ colonies \times Dilution\ factor}{\text{Dry wt. of soil}}$$

3.6 Tree growth observations

The total tree height and diameter at breast height of individual tree were taken and the trees in the plots were recorded at the start of the experiment and again after one year. The tree growth observations were recorded for reference of the tree plots where the study carried out.

3.7 Statistical analysis

Statistical analysis was done by using statistical software SPSS V.20.0. Duncan's Multiple Range Test (DMRT) was used to test the differences among treatment means.

RESULTS

The present investigation involved analysis of soil physico-chemical properties viz., moisture content, bulk density, pH, organic carbon, available nitrogen, total nitrogen, available phosphorus, exchangeable potassium and measurement of tree growth parameters viz., height DBH. Isolation and enumeration of beneficial microflora viz., actinomycetes, bacteria, fungi, nitrogen fixing bacteria, phosphate solubilizer and potash solubilizing bacteria were carried out. The results of the study detailed hereunder.

4.1 Physico-chemical properties of soil

4.1.1 Physico-chemical properties of initial soil sample at thirty two years age of exotic forest tree species (May, 2013)

Soil moisture content did not show significant difference in different plantations (Table 1). Soil moisture was highest in *A. mangium* (6.47 %) and the lowest in treeless control plot (3.65 %). However, effect of tree species were found to have significant effect on bulk density of soil. Bulk density was high in treeless control plot (1.56) compared to plantations. Bulk density was the lowest in *A. auriculiformis* (1.25) and it was at par with *A. mangium*, *S. macrophylla* and *C. equisetifolia*. Soil pH was highest in treeless control plot (5.49) and the lowest in *A. mangium* (4.75).

Organic carbon was highest in *A. auriculiformis* (1.99 %) and the lowest in treeless control plot (1.15 %). There was no significant difference in organic carbon between the tree species. Tree species were found to have significant effect on available nitrogen. Available nitrogen was significantly higher in *A. mangium* (64.10 kg ha^{-1}) and the lowest in treeless control plot (32.99 10 kg ha^{-1}). Available nitrogen in *A. mangium* was at par with *A. auriculiformis* and *C. equisetifolia*. Available nitrogen in *C. equisetifolia* was at par with *S. macrophylla*. Total nitrogen was highest in *A. mangium* (0.08 %) and lowest in treeless control plot (0.06 %). Total nitrogen in *A. mangium* was at par with *S. macrophylla*, *A. auriculiformis*, *C.*

Results

RESULTS

The present investigation involved analysis of soil physico-chemical properties viz., moisture content, bulk density, pH, organic carbon, available nitrogen, total nitrogen, available phosphorus, exchangeable potassium and measurement of tree growth parameters viz., height DBH. Isolation and enumeration of beneficial microflora viz., actinomycetes, bacteria, fungi, nitrogen fixing bacteria, phosphate solubilizer and potash solubilizing bacteria were carried out. The results of the study detailed hereunder.

4.1 Physico-chemical properties of soil

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Organic carbon was highest in *A. auriculiformis* (1.99 %) and the lowest in treeless control plot (1.15 %). There was no significant difference in organic carbon between the tree species. Tree species were found to have significant effect on available nitrogen. Available nitrogen was significantly higher in *A. mangium* (64.10 kg ha^{-1}) and the lowest in treeless control plot (32.99 10 kg ha^{-1}). Available nitrogen in *A. mangium* was at par with *A. auriculiformis* and *C. equisetifolia.* Available nitrogen in *C. equisetifolia* was at par with *S. macrophylla.* Total nitrogen was highest in *A. mangium* (0.08 %) and lowest in treeless control plot (0.06 %). Total nitrogen in *A. mangium* was at par with *S. macrophylla, A. auriculiformis, C.*

equisetifolia and treeless control plot. *A. auriculiformis* and *A. mangium* were found to have significant effect on available phosphorus. Available phosphorus was highest in *A. auriculiformis* (4.16 kg ha^{-1}) and lowest in treeless control plot (3.88 kg ha^{-1}). Available phosphorus in *A. mangium* was at par with *C. equisetifolia* and in *C. equisetifolia* was at par with *S. macrophylla* and treeless control plot. Exchangeable potassium was highest in *S. macrophylla* (94.27 kg ha^{-1}) and lowest in treeless control plot (61.41 kg ha^{-1}). Exchangeable potassium in *S. macrophylla* was at par with *C. equisetifolia*, *A. mangium*, *A. auriculiformis* and treeless control plot.

4.1.2 Physico-chemical properties of final soil sample at thirty two years age of exotic forest tree species (May, 2014)

Soil physico-chemical properties were influenced by tree species. Data presented in the Table 2 reveal that, there was no significant difference in soil moisture in the tree plots. Soil moisture was highest in *S. macrophylla* (10.88 %) and lowest in treeless control plot (9.91 %). However, the tree plantations were found to have significant effect on bulk density of soil. Bulk density was high in treeless control plot (1.47) compared to tree plots. Bulk density was lowest in *A. auriculiformis* (1.16) and it was at par with *S. macrophylla.* Bulk density in *S. macrophylla* was at par with *C. equisetifolia* and *A. mangium.* Soil pH was highest in treeless control plot (5.47) and lowest in *A. auriculiformis* (5.00). Soil pH in *A. auriculiformis* was at par with *A. mangium* and *C. equisetifolia.* Soil pH in *C. equisetifolia* was at par with *S. macrophylla.* Soil pH in *S. macrophylla* was higher and was at par with treeless control plot.

Organic carbon was significantly higher in *S. macrophylla* (2.15 %) and lowest in treeless control plot (1.38 %). Organic carbon in treeless control plot was at par with *A. mangium*, *A. auriculiformis* and *C. equisetifolia.* Tree species were found to have significant effect on available nitrogen. Available nitrogen was significantly higher in plantations compared to treeless control plot. Available nitrogen was highest in *A. mangium* (71.60 kg ha^{-1}) and lowest in treeless control

Table 1. Physico-chemical properties of initial (May, 2013) soil sample.

Treatment	Moisture content (%)	Bulk Density	pH	Organic carbon (%)	Avail N (kg/ha)	Total N (%)	Avail P (kg/ha)	Exchangeable K (kg/ha)
Acacia auriculiformis	6.37	1.25^{b}	4.85	1.99	62.80^{a}	0.07	4.16^{a}	76.53
Acacia mangium	6.47	1.33^{b}	4.75	1.35	64.10^{a}	0.08	4.01^{b}	85.87
Casuarina equisetifolia	5.99	1.35^{b}	4.79	1.75	52.44^{ab}	0.07	3.94^{bc}	92.96
Swietenia macrophylla	5.59	1.33^{b}	5.29	1.75	46.27^{b}	0.08	3.92^{c}	94.27
Treeless control plot	3.65	1.56^{a}	5.49	1.15	32.99^{c}	0.06	3.88^{c}	61.41

Values followed by same superscript in a column do not differ significantly (LSD, P, 0.05).

Table 2. Physico-chemical properties of final (May, 2014) soil sample.

Treatment	Moisture content (%)	Bulk Density	pH	Organic carbon (%)	Avail N (kg/ha)	Total N (%)	Avail P (kg/ha)	Exchangeable K (kg/ha)
Acacia auriculiformis	10.79	1.16^{c}	5.00^{c}	1.68^{b}	64.65^{ab}	0.08^{b}	4.32^{ab}	67.08^{ab}
Acacia mangium	10.77	1.30^{b}	5.05^{c}	1.47^{b}	71.6^{a}	0.07^{b}	4.42^{a}	56.41^{bc}
Casuarina equisetifolia	10.50	1.29^{b}	5.17^{bc}	1.74^{b}	70.02^{ab}	0.09^{b}	4.29^{ab}	57.41^{bc}
Swietenia macrophylla	10.88	1.25^{bc}	5.44^{ab}	2.15^{a}	58.36^{b}	0.13^{a}	$4.20b^{c}$	80.15^{a}
Treeless control plot	9.91	1.47^{a}	5.47^{a}	1.38^{b}	39.05^{c}	0.07^{b}	4.08^{c}	52.34^{c}

Values followed by same superscript in a column do not differ significantly (LSD, P, 0.05).

plot (39.05 kg ha^{-1}). Available nitrogen in *A. mangium* was at par with *C. equisetifolia* and *A. auriculiformis*. Available nitrogen in *A. auriculiformis* was at par with *S. macrophylla*. Total nitrogen was significantly higher in *S. macrophylla* (0.13 %) and lowest in treeless control plot (0.07 %). *A. auriculiformis* and *C. equisetifolia* were found to have significant effect on available phosphorus. Available phosphorus was highest in *A. mangium* (4.42 kg ha^{-1}) and the lowest in treeless control plot (4.08 kg ha^{-1}). Available phosphorus in *A. mangium* was at par with *A. auriculiformis* and *C. equisetifolia*. Available phosphorus in *C. equisetifolia* was at par with *S. macrophylla*. Available phosphorus in *S. macrophylla* was at par with treeless control plot. Exchangeable potassium was highest in *S. macrophylla* (80.15 kg ha^{-1}) and the lowest in treeless control plot (52.34 kg ha^{-1}). Exchangeable potassium in *S. macrophylla* and *A. auriculiformis* were significantly higher than the treeless control plot. Exchangeable potassium in *A. auriculiformis* was at par with *C. equisetifolia* and *A. mangium*.

4.2 Microbial population during different sampling period.

4.2.1 Microbial population of soil as affected by different exotic forest tree species

Soil samples for microbial enumeration were collected at quarterly interval during different seasons of one year period. The population of microflora was expressed as a colony forming units (cfu).

4.2.1.1 Late summer-I (Initial sample during May 2013)

The tree species had influenced the microbial population. Among all the tree species *Casuarina equisetifolia* had highest actinomycetes population (6.33 × 10^3cfu g^{-1}) followed by *Acacia auriculiformis, Acacia mangium* and *Swietenia macrophylla* The lowest actinomycetes population was recorded in treeless control plot.

Table 3. Microbial population under different exotic tree species during late summer-I (May, 2013).

Treatment	Actinomycetes (x 10^3 cfu g^{-1})	Bacteria (x 10^4 cfu g^{-1})	Fungi (x 10^2 cfu g^{-1})	NFB (x 10^2 cfu g^{-1})	PSM (x 10^3 cfu g^{-1})	KSB (x 10^3 cfu g^{-1})
Acacia auriculiformis	5.33^{ab} (1.15)	13.00 (2.00)	28.33 (10.40)	4.00^{a} (1.00)	7.66^{ab} (3.05)	19.67^{a} (6.02)
Acacia mangium	5.33^{ab} (1.52)	18.33 (4.04)	33.00 (13.00)	4.67^{a} (1.15)	15.33^{a} (1.52)	23.67^{a} (6.42)
Casuarina equisetifolia	6.33^{a} (1.52)	16.67 (6.65)	24.33 (3.21)	2.33^{ab} (0.57)	12.00^{bc} (3.60)	03.67^{b} (2.88)
Swietenia macrophylla	5.00^{ab} (0)	10.00 (1.00)	20.33 (1.52)	1.33^{b} (0.57)	09.00^{b} (1.00)	06.67^{b} (1.52)
Treeless control plot	3.33^{b} (0.57)	12.67 (6.11)	18.33 (01.15)	3.33^{ab} (2.08)	04.33^{c} (2.08)	03.33^{b} (1.52)

NFB: Nitrogen Fixing Bacteria

PSM: Phosphate Solubilizing Microorganism

KSB: Potash Solubilizing Bacteria

Values in the parenthesis are mean ± standard deviation.

Values followed by same superscript in a column do not differ significantly (LSD, P, 0.05).

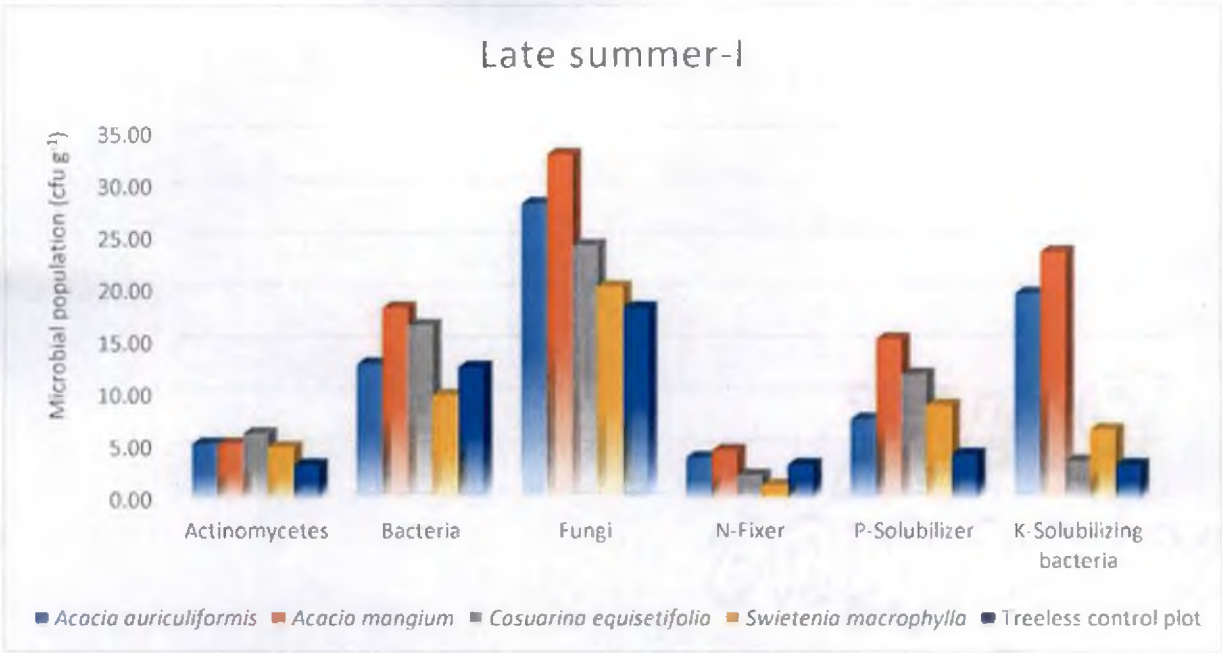


Figure 1. Microbial population under different exotic tree species during late summer-I (May, 2013).

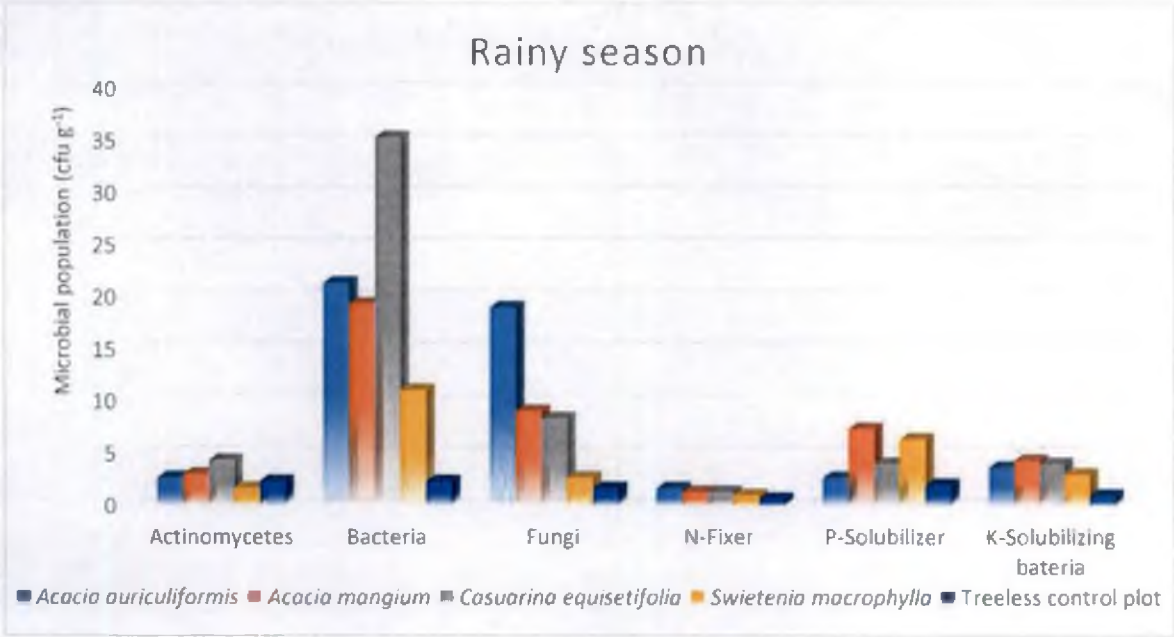


Figure 2. Microbial population under different exotic tree species during rainy season (August, 2013).

Note: Population of actinomycetes, bacteria, fungi, nitrogen fixing bacteria, phosphate solubilizing microorganism and KSB are $\times 10^{-3}$, $\times 10^{-4}$, $\times 10^{-2}$, $\times 10^{-2}$, $\times 10^{-3}$ and $\times 10^{-3}$ respectively.

It was found that tree species did not differ significantly with respect to the bacterial and fungal population. The bacterial population was highest in *A. mangium* plantation (18.33×10^4 cfu g^{-1}) and the lowest in *S. macrophylla* (10.00×10^4 cfu g^{-1}). However, *C. equisetifolia, A. auriculiformis,* treeless control plot and *S. macrophylla* were at par with *A. mangium.*

The fungal population was highest in *Acacia mangium* plantation (33.00×10^2 cfu g^{-1}) and lowest in treeless control plot (18.33×10^2 cfu g^{-1}). *A. mangium, A. auriculiformis, C. equisetifolia, S. macrophylla* and treeless control plot had a moderate fungal population.

The nitrogen fixing bacteria was highest in *Acacia mangium* plantation (4.67×10^2 cfu g^{-1}) followed by *A. auriculiformis*, treeless control plot and *C. equisetifolia.* It was lowest in *S. macrophylla* (1.33×10^2 cfu g^{-1}).

The population of phosphate solubilizing microorganism in all the plantations were significantly higher than treeless control plot. The population was highest in *Acacia mangium* plantation (15.33×10^3 cfu g^{-1}) and lowest in treeless treeless control plot (4.33×10^3 cfu g^{-1}).

Acacia mangium and *A. auriculiformis* had high potash solubilizing bacteria (KSB) and it was significantly higher from other plantations and treeless control plot. The population of KSB was highest under *Acacia mangium* (23.67×10^3 cfu g^{-1}) and lowest in treeless control plot (3.33×10^3 cfu g^{-1}).

Generally, all the beneficial microflora such as nitrogen fixing bacteria, phosphate solubilizing microorganism and potash solubilizing bacteria were highest in the *A. auriculiformis and A. mangium* compared to the *C. equisetifolia* and *S. macrophylla.*

4.2.1.2 Rainy season (August 2013)

The soil sample for second quarter collected in August 2013 showed that tree species had influence on microbial population (Table 4). The population of

Table 4. Microbial population under different exotic tree species during rainy season (August, 2013).

Treatment	Actinomycetes (x 10^3 cfu g^{-1})	Bacteria (x 10^4 cfu g^{-1})	Fungi (x 10^2 cfu g^{-1})	NFB (x 10^2 cfu g^{-1})	PSM (x 10^3 cfu g^{-1})	KSB (x 10^3 cfu g^{-1})
Acacia auriculiformis	2.67 (1.52)	21.33^{b} (3.21)	19.00^{a} (7.81)	1.67 (0.57)	2.67^{ab} (0.57)	3.67^{a} (0.57)
Acacia mangium	3.00 (2.64)	19.33^{bc} (7.57)	9.00^{b} (2.64)	1.33 (0.57)	7.33^{a} (5.03)	4.33^{a} (0.57)
Casuarina equisetifolia	4.33 (1.15)	35.33^{a} (8.32)	8.33^{b} (2.51)	1.33 (0.57)	4.00^{ab} (1.00)	4.00^{a} (1.00)
Swietenia macrophylla	1.67 (1.15)	11.00^{cd} (2.00)	2.67^{b} (1.52)	1.00 (1.00)	6.33^{ab} (1.15)	3.00^{a} (1.00)
Treeless control plot	2.33 (0.57)	2.33^{d} (1.52)	1.67^{b} (0.57)	0.67 (0.57)	2.00^{b} (1.00)	1.00^{b} (1.00)

NFB: Nitrogen Fixing Bacteria

PSM: Phosphate Solubilizing Microorganism

KSB: Potash Solubilizing Bacteria

Values in the parenthesis are mean ± standard deviation.

Values followed by same superscript in a column do not differ significantly (LSD, P, 0.05).

actinomycetes was highest in *Casuarina equisetifolia* (4.33×10^3 cfu g^{-1}) and lowest in *S. macrophylla* (1.67×10^3 cfu g^{-1}).

The bacterial population was significantly higher in plantations compared to treeless control plot. The bacterial population was highest in *C. equisetifolia* (35.33×10^4 cfu g^{-1}) followed by *A. auriculiformis* (21.22×10^4 cfu g^{-1}), *A. mangium* (19.33×10^4 cfu g^{-1}) and *S. macrophylla* (11.00×10^4 cfu g^{-1}). The bacterial population was lowest in treeless control plot (2.33×10^4 cfu g^{-1}).

Fungal population in *A. auriculiformis* plantation (19.00×10^2 was significantly higher than other treatments and it was least in treeless control plot (1.67×10^2 cfu g^{-1}).

The population of nitrogen fixing bacteria was highest in *A. auriculiformis* (1.67×10^2 cfu g^{-1}) followed by *A. mangium* (1.33×10^2 cfu g^{-1}) and *C. equisetifolia* (1.33×10^2 cfu g^{-1}). The nitrogen fixing bacteria population was lowest in treeless control plot (0.67×10^2 cfu g^{-1}).

Phosphate solubilizing microorganism population was significantly higher in *A. mangium* plantation (7.33×10^3 cfu g^{-1}) than treeless control plot (2.00×10^3 cfu g^{-1}). The phosphate solubilizing microorganism population in *A. mangium* was at par with *S. macrophylla*, *C. equisetifolia* and *A. auriculiformis.*

The population of KSB was significantly higher in plantations than treeless control plot. The KSB population recorded highest in *A. mangium* (4.33×10^3 cfu g^{-1}) and it was recorded lowest in treeless control plot (1.00×10^3 cfu g^{-1}).

4.2.1.3 Winter season (November 2013)

The results of third quarter sampling are given in Table 5. The population of actinomycetes in *S. macrophylla* was at par with *C. equisetifolia* and it was significantly higher than *A. auriculiformis*, *A. mangium* and treeless control plot. Actinomycetes was highest in *S. macrophylla* (11.67×10^3 cfu g^{-1}) and lowest in *A. mangium* (4.00×10^3 cfu g^{-1}).

Table 5. Microbial population under different exotic tree species during winter season (November, 2013).

Treatment	Actinomycetes (x 10^3 cfu g^{-1})	Bacteria (x 10^4 cfu g^{-1})	Fungi (x 10^2 cfu g^{-1})	NFB (x 10^2 cfu g^{-1})	PSM (x 10^3 cfu g^{-1})	KSB (x 10^3 cfu g^{-1})
Acacia auriculiformis	6.67^{bc} (2.08)	5.00 (1.00)	5.33^{a} (0.57)	3.33^{a} (1.52)	6.67^{b} (1.52)	1.00^{ab} (1.00)
Acacia mangium	4.00^{c} (1.00)	4.67 (0.57)	4.67^{a} (0.57)	1.33^{ab} (0.57)	14.00a (5.00)	1.67^{a} (0.57)
Casuarina equisetifolia	8.67^{ab} (0.57)	5.33 (4.93)	3.67^{b} (0.57)	3.00^{a} (1.73)	6.33^{b} (1.15)	0.67^{ab} (0.57)
Swietenia macrophylla	11.67^{a} (4.16)	8.67 (3.51)	3.00^{b} (0)	2.00^{ab} (0.00)	8.00^{b} (3.46)	1.67^{a} (0.57)
Treeless control plot	7.00^{bc} (1.00)	3.67 (0.57)	3.67^{b} (0.57)	0.33^{b} (0.57)	4.67^{b} (0.57)	0

NFB: Nitrogen Fixing Bacteria

PSM: Phosphate Solubilizing Microorganism

KSB: Potash Solubilizing Bacteria

Values in the parenthesis are mean ± standard deviation.

Values followed by same superscript in a column do not differ significantly (LSD, P, 0.05).

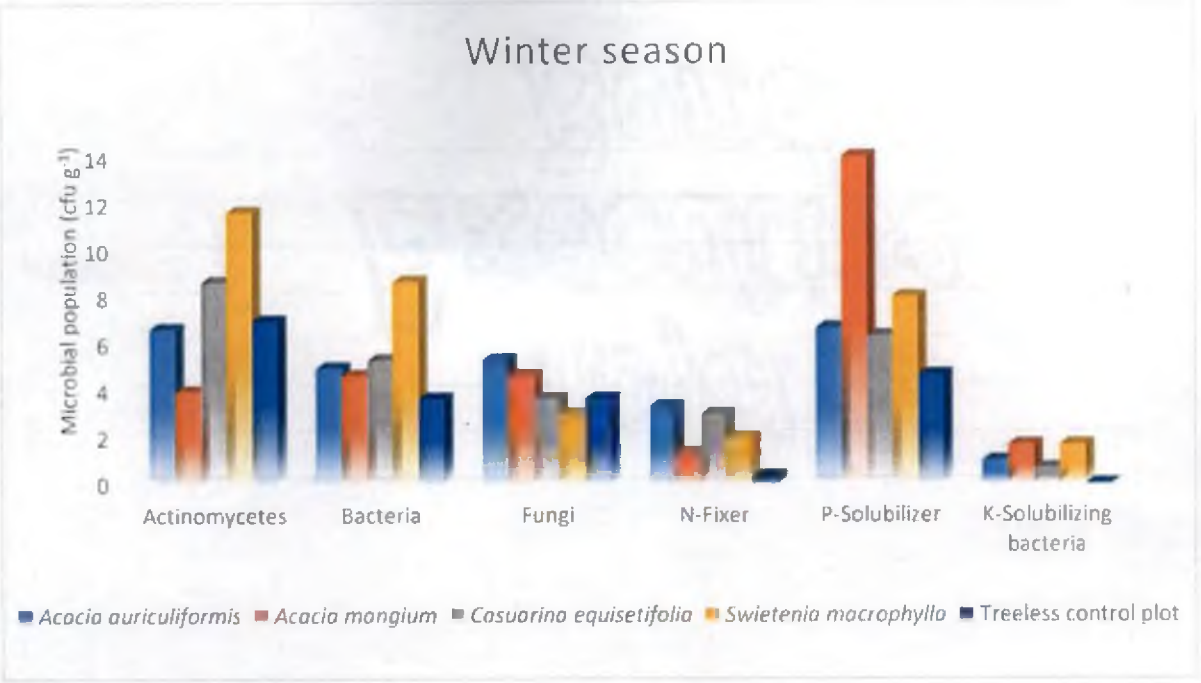


Figure 3. Microbial population under different exotic tree species during winter season (November, 2013).

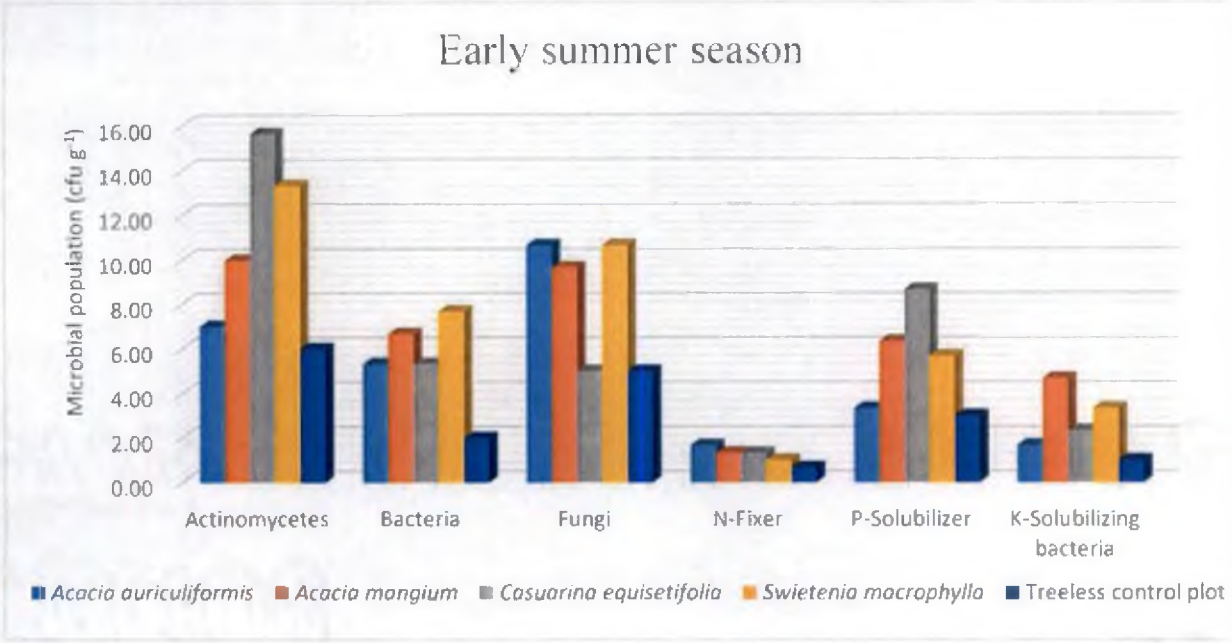


Figure 4. Microbial population under different exotic tree species during early summer season (February, 2014).

Note: Population of actinomycetes, bacteria, fungi, nitrogen fixing bacteria, phosphate solubilizing microorganism and KSB are $\times 10^{-3}$, $\times 10^{-4}$, $\times 10^{-2}$, $\times 10^{-2}$, $\times 10^{-3}$ and $\times 10^{-3}$ respectively.

The bacterial population was highest in *S. macrophylla* (8.67×10^4 cfu g^{-1}) which was on par with *A. auriculiformis*, *A. mangium* and treeless control plot. Bacterial population was lowest in treeless control plot (3.67×10^4 cfu g^{-1}).

The fungal population in *A. auriculiformis* and *A. mangium* were significantly higher than *C. equisetifolia*, treeless control plot and *S. macrophylla.* Fungal population was highest in *A. auriculiformis* (5.33×10^2 cfu g^{-1}) and was found lowest in *S. macrophylla* (3.00×10^2 cfu g^{-1}).

Nitrogen fixing bacteria was significantly higher in *A. auriculiformis* (3.33×10^2 cfu g^{-1}) and *C. equisetifolia* (3.00×10^2 cfu g^{-1}) than treeless control plot (0.33×12^3 cfu g^{-1}) and it was at par with *A. mangium* and *S. macrophylla.*

The population of phosphate solubilizing microorganism was significantly higher in *A. mangium* (14.00×10^3 cfu g^{-1}) when compared to all other treatments. Phosphate solubilizing microorganism was lowest in treeless control plot (4.67×10^3 cfu g^{-1}).

Potash solubilizing bacteria population was significantly higher in *A. mangium* (1.67×10^3 cfu g^{-1}) and *S. macrophylla* (1.67×10^3 cfu g^{-1}) compared to treeless control plot. The population of KSB in *A. mangium* and *S. macrophylla* were at par with *A. auriculiformis* and *C. equisetifolia.* KSB recorded lowest in treeless control plot.

4.2.1.4 Early summer season (February 2014)

Soil samples for fourth quarter were collected in the month of February 2014. The tree species had influence on the microbial population. Actinomycetes population was significantly higher in *C. equisetifolia* (15.67×10^3 cfu g^{-1}) and it was on par with *S. macrophylla* and *A. mangium.* Actinomycetes population in *A. auriculiformis* was at par with treeless control plot (6.00×10^3 cfu g^{-1}).

Bacterial population was recorded significantly higher in *S. macrophylla* (7.67×10^4 cfu g^{-1}) and *A. mangium* (6.67×10^4 cfu g^{-1}) compared to treeless control

Table 6. Microbial population under different exotic tree species during early summer season (February, 2014).

Treatment	Actinomycetes (x 10^3 cfu g^{-1})	Bacteria (x 10^4 cfu g^{-1})	Fungi (x 10^2 cfu g^{-1})	NFB (x 10^2 cfu g^{-1})	PSM (x 10^3 cfu g^{-1})	KSB (x 10^3 cfu g^{-1})
Acacia auriculiformis	7.00^{bc} (2.64)	5.33^{ab} (1.15)	10.67^{a} (3.51)	1.67 (0.57)	3.33^{b} (1.15)	1.67^{ab} (1.15)
Acacia mangium	10.00^{abc} (1.00)	6.67^{a} (1.15)	9.67^{ab} (3.21)	1.33 (0.57)	6.33^{ab} (2.08)	4.67^{a} (2.88)
Casuarina equisetifolia	15.67^{a} (6.65)	5.33^{ab} (2.08)	5.00^{b} (1.73)	1.33 (0.57)	8.67^{a} (3.05)	2.33^{ab} (0.57)
Swietenia macrophylla	13.33^{ab} (3.05)	7.67^{a} (2.88)	10.67^{a} (2.08)	1.00 (1.00)	5.67^{ab} (0.57)	3.33^{ab} (1.52)
Treeless control plot	6.00^{c} (2.64)	2.00^{b} (1.00)	5.00^{b} (3.00)	0.67 (0.57)	3.00^{b} (1.00)	1.00^{b} (1.00)

NFB: Nitrogen Fixing Bacteria

PSM: Phosphate Solubilizing Microorganism

KSB: Potash Solubilizing Bacteria

Values in the parenthesis are mean ± standard deviation.

Values followed by same superscript in a column do not differ significantly (LSD, P, 0.05).

plot. The population of bacteria in *A. mangium* and *S. macrophylla* was at par with *A. auriculiformis* and *C. equisetifolia.* Bacterial population was lowest in treeless control plot (2.00×10^4 cfu g^{-1}).

Fungal population recorded significantly higher in *S. macrophylla* (10.67×10^2 cfu g^{-1}) and *A. auriculiformis* (10.67×10^2 cfu g^{-1}) compared to *C. equisetifolia* and treeless control plot. Fungal population in *S. macrophylla* was at par with *A. auriculiformis* and *A. mangium*. Fungal population in *A. mangium* was at par with *C. equisetifolia* and treeless control plot and it was found lowest in treeless control plot 5.00×10^2 cfu g^{-1}).

There was no significantly difference between species with respect to the nitrogen fixing bacteria population. However highest nitrogen fixing bacteria population was found in *A. auriculiformis* plantation (1.67×10^2 cfu g^{-1}) and the lowest in treeless control plot (0.67×10^2 cfu g^{-1}).

Phosphate solubilizing microorganism population in *C. equisetifolia* (8.67×10^3 cfu g^{-1}) was significantly higher compared to *A. auriculiformis* and treeless control plot. Phosphate solubilizing microorganism population in *C. equisetifolia* was at par with *A. auriculiformis* and *S. macrophylla.* Phosphate solubilizing microorganism population in *S. macrophylla* was at par with *A. auriculiformis* and treeless control plot (3.00×10^3 cfu g^{-1}).

Potash solubilizing bacteria population recorded significantly higher in *A. mangium* (4.67×10^3 cfu g^{-1}) compared to treeless control plot. The population of KSB in *A. mangium* was at par with *S. macrophylla, C. equisetifolia* and *A. auriculiformis.* KSB recorded lowest in treeless control plot (1.00×10^3 cfu g^{-1}).

4.2.1.5 Late summer-II (May 2014)

The results of the soil samples for fifth quarter were collected in the month of May 2014 are presented in Table 7. It was found that plantations had significant influence on microbial population. The population of actinomycetes in *S.*

macrophylla and *C. equisetifolia* recorded significantly higher than *A. mangium* and treeless control plot. Actinomycetes population in *A. auriculiformis* was at par with treeless control plot.

Bacterial population in *A. auriculiformis* (35.67×10^4 cfu g^{-1}) was recorded significantly higher than all other treatment. Bacterial population in *S. macrophylla* was at par with *C. equisetifolia*, *A. mangium* and treeless control plot. Treeless control plot (6.67×10^4 cfu g^{-1}) was found to have lowest bacterial population.

Fungal population in *A. auriculiformis* (15.33×10^2 cfu g^{-1}), *A. mangium* and *C. equisetifolia* were recorded significantly higher than treeless control plot and it was at par with *S. macrophylla.* Fungal population in *S. macrophylla* was at par with treeless control plot (10.00×10^2 cfu g^{-1}).

There was no significant difference in nitrogen fixing bacteria population between the tree species. Nitrogen fixing bacteria population was found highest in *A. auriculiformis* and *S. macrophylla* plantation (1.67×10^2 cfu g^{-1}) and was found lowest in treeless control plot (0.33×10^2 cfu g^{-1}).

Phosphate solubilizing microorganism population was significantly higher in *A. auriculiformis* (8.00×10^3 cfu g^{-1}) than *S. macrophylla* and treeless control plot. The Phosphate solubilizing microorganism population in *A. auriculiformis* was at par with *C. equisetifolia* and *A. mangium*. The phosphate solubilizing microorganism population was lowest in treeless control plot (3.67×10^3 cfu g^{-1}).

The population of KSB was recorded significantly higher in *A. auriculiformis* (2.67×10^3 cfu g^{-1}) than *C. equisetifolia* and treeless control plot. Potash solubilizing bacteria population in *A. auriculiformis* was at par with *A. mangium* and *S. macrophylla.* The lowest KSB population was recorded in treeless control plot (0.67×10^3 cfu g^{-1}).

Table 7. Microbial population under different exotic tree species during late summer-II (May, 2014).

Treatment	Actinomycetes (x 10^3 cfu g^{-1})	Bacteria (x 10^4 cfu g^{-1})	Fungi (x 10^2 cfu g^{-1})	NFB (x 10^2 cfu g^{-1})	PSM (x 10^3 cfu g^{-1})	KSB (x 10^3 cfu g^{-1})
Acacia auriculiformis	10.00^{ab} (1.73)	35.67^{a} (4.16)	15.33^{a} (3.51)	0.67 (0.57)	8.00^{a} (2.64)	2.67^{a} (0.57)
Acacia mangium	6.33^{c} (1.52)	15.33^{b} (2.30)	14.67^{a} (1.52)	0.33 (0.57)	4.67^{ab} (2.08)	2.00^{ab} (0)
Casuarina equisetifolia	11.67^{a} (2.08)	17.00^{b} (3.60)	14.67^{a} (2.08)	0.33 (0.57)	5.67^{ab} (2.08)	1.33^{bc} (0.57)
Swietenia macrophylla	12.00^{a} (2.00)	18.00^{b} (2.64)	12.33^{ab} (1.15)	0.67 (0.57)	4.00^{b} (1.00)	1.67^{abc} (1.15)
Treeless control plot	8.00^{bc} (1.00)	6.67^{b} (3.21)	10.00^{b} (2.00)	0.33 (0.57)	3.67^{b} (0.57)	0.67^{c} (0.57)

NFB: Nitrogen Fixing Bacteria

PSM: Phosphate Solubilizing Microorganism

KSB: Potash Solubilizing Bacteria

Values in the parenthesis are mean ± standard deviation.

Values followed by same superscript in a column do not differ significantly (LSD, P, 0.05).

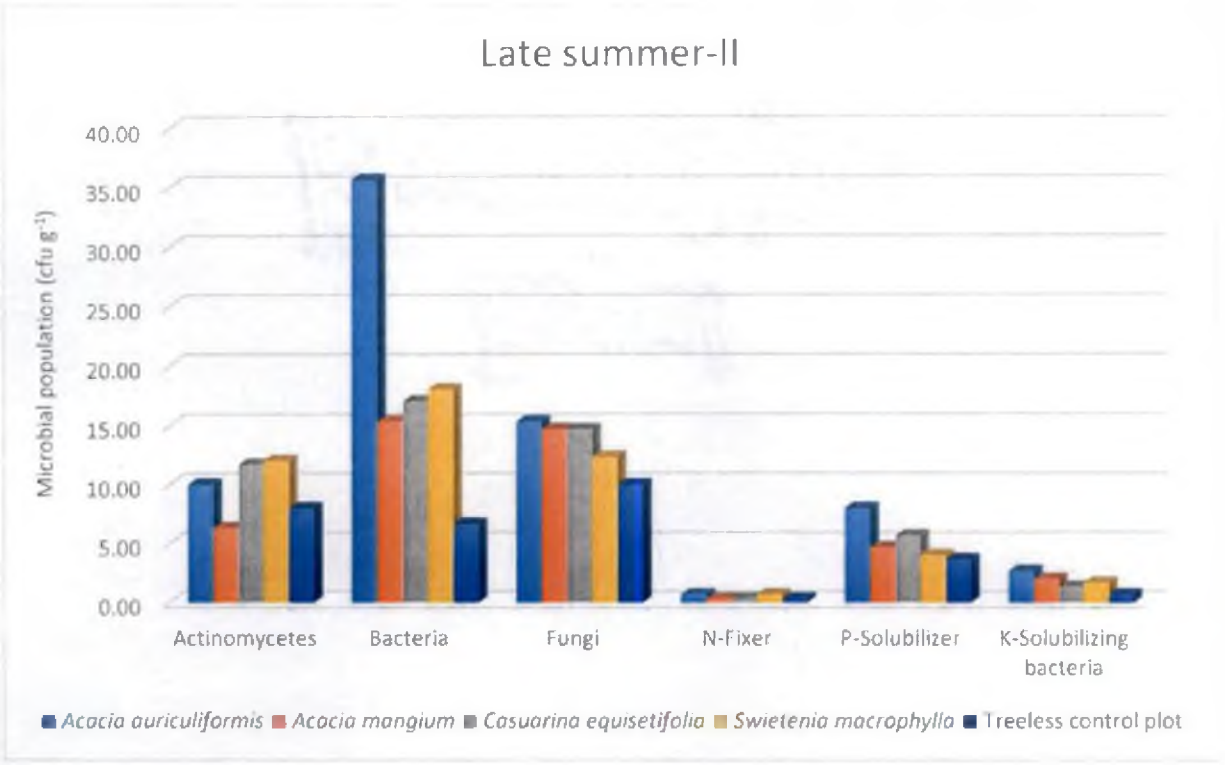


Figure 5. Microbial population under different exotic tree species during late summer-II (May, 2014).

Note: Population of actinomycetes, bacteria, fungi, nitrogen fixing bacteria, phosphate solubilizing microorganism and KSB are $\times 10^{-3}$, $\times 10^{-4}$, $\times 10^{-2}$, $\times 10^{-2}$, $\times 10^{-3}$ and $\times 10^{-3}$ respectively.

4.2.2 Seasonal changes in microbial population of soil under different exotic forest tree species

Soil sample for analysing microbial population was collected quarterly for one year period. Initial sample and then samples in rainy season, winter season, early summer season and late summer-II were collected in the month of May-2013, August-2013, November-2013, February-2014 and May-2014 respectively.

4.2.2.1 Seasonal changes in actinomycetes population of soil

Seasonal changes in actinomycetes population of soil is presented in Table 8. It is revealed that actinomycetes population in *A. auriculiformis* was highest in late summer-II (10.0×10^3 cfu g^{-1}) followed by early summer season, winter season, late summer-I and lowest in rainy season (2.67×10^3 cfu g^{-1}). Actinomycetes in *A.*

Table 8. Seasonal changes in actinomycetes population (× 10^3 cfu g^{-1}) of soil under different exotic tree species.

Treatment	Late summer-I	Rainy season	Winter season	Summer season	Late summer-II	Mean (over 12 months)
Acacia auriculiformis	5.33	2.67	6.67	7.00	10.00	6.33
Acacia mangium	5.33	3.00	4.00	10.00	6.33	5.73
Casuarina equisetifolia	6.33	4.33	8.67	15.67	11.67	9.33
Swietenia macrophylla	5.00	1.67	11.67	13.33	12.00	8.73
Treeless control plot	3.33	2.33	7.00	6.00	8.00	5.33

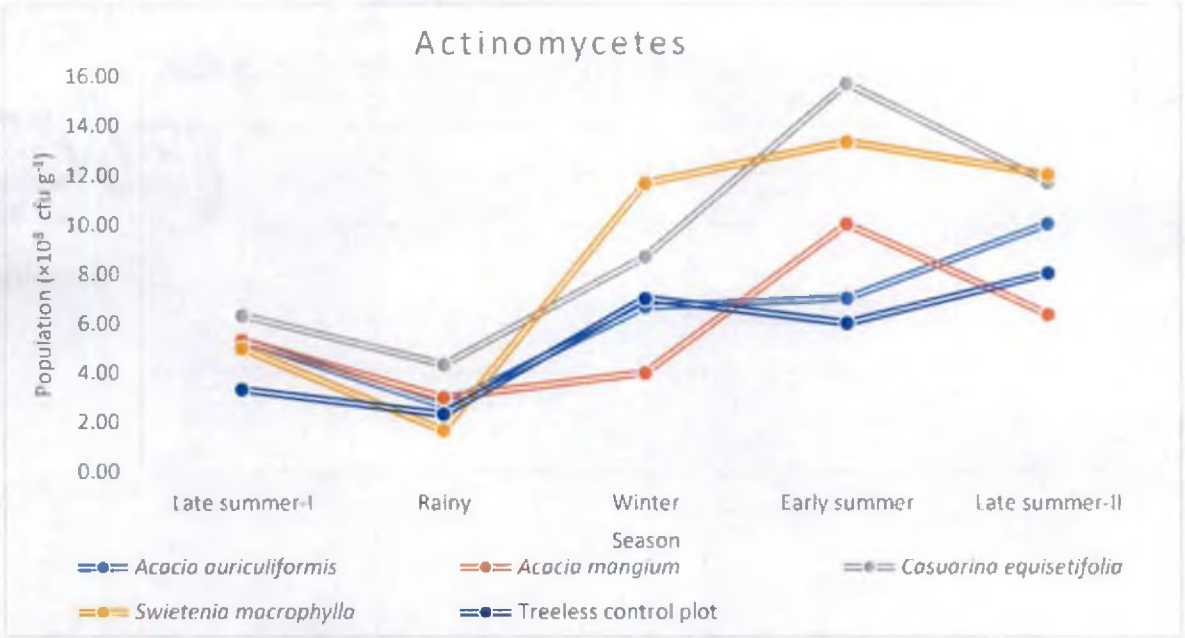


Figure 6. Seasonal changes in actinomycetes population of soil under different exotic tree species.

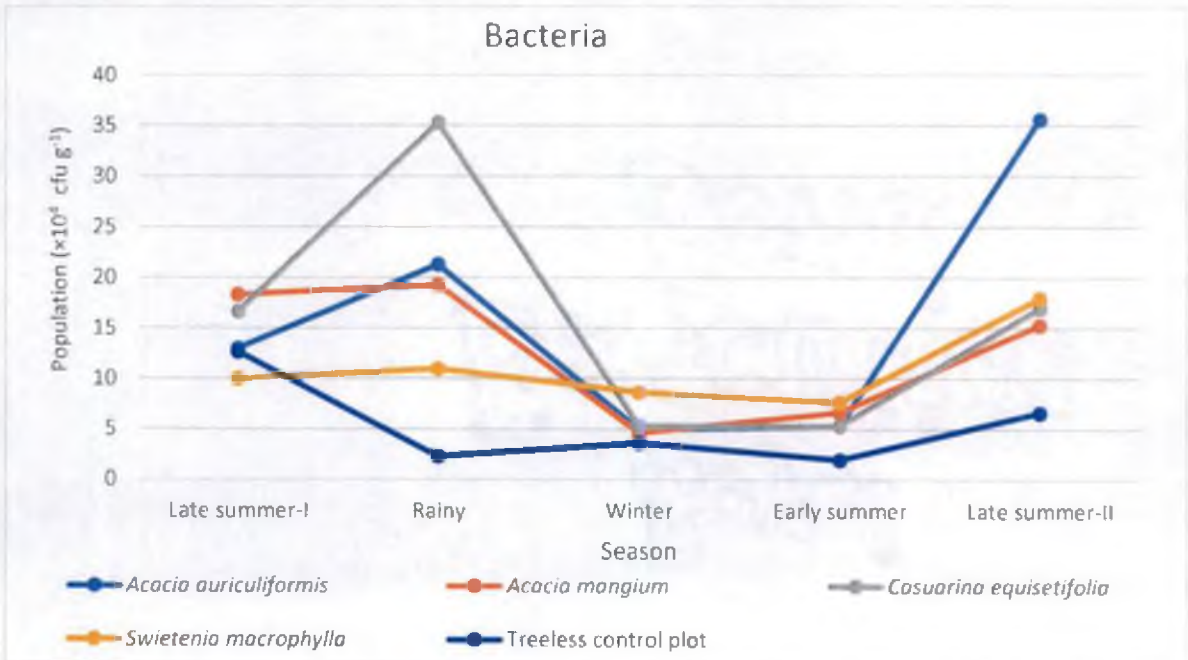
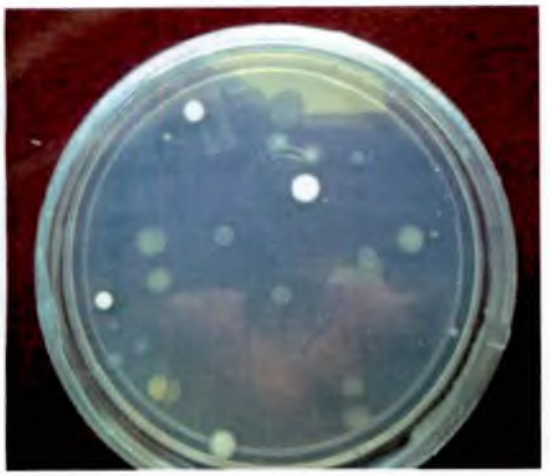
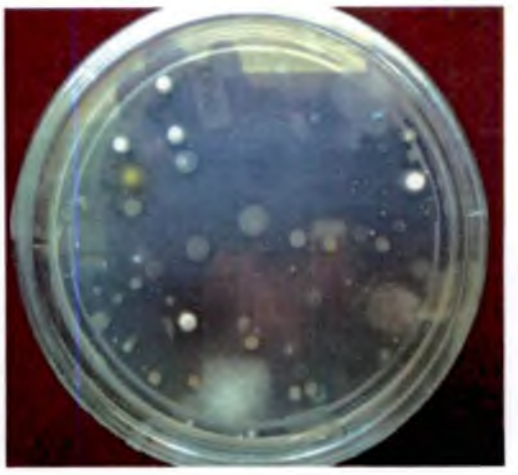


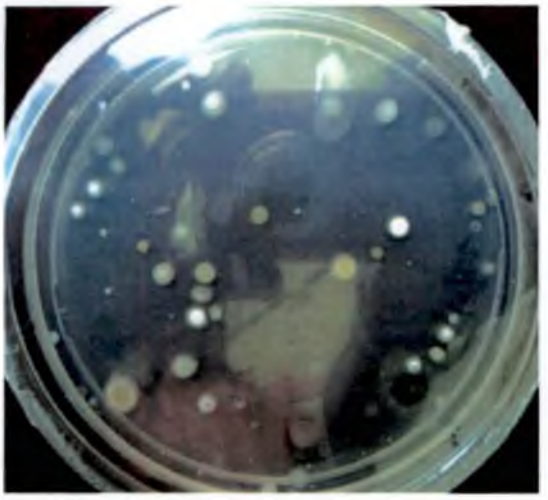
Figure 7. Seasonal changes in bacteria population of soil under different exotic tree species.



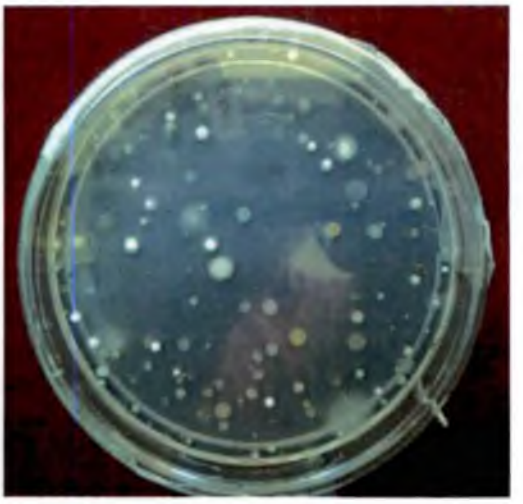
Acacia auriculiformis



Acacia mangium



Casuarina equisetifolia



Swietenia macrophylla

Plate 1. Actinomycetes in different exotic tree species.

mangium was highest in early summer season (10.00×10^3 cfu g^{-1}), followed by late summer-II, late summer-I and winter season and lowest in rainy season (3.00×10^3 cfu g^{-1}). Actinomycetes in *C. equisetifolia* and *S. macrophylla* were highest in late summer-II (11.67×10^3 cfu g^{-1} and 12.00×10^3 cfu g^{-1} respectively), followed by early summer season, winter season and late summer-I and lowest in rainy season (4.33×10^3 cfu g^{-1} and 1.67×10^3 cfu g^{-1} respectively). In treeless control plot it was highest in late summer-II (8.00×10^3 cfu g^{-1}), followed by winter season, early summer season and late summer-I and lowest in rainy season (2.33×10^3 cfu g^{-1}).

Generally actinomycetes population was the lowest during rainy season. The actinomycetes population was found to increase gradually after the rainy season and it is at its peak population during early summer season (Fig. 6) and late summer-II.

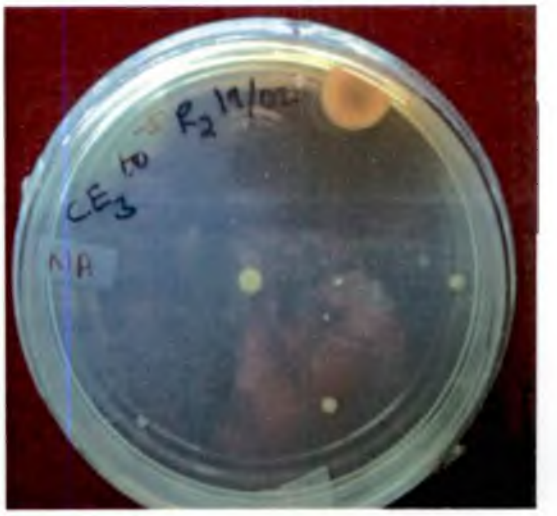
4.2.2.2 Seasonal changes in bacterial population of soil

Seasonal changes in bacterial population of soil is presented in Table 9. Bacterial population in *A. auriculiformis* was highest in late summer-II (35.67×10^4 cfu g^{-1}), followed by rainy season, late summer-I, early summer season and lowest in third sample (5.00×10^4 cfu g^{-1}). *A. mangium* was having highest number of bacterial population in rainy season (19.33×10^4 cfu g^{-1}), followed by late summer-I, late summer-II, early summer season and lowest was in sample third (4.67×10^4 cfu g^{-1}). In *C. equisetifolia* bacterial population was highest in rainy season (35.33×10^4 cfu g^{-1}), followed by five sample, late summer-I and it was lowest in third and fourth sample. Bacterial population was same in winter season and early summer season (5.33×10^4 cfu g^{-1}). In *S. macrophylla* bacterial population was highest in late summer-II (18.00×10^4 cfu g^{-1}), followed by rainy season, late summer-I, winter season and lowest in early summer season (7.67×10^4 cfu g^{-1}). In treeless control plot it was highest in late summer-I (12.67×10^4 cfu g^{-1}), followed by late summer-II, winter season, rainy season and it was lowest in early summer season (2.00×10^4 cfu g^{-1}).

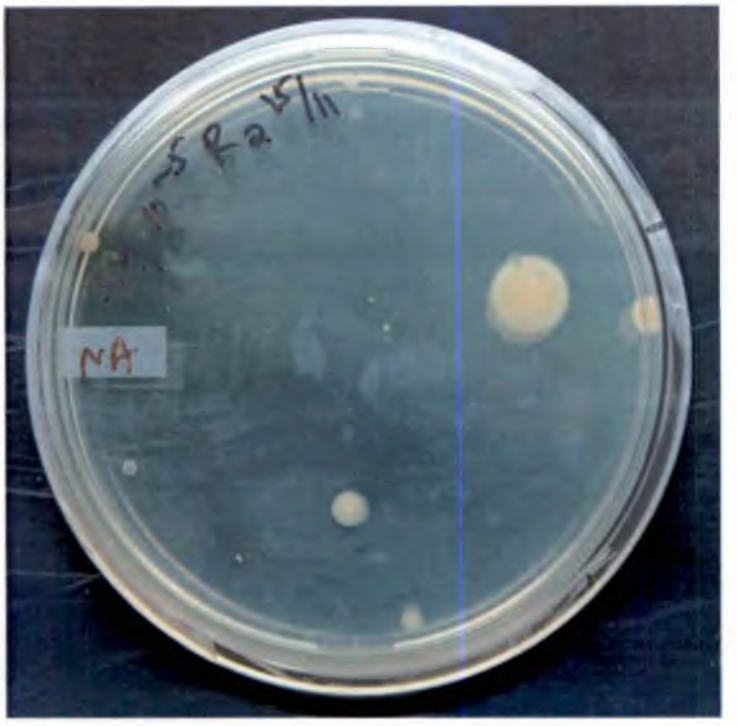
Table 9. Seasonal changes in bacteria ($\times 10^4$ cfu g^{-1}) population of soil under different exotic tree species.

Treatment	Late summer-I	Rainy season	Winter season	Summer season	Late summer-II	Mean (over 12 months)
Acacia auriculiformis	13	21.33	5	5.33	35.67	16.06
Acacia mangium	18.33	19.33	4.67	6.67	15.33	12.86
Casuarina equisetifolia	16.67	35.33	5.33	5.33	17.00	15.93
Swietenia macrophylla	10	11.00	8.67	7.67	18.00	11.06
Treeless control plot	12.67	2.33	3.67	2	6.67	5.46

Acacia auriculiformis



Casuarina equisetifolia



Swietenia macrophylla

Plate 2. Bacteria in different exotic tree species.

A general trend was found in bacterial population. Bacterial population was the maximum during rainy season. After monsoon, it was decreased in winter season and was the lowest in early summer season. During late summer, it was found to increase again towards the next rainy season.

4.2.2.3 Seasonal changes in fungal population of soil

The data presented in Table 10 reveal that fungal population in *A. auriculiformis* was highest in late summer-I (28.33×10^2 cfu g^{-1}), followed by rainy season, late summer-II, early summer season and lowest in winter season (5.33×10^2 cfu g^{-1}). In *A. mangium* fungal population was highest in late summer-I (33.00×10^2 cfu g^{-1}), followed by late summer-II, early summer season, rainy season and lowest in winter season (9.67×10^2 cfu g^{-1}). In *C. equisetifolia* it was highest in late summer-I (24.33×10^2 cfu g^{-1}), followed by late summer-II, rainy season, early summer season and lowest in winter season (3.67×10^2 cfu g^{-1}). *S. macrophylla* and treeless control plot shows same effect on fungal population it was highest in late summer-I (20.33×10^2 cfu g^{-1} and 18.33×10^2 cfu g^{-1} respectively), followed by late summer-II, early summer season, winter season and lowest in rainy season (2.67×10^2 cfu g^{-1} and 1.67×10^2 cfu g^{-1} respectively).

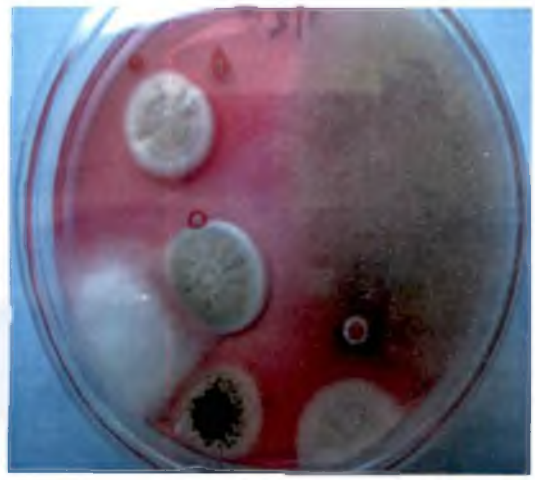
Generally fungal population decreased after late summer-I but after winter season again, it increased. It was found that fungal population was more in late summer-I and late summer-II in all treatments and it was the lowest in the winter season.

4.2.2.4 Seasonal changes in nitrogen fixing bacteria population of soil

As shown in Table 11, *A. auriculiformis* was found to have highest number of nitrogen fixing bacteria population in late summer-I (4.00×10^2 cfu g^{-1}), followed by rainy season. It was same in rainy season and early summer season. Lowest population was found in late summer-II (0.67×10^2 cfu g^{-1}). In *A. mangium* it was highest in late summer-I (4.67×10^2 cfu g^{-1}), it was same in rainy season, three and four and it was found lowest in late summer-II (0.33×10^2 cfu g^{-1}). *C. equisetifolia*

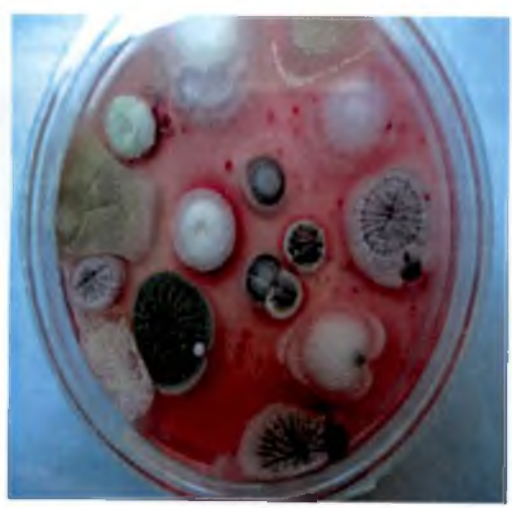
Table 10. Seasonal changes in fungi ($\times 10^2$ cfu g^{-1}) population of soil under different exotic tree species.

Treatment	Late summer-I	Rainy season	Winter season	Summer season	Late summer-II	Mean (over 12 months)
Acacia auriculiformis	28.33	19.00	5.33	10.67	15.33	15.73
Acacia mangium	33.00	9.00	4.67	9.67	14.67	14.20
Casuarina equisetifolia	24.33	8.33	3.67	5	14.67	11.20
Swietenia macrophylla	20.33	2.67	3	10.67	12.33	9.80
Treeless control plot	18.33	1.67	3.67	5	10.00	7.73



Acacia auriculiformis

Casuarina equisetifolia



Swietenia macrophylla

Treeless plot

Plate 3. Fungi in different exotic tree species.

Table 11. Seasonal changes in nitrogen fixing bacteria ($\times 10^2$ cfu g^{-1}) population of soil under different exotic tree species.

Treatment	Late summer-I	Rainy season	Winter season	Summer season	Late summer-II	Mean (over 12 months)
Acacia auriculiformis	4.00	1.67	3.33	1.67	0.67	2.26
Acacia mangium	4.67	1.33	1.33	1.33	0.33	1.79
Casuarina equisetifolia	2.33	1.33	3.00	1.33	0.33	1.66
Swietenia macrophylla	1.33	1.00	2.00	1.00	0.67	1.20
Treeless control plot	3.33	0.67	0.33	0.67	0.33	1.06

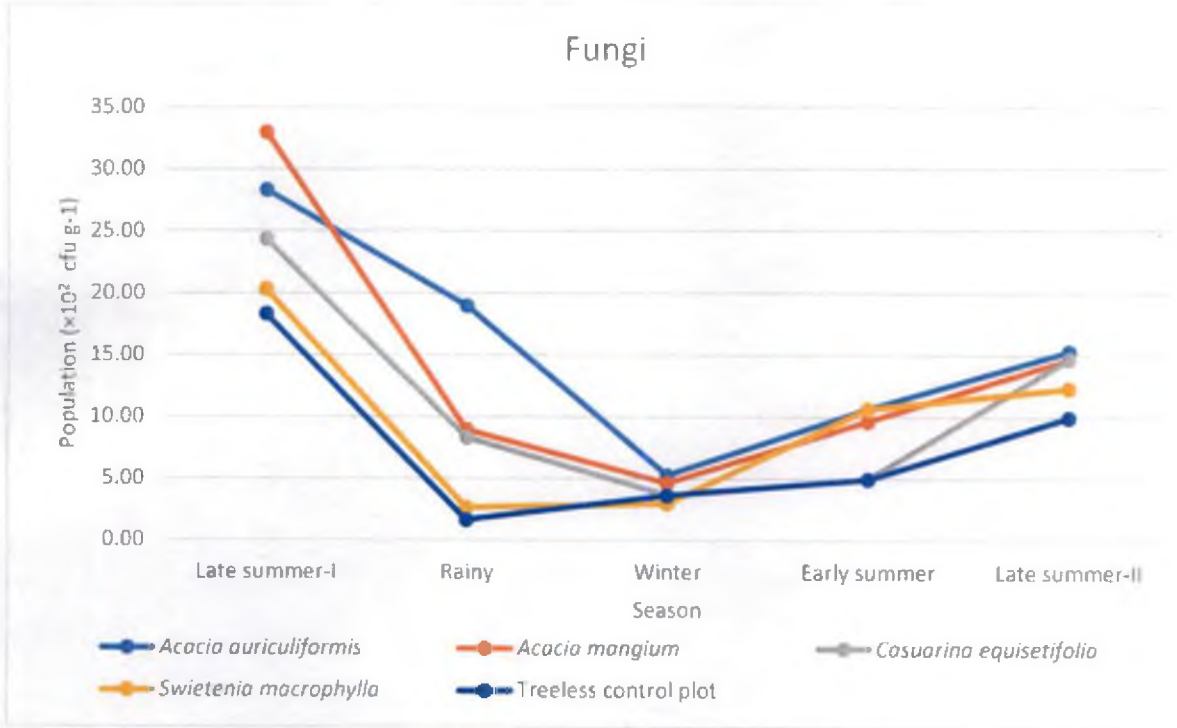


Figure 8. Seasonal changes in fungi population of soil under different exotic tree species.

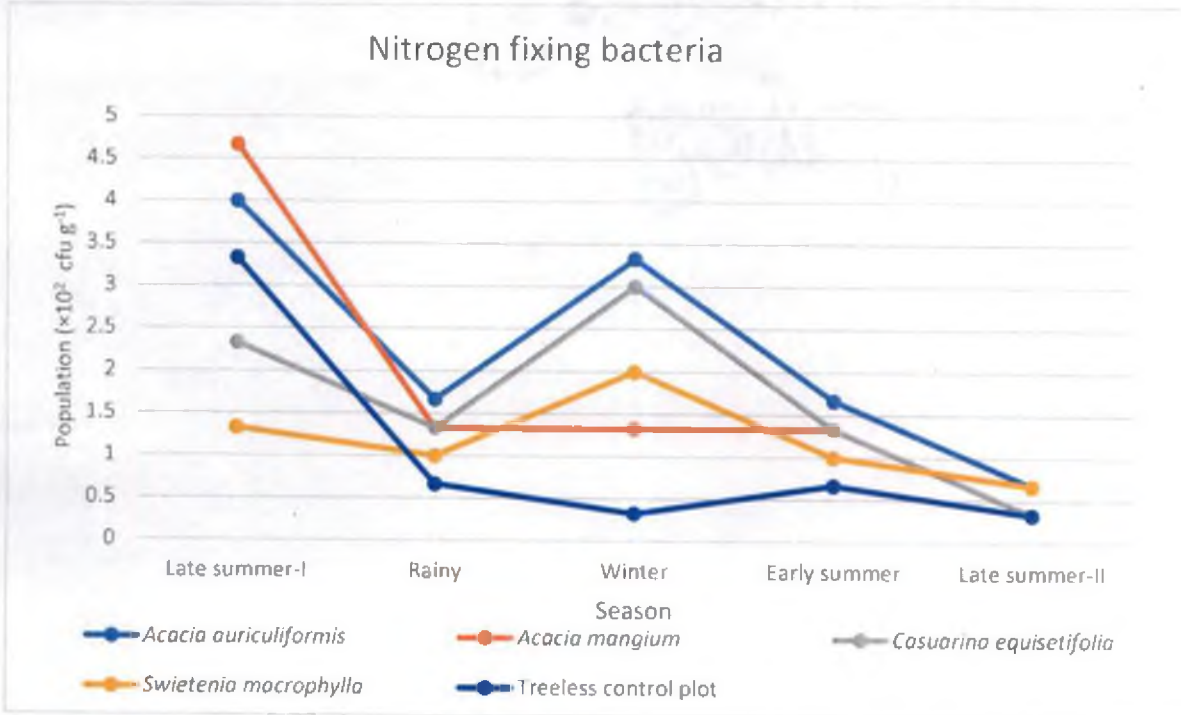
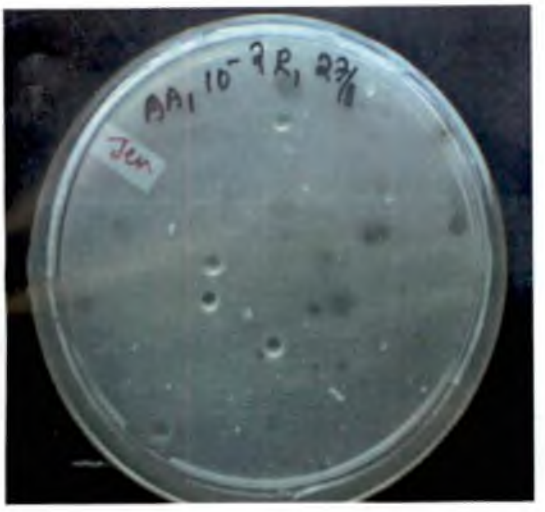
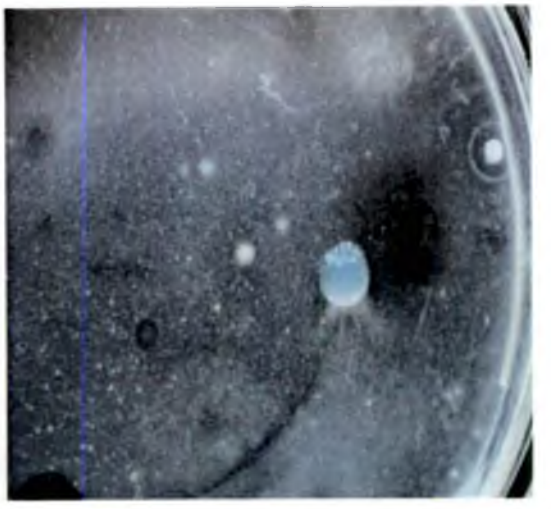


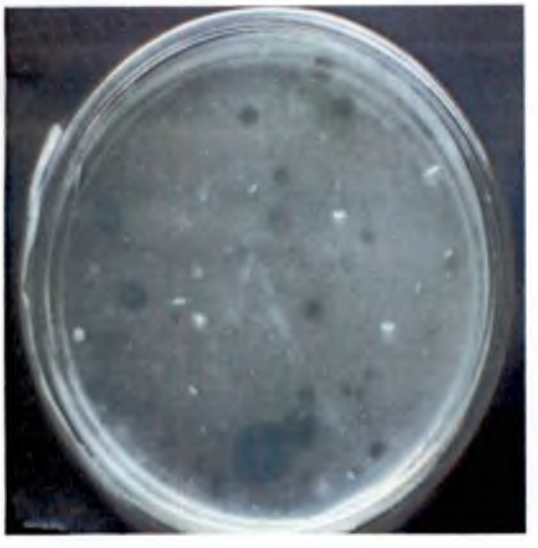
Figure 9. Seasonal changes in nitrogen fixing bacteria population of soil under different exotic tree species.



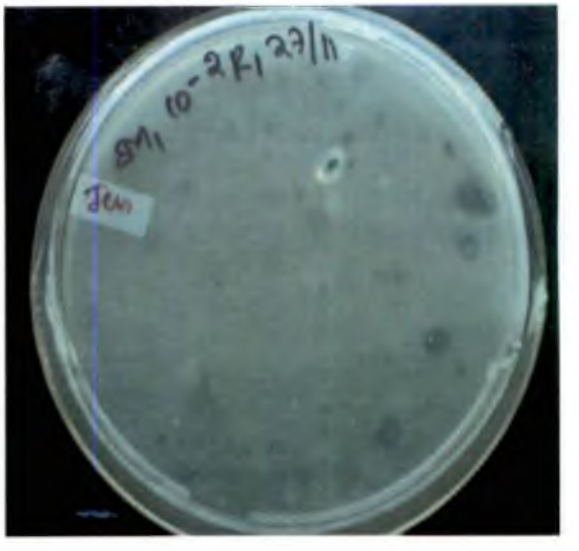
Acacia auriculiformis



Acacia mangium



Casuarina equisetifolia



Swietenia macrophylla

Plate 4. Nitrogen fixing bacteria in different exotic tree species.

and *S. macrophylla* were found to have same pattern in all seasons. In *C. equisetifolia* and *S. macrophylla* were highest in winter season (3.00×10^2 cfu g^{-1} and 2.00×10^2 cfu g^{-1} respectively), followed by late summer-I, it was same in rainy season and early summer season and lowest population was in late summer-II (0.33×10^2 cfu g^{-1} and 0.67×10^2 cfu g^{-1} respectively). In treeless control plot it was highest in late summer-I (3.33×10^2 cfu g^{-1}), it was same in rainy season and early summer season and lowest in winter season and late summer-II which were having same number of population (0.33×10^2 cfu g^{-1}).

Generally, the nitrogen fixing bacteria population decreased in rainy season and again increased in winter season and then decreased slightly through the early summer season and late summer-II. Nitrogen fixing bacteria population was generally lowest in late summer-II. Nitrogen fixing bacteria population in *A. auriculiformis*, *A. mangium* and treeless control plot were highest in late summer-I but in *C. equisetifolia* and *S. macrophylla* it was highest in winter season.

4.2.2.5 Seasonal changes in phosphate solubilizer population of soil

From Table 12 it was revealed that *A. auriculiformis* was found to have highest number of phosphate solubilizer population in late summer-II (8.00×10^3 cfu g^{-1}), followed by late summer-I, winter season, early summer season and lowest in rainy season (2.67×10^3 cfu g^{-1}). *A. mangium* and *S. macrophylla* were found to have same pattern in all season. It was highest in late summer-I (15.33×10^3 cfu g^{-1} and 9.0×10^3 cfu g^{-1} respectively), followed by winter season, rainy season, early summer season and lowest in late summer-II (4.67×10^3 cfu g^{-1} and 4.00×10^3 cfu g^{-1} respectively). In *C. equisetifolia,* it was highest in late summer-I (12.00×10^3 cfu g^{-1}), followed by early summer season, winter season, late summer-II and lowest in rainy season (4.00×10^3 cfu g^{-1}). In treeless control plot it was highest in winter season (4.67×10^3 cfu g^{-1}), followed by late summer-I, late summer-II, early summer season and lowest in rainy season (2.00×10^3 cfu g^{-1}).

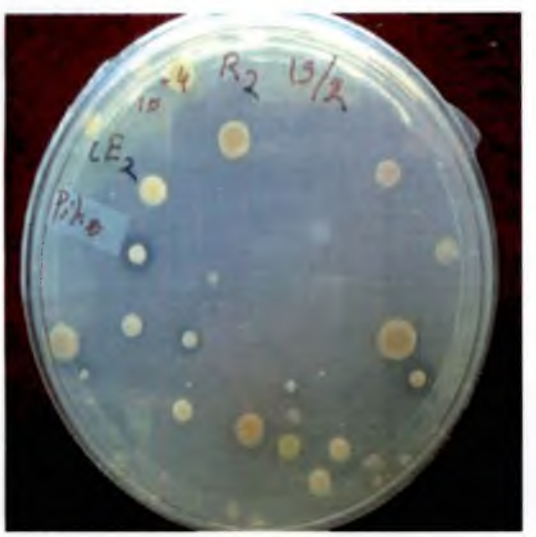
Phosphate solubilizer population in *A. mangium*, *C. equisetifolia* and *S. macrophylla* were highest in late summer-I but in *A. auriculiformis* and treeless

Table 12. Seasonal changes in phosphate solubilizer ($\times 10^3$ cfu g^{-1}) population of soil under different exotic tree species.

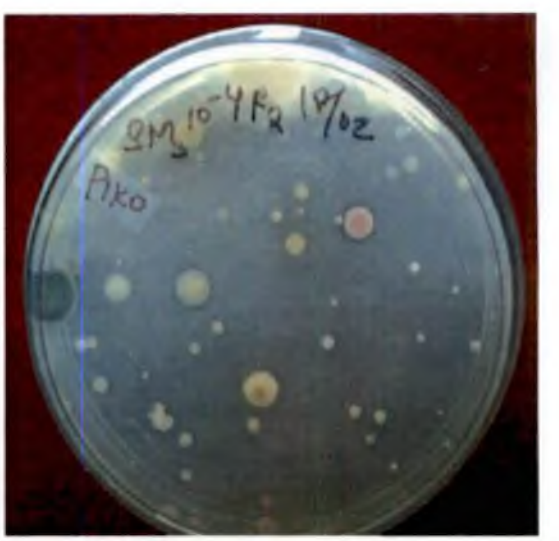
Treatment	Late summer-I	Rainy season	Winter season	Summer season	Late summer-II	Mean (over 12 months)
Acacia auriculiformis	7.66	2.67	6.67	3.33	8.00	5.66
Acacia mangium	15.33	7.33	14.00	6.33	4.67	9.53
Casuarina equisetifolia	12.00	4.00	6.33	8.67	5.67	7.33
Swietenia macrophylla	9.00	6.33	8.00	5.67	4.00	6.60
Treeless control plot	4.33	2.00	4.67	3.00	3.67	3.53

Acacia auriculiformis

Acacia mangium



Casuarina equisetifolia



Swietenia macrophylla

Plate 5. Phosphate solubilizing microorganism in different exotic tree species.

control plot it was highest in late summer-II and winter season respectively. *A. mangium* and *S. macrophylla* shows lowest population in late summer-II and *A. auriculiformis*, *C. equisetifolia* and treeless control plot shows in rainy season.

Among the beneficial microflora, phosphate solubilizing microorganism was found to be least responding (Fig. 10) to the seasonal changes except for a reduction from late summer-I to the rainy season.

4.2.2.6 Seasonal changes in potash solubilizing bacteria population of soil

As shown in Table 13, it was found that KSB population in *A. auriculiformis* was highest in late summer-I (19.67×10^3 cfu g^{-1}), followed by rainy season, late summer-II, early summer season and lowest in winter season (1.00×10^3 cfu g^{-1}). In *A. mangium* it was highest in late summer-I (23.67×10^3 cfu g^{-1}), followed by early summer season, rainy season, late summer-II and lowest in winter season (1.67×10^3 cfu g^{-1}). In *C. equisetifolia* it was highest in rainy season (4.00×10^3 cfu g^{-1}), followed by late summer-I, early summer season, late summer-II and lowest in winter season (0.67×10^3 cfu g^{-1}). In *S. macrophylla* it was highest in late summer-I (6.67×10^3 cfu g^{-1}), followed by early summer season, rainy season and lowest was in winter season and late summer-II which were having same number of KSB (1.67×10^3 cfu g^{-1}). In treeless control plot it was highest in late summer-I (3.33×10^3 cfu g^{-1}), followed by rainy season, early summer season, late summer-II and KSB was not found in winter season.

Generally, it was found that potash solubilizing bacterial population was high in late summer-I, it was maximum in *A. auriculiformis* and *A. mangium*. Than it was decreased and it was found lowest in the winter season in all species. Again it increased in early summer season.

4.3 Tree growth observations

Tree growth observations were recorded for a base reference of plots where the study is carried out before starting the study.

Table 13. Seasonal changes in potash solubilizing bacteria ($\times 10^3$ cfu g^{-1}) population of soil under different exotic tree species.

Treatments	Late summer-I	Rainy	Winter	Early summer	Late summer-II	Mean (over 12 months)
Acacia auriculiformis	19.67	3.67	1.00	1.67	2.67	5.73
Acacia mangium	23.67	4.33	1.67	4.67	2.00	7.26
Casuarina equisetifolia	3.67	4.00	0.67	2.33	1.33	2.40
Swietenia macrophylla	6.67	3.00	1.67	3.33	1.67	3.26
Treeless control plot	3.33	1.00	0	1.00	0.67	1.20

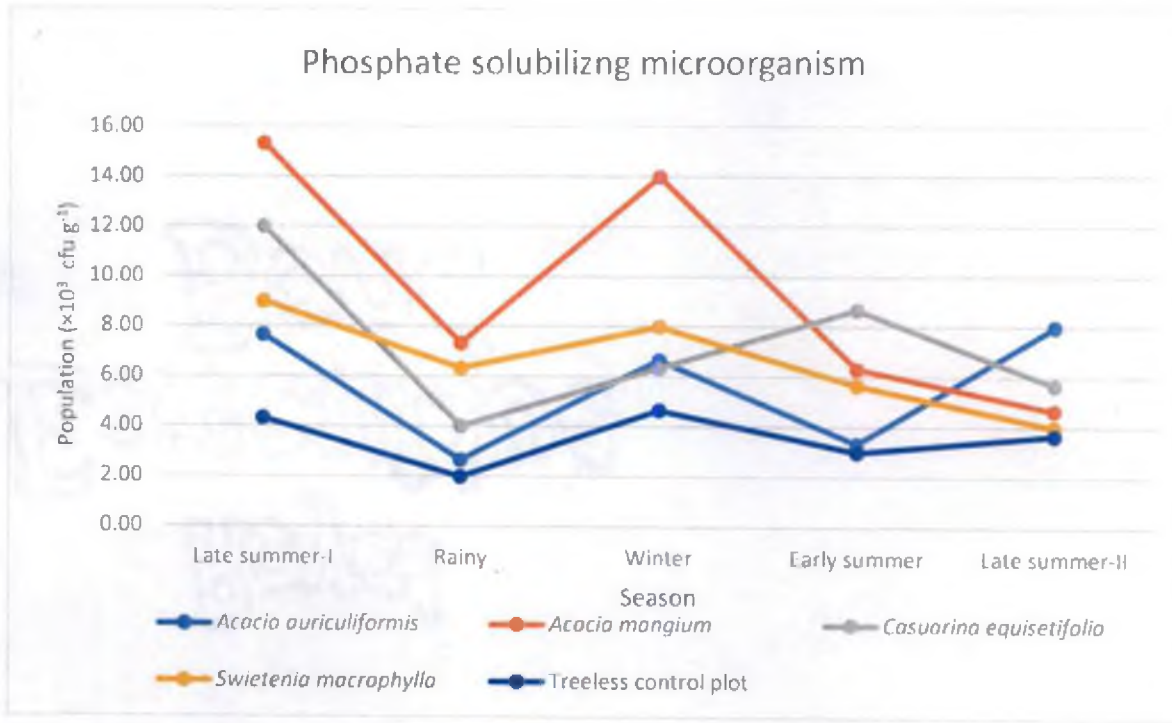


Figure 10. Seasonal changes in phosphate solubilizing microorganism population of soil under different exotic tree species.

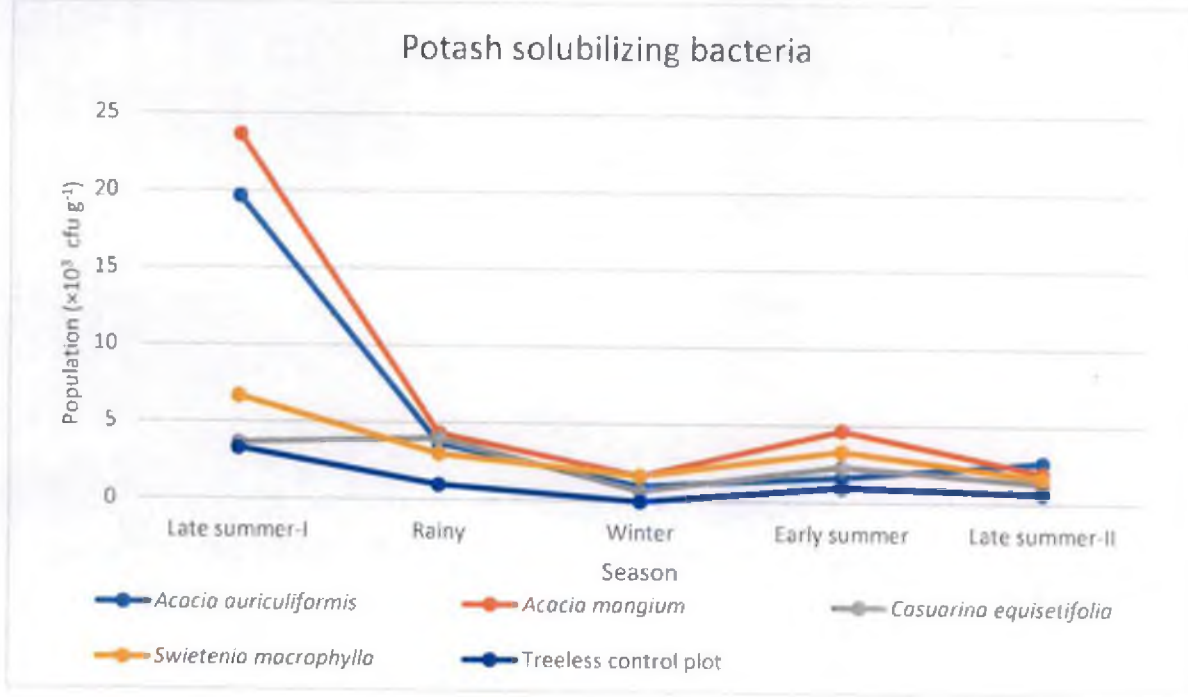


Figure 11. Seasonal changes in potash solubilizing bacteria population of soil under different exotic tree species.

Acacia auriculiformis

Acacia mangium

Casuarina equisetifolia

Swietenia macrophylla

Plate 6. Potassium solubilizing bacteria in different exotic tree species.

The results are presented in Table 14.

Table 14. Mean tree growth characteristics of different exotic tree species at Nilambur, Kerala.

Species	May, 2013		May, 2014	
	Total height (m)	DBH (cm)	Total height (m)	DBH (cm)
Acacia auriculiformis	18.00[ab]	20.61	18.06[ab]	20.67
Acacia mangium	19.90[a]	24.31	19.99[a]	24.40
Casuarina equisetifolia	19.50[a]	19.42	19.52[a]	19.48
Swietenia macrophylla	15.53[b]	21.51	15.70[b]	21.57

Values followed by same superscript in a column do not differ significantly (P, 0.05).

The results revealed that mean tree height of *A. mangium* and *C. equisetifolia* was significantly larger than *S. macrophylla.* Mean tree height was largest in *A. mangium* (19.90 m) and lowest in *S. macrophylla* (15.53 m). However, *C. equisetifolia* and *A. auriculiformis* were at par with *A. mangium* and *A. auriculiformis* was at par with *S. macrophylla.* The highest mean DBH was found in *A. mangium* (24.31 cm) and lowest in *C. equisetifolia* (19.42 cm). However, the mean DBH of *A. mangium* was at par at with *A. auriculiformis*, *S. macrophylla* and *C. equisetifolia.* The same trend was retained at the end of the experiment i.e. after one year.

Discussion

DISCUSSION

Exotic forest tree species in the recent years have achieved wide acceptance in the plantation programmes in Kerala, owing to their multi-purpose and fast growing nature. As invasive species these species have might some effect on soil habitat and it is the basic requisite and very much important to examine the soil productivity changes under exotic forest tree species. The present study was undertaken to study the soil productivity changes with special reference to beneficial microflora. The tree plots showed a structurally better physico-chemical properties as well as a rich microfloral population compared to the contiguous treeless control plot. Thus the selection of suitable exotic species is very important not only to obtain the high yield but also to maintain soil productivity. The changes in physic-chemical properties and beneficial microflora population of soil under the selected exotic forest tree species viz. *A. auriculiformis, A. mangium, C. equisetifolia* and *S. macrophylla* is discussed hereunder in detail.

5.1 Physico-chemical properties of soil under the exotic tree species

The long term changes in the soil on account of the retention of exotic tree species cover has been investigated in the present work. Prominent soil physico-chemical parameters like moisture content, bulk density, pH, organic carbon, available nitrogen, total nitrogen, available phosphorus and exchangeable potassium were analysed and compared with treeless control plot for this purpose. Chavan *et al.* (1995) reported that forest tree species (*Tectona grandis, Terminalia tomentosa, Pongamia pinnata, Gmelina arborea, Eucalyptus, Acacia auriculiformis*, and *Casuarina equisetifolia*) in ten-year-old plantations at Wakawali [Maharashtra], India, did not change the soil physical properties under the canopy, but there were marked effects on the soil chemical properties compared with natural forest soils. They also observed that organic carbon, available nitrogen, phosphorus and potassium increased significantly in the surface layer.

In the present study, all tree species showed higher soil moisture content compared to treeless control plot which may be because of tree cover. Soil pH

showed marginal variation in tree species and treeless control plot and it was acidic soil. Soil pH was lowest in *A. mangium* and highest in treeless control plot, which is in tune with other studies. Tamilselvi et al. (2010) also found that the soil was acidic with moderate amounts of macronutrient and with no appreciable variation in micronutrient under *Acacia mangium*. Bulk density was lower in tree species compared to treeless control plot. The top soil in tropical areas in usually low in bulk density owing to the highly weathered soil rich in litter and organic matter. Above observation is strongly validated by the higher organic carbon content in the soil under tree species compared to treeless control plot in the present study (Table 1). These changes might be because of long term addition of organic matter through litter fall. FaMing *et al.* (2010) observed that the N-fixing forests trees had 40-50% higher soil organic matter and 20-50% higher total nitrogen concentration in the 0-5 cm soils than the non-N-fixing forests. They also observed that the N-fixing *Acacia auriculiformis* plantation had the highest soil available P, which is found true in present study also.

All tree species showed significantly higher available nitrogen concentrations compared to treeless control plot area reiterating their potential to influence the long term productivity of the soil. Among the tree species, the dominant role of *Acacia* species in improving the available nitrogen of the soil is evident in the present study. It can be better explained by the release of biologically fixed N to the rhizosphere (Shantharam and Mattoo, 1997; Tilki and Fisher, 1998; Sprent and Parsons, 2000; FaMing *et al.*, 2010; Karthikeyan *et al.*, 2013b). Nutrient fluxes are also affected by factors such as changes in microclimatic conditions (temperature and moisture) and the rate of litter decomposition (Khanna, 1998).

Invariably both soil available phosphorus and Exchangeable potassium were higher in the soil under tree cover compared to treeless control plot. Among the tree species variation was more prominent for soil potassium with highest value shown by *S. macrophylla* closely followed by *C. equisetifolia*. Potassium being an element with high mobility, probably, its inconsistent presence in the soil explain

the variability (George and Kumar, 1998). Similar results for *A. auriculiformis* and *C. equisetifolia* was also found by Aneesh (2013).

Physico-chemical properties of soil at the end of study had some differences compared to the first sampling. Moisture content was higher in all plots which might be because of the pre-monsoon shower received during late summer-II season (May, 2014). In this sampling organic carbon content was higher in *S. macrophylla* which may be because of high moisture content which affect the decomposition rate. Available nitrogen was higher in nitrogen fixing tree species because of biological nitrogen fixation (Gueye and Ndoye *et al.*, 1998). Total nitrogen was high in *S. macrophylla* which may be because of higher addition of organic carbon content compare to other tree species (Table 2). Soil P and K were shown same pattern as shown in previous sampling.

5.2 Microbial population of different sampling period

The discussion hereunder pertains to beneficial microfloral population of soil for the selected exotic forest tree species viz. *A. auriculiformis*, *A. mangium*, *C. equisetifolia* and *S. macrophylla*.

5.2.1 Microbial population in the rhizosphere soil of different exotic forest tree species

In general, the present study showed that the microbial population was higher in tree plots compared to treeless control plot. In late summer-I, *A. mangium* was found dominant species among the tree species and among the microflora, fungi population was highest. *C. equisetifolia* had highest population of actinomycetes it might be because of symbiotic relationship of *C. equisetifolia* with actinomycetes. *A. mangium* had highest population of bacteria, fungi, nitrogen fixing bacteria, phosphorus and potash solubilizing bacteria which might be because of high nitrogen fixing capacity of legume tree species and addition of leaf litter. A fairly high N-fixing potential also has been recorded for *Acacia mangium* by Gueye and Ndoye *et al.* (1998). The highest microbial population in *A. mangium*

is supported by Bakarr and Janos (1996). They also found the higher number of microorganism colonization in *A. mangium.*

In the rainy season, among all the microflora, bacteria population was highest. *C. equisetifolia* was found dominant species with highest population of actinomycetes and bacteria. It might be because of symbiotic relation with microorganism which is found in *C. equisetifolia*. *A. auriculiformis* had highest fungi and nitrogen fixing bacterial population. *A. mangium* had highest phosphorus solubilizing microorganism and KSB population which was found in previous sampling also. As shown earlier, this higher number of microbial population in tree species might be because of litterfall, symbiotic relation of microorganism with tree species and microclimate developed in rhizosphere (root soil) soil by tree species (Katznelson *et al.*, 1962; Raghu and MacRae, 1966; Sharma *et al.*, 2009; Golinska and Dahm, 2011). Silva *et al.* (2005) found that microbial population were significantly ($p<0.01$) greater in forest soil than in old-field soil, which could also be related to the higher level of soil organic matter in the forest soil.

In the winter season, among all the microflora population, phosphate solubilizing microorganism was highest. *S. macrophylla* was found dominant species and it had highest population of actinomycetes and bacteria and lowest in *A. mangium*. In *A. mangium*, actinomycetes population might be less because of water logged condition in the plot. Fungi and nitrogen fixing bacterial population was highest in *A. auriculiformis*, similar result was found in previous season also. Phosphorus solubilizing microorganism and KSB was highest in *A. mangium* which was found in previous both sampling also. KSB population was also same in *C. equisetifolia.*

In the early summer season all the microbial population were found lowest in treeless control plot. The highest population of actinomycetes was shown in *C. equisetifolia* and among all microflora actinomycetes population was highest. Bacterial and Fungal population were highest in *S. macrophylla* and fungal population was same in *A. auriculiformis* also. Nitrogen fixing bacteria,

phosphorus solubilizing microorganism and KSB were highest in *A. auriculiformis*, *C. equisetifolia* and *A. mangium* respectively.

In late summer-II (May, 2014) season, bacteria population was highest among all the microfloral population it might be because of summer showers. Rodrigues *et al.* (2011) reported that fungi developed better during the dry season and bacteria during rainy season. Actinomycetes population was highest in *S. macrophylla* and lowest in *A. mangium* which might be because of water logged condition in the *A. mangium* plot. *A. auriculiformis* was found dominant than other species. *A. auriculiformis* has shown highest number of bacteria, fungi, nitrogen fixing bacteria, phosphorus solubilizing microorganism and KSB and lowest in treeless control plot.

5.2.2 Seasonal changes in microbial population in different exotic forest tree species

Recent studies have found the effect of seasonal changes on microfloral population. ShangShyng *et al.* (2006) investigated the role of microorganisms in the ecology and nutrient transformation of forest soil in Taiwan. They found that summer season had higher microbial populations, biomass and organic content than winter season, which found in the present study also. Schiavo *et al.* (2009) also reported that the population of microorganisms was higher in the summer, where it was observed a positively correlation with total carbon.

Among all the tree species *C. equisetifolia* was found to have higher actinomycetes population because it has symbiotic relation with actinomycetes (Rajendran and Devraj, 2004). Generally, actinomycetes population increased after monsoon shower in *A. auriculiformis* and treeless control plot. However, such changes were not found in *A. mangium*, *C. equisetifolia* and *S. macrophylla*, in these species actinomycetes population increased after monsoon but it was marginally decreased in late summer-II season. Buvaneswaran *et al.* (2003) revealed that the actinomycetes population was higher in tree plots compared to treeless control plot. The actinomycetes population ranged between 1.67×10^3 cfu g^{-1} in rainy season to

15.67 $\times 10^3$ cfu g^{-1} in early summer season. ShangShyng *et al.* (2006) also found that each gram of soil contained 10^2-10^5 CFU actinomycetes. Buvaneswaran *et al.* (2003) found that the actinomycetes population ranged from 18 to 21 $\times 10^5$ per g of soil in *Enterolobium cyclocarpum, Peltophorum pterocarpum* and *Acacia auriculiformis* stands and Abbasi *et al.* (2010) found 8.2 (10^5) and 3.2 (10^5) actinomycetes population in forest and arable land respectively.

Among the tree species, *C. equisetifolia* found to have higher population of bacteria. Bacteria population was more in late summer-I and rainy season. After monsoon, it vastly decreased in winter season and early summer season and it was again increased in late summer-II season. The other study also revealed that the bacteria population was higher in tree plots compared to treeless control plot (Buvaneswaran *et al.,* 2003). In the present study bacterial population was highest in rainy season which was also found by Rodrigues *et al.* (2011); Das *et al.* (2012). The bacterial population ranged from 2.00 $\times 10^4$ cfu g^{-1} in early summer season to 35.33 $\times 10^4$ cfu g^{-1} in rainy season, which was less than other studies. It might be because of stand age and soil depth from soil sample was collected. Hong *et al.* (2007) reported that the number of bacteria and fungi increased at first then decreased, and eventually increased again after 40 years of restoration of forest soils. Abbasi *et al.* (2010) reported that depth showed significant effects on microbial activity and nutrient concentration, and both decreased significantly in the subsurface layer of 15-30 cm. ShangShyng *et al.* (2006) found that in topsoil, each gram of soil contained 10^5-10^7 colony-forming units (cfu) culturable bacteria.

Among the tree species, *A. auriculiformis* was found to have highest fungi population. Generally fungal population was decreased from rainy season but again it increased after winter season. Fungal community was more sensitive than the bacterial community in characterizing the differences in plant cover impacts on the microbial flora in natural pine and planted forests in subtropical region of China (Ming *et al.,* 2012). It was found that fungal population was more in late summer-I and late summer-II season in all treatments and it was less in rainy season, except for *A. auriculiformis.* Buvaneswaran *et al.* (2003) revealed that the fungi population

was higher in tree plots compared to treeless control plot. In the present study, fungi population was highest in late summer-I which was also found by Rodrigues *et al.* (2011); Das *et al.* (2012). Das *et al.* (2013) also found that the Shannon diversity index for fungi diversity was high in the month of May in *A. auriculiformis* and *B. balcooa*. Evenness, was high in the month of March in *A. auriculiformis* and in the month of May for *B. balcooa*. The fungi population ranged from 1.67×10^2 cfu g^{-1} in rainy season to 33.00×10^2 cfu g^{-1} in late summer-I. However fungi population was found higher in other studies. Sankaran and Balasundaran (2001) found that the density of fungal propagules in the shola forests of Eravikulam National Park, Idukki, ranged between 10.23 - 28.78×10^3 per gram of soil. The fungi isolated from grassland soils ranged between 14.26 - 42.04×10^3 per gram of dry soil. ShangShyng *et al.* (2006) found that in topsoil, each gram of soil contained 10^3-10^5 cfu fungi. Abbasi *et al.* (2010) found 2.5 (10^3) fungi population in forest and while arable land exhibited 0.87 (10^3).

A. auriculiformis had highest population of nitrogen fixing bacteria among all the tree species. Generally nitrogen fixing bacteria population was decreased slightly in rainy season and increased in winter season and after winter season it again decreased in next both seasons. Nitrogen fixing bacteria population are generally lowest in winter season. Nitrogen fixing bacteria population in *A. auriculiformis*, *A. mangium* and treeless control plot were highest in late summer-I but in *C. equisetifolia* and *S. macrophylla* it was highest in winter season. Sarkar (2010) also found that size of symbiotic rhizobial population is varied in different season; the size is greater in early winter than summer whereas top soil (0-15 cm) contained more *Rhizobial* population than subsurface (15-30 cm) soil. The nitrogen fixing bacteria population ranged from 0.33×10^2 cfu g^{-1} to 4.67×10^2 cfu g^{-1}. However fungi population was found higher in other studies. ShangShyng *et al.* (2006) found that in topsoil, each gram of soil contained 10^3-10^6 cfu nitrogen-fixing microbes. Das *et al.* (2012) found $1.125 \pm 0.359 \times 10^6$ cfu g^{-1} and $0.417 \pm 0.120 \times 10^6$ cfu g^{-1} nitrifying bacteria and free living nitrogen fixing bacteria respectively.

A. mangium found to have more population of phosphate solubilizing microorganism among all the tree species. Generally, Phosphate solubilizing microorganism population in *A. mangium*, *C. equisetifolia* and *S. macrophylla* were found highest in late summer-I but in *A. auriculiformis* and treeless control plot it was highest in late summer-II season and winter season. *A. mangium* and *S. macrophylla* showed lowest population in late summer-II season and *A. auriculiformis*, *C. equisetifolia* and treeless control plot shows in rainy season. The phosphate solubilizing microorganism population ranged from 3.00×10^2 cfu g^{-1} in early summer season to 15.33×10^2 cfu g^{-1} in late summer-I. However fungi population was found higher in other studies. ShangShyng *et al.*, (2006) found that in topsoil, each gram of soil contained 10^4-10^6 cfu phosphate-solubilizing microbes. Das *et al.* (2012) found $0.805 \pm 0.322 \times 10^6$ [mean value of cfu (g dry weight of sediment)$^{-1}$] phosphorous solubilizing bacteria.

Among the tree species, *A. mangium* found to have highest population of KSB. Generally, it was found that potash solubizing bacterial population was high in late summer-I, it was tremendously high in *A. auriculiformis* and *A. mangium*. After late summer-I, it decreased and it was found lowest in late summer-II season in all species. However, it increased in early summer season compare to winter season and in winter season it again decreased but increased in *A. auriculiformis*.

5.3 Tree growth

In the present study height and diameter increment vary among the species. The largest height in *A. mangium* (19.90 m) and smallest height in *S. macrophylla* (15.53 m). Kunhamu et al. (2011) also reported similar height in *A. mangium* for 61-75 cm girth class in 7 year old stand. However, the lowest diameter was recorded in *C. equisetifolia* (19.42 cm) and highest in *A. mangium* (24.31 cm). Though, the tree growth differs with age and Kumar *et al.* (1999) recorded 12.45 m and 11.64 cm and 9.43 m and 5.69 cm height and DBH growth in a 7 year old *A. auriculiformis* and *C. equisetifolia* respectively. Patil *et al.* (2012) also reported

10.30 m height and 22.68 cm DBH in 8 year old stand of *A. mangium*. Perera *et al.* (2012) reported 18 m height and 36 cm DBH in 79 year old stand of *S. macrophylla*.

Consequent to the improved physico-chemical properties coupled with the high microbial population particularly the beneficial microflora, the tree plots in general accrued good growth and in turn, maintained the soil condition due to long term occupancy of these exotic tree species. The potential ability of the exotic fast growing multipurpose tree species like *A. auriculiformis, A. mangium* and *C. equisetifolia* for improving the soil productivity and soil health is highlighted throughout the course of this investigation.

Summary

SUMMARY

A field investigation involving thirty two year old exotic forest tree species, viz. *Acacia auriculiformis* A. Cunn. ex. Benth., *Acacia mangium* Willd., *Casuarina equisetifolia* J.R. & G. Forst., and *Swietenia macrophylla* King stand was conducted in the research plots of Kerala Forest Research Institute sub-centre Nilambur during the period 2013-14. The specific objective of the study was to monitor the changes in soil productivity due to long-term occupancy of four exotic tree species with special reference to the quantity and quality of the beneficial microflora. This investigation also looked into physico-chemical properties of the soil and enumeration of the microbial population.

Salient results are summarized as follows:

1. Soil moisture content was found to be the maximum in tree plots and the minimum in treeless control plots. The least bulk density, which is most ideal for good plant growth, was recorded in tree species plots while the treeless plot recorded the highest bulk density.
2. Soil pH was observed maximum in treeless plot while the most acidic soil was from tree plots. Organic carbon, available nitrogen, total nitrogen available phosphorus and exchangeable potassium were higher in tree plots and lower in treeless control plots.
3. Over the 12 months period, *A. auriculiformis* had highest bacteria, fungi and nitrogen fixing bacteria population (Table 9-11) while the highest population of phosphorus solubilizing microorganism and potash solubilizing bacteria was recorded in *A. mangium* (Table 12 & 13). The highest population of actinomycetes was associated with *C. equisetifolia* (Table 8).
4. Actinomycetes population was, generally, the lowest during rainy season and was found to increase gradually after the rainy season and it is at its peak population during early summer season and late summer-II (Fig. 6).

5. The bacterial population was the maximum during rainy season. After the monsoon, it was decreased in winter season and was the lowest in early summer season Fig.7). During late summer, it was found to increase again towards the next rainy season.
6. Fungal population decreased after late summer-I, but after winter season again, it increased. It was found that fungal population was more in both the late summer (2013 and 2014) in all treatments and it was the lowest in the winter season (Fig. 8).
7. Generally, the nitrogen fixing bacteria population decreased in rainy season and again increased in winter season and then decreased slightly through the early summer season and with the lowest population in late summer-II (Fig. 9).
8. Phosphate solubilizer population was highest in late summer season and lowest in the rainy season (Fig. 10).
9. Potash solubilizing bacteria population was high in late summer-I and was the lowest in the winter season (Fig. 11).
10. Among the beneficial microflora, phosphate solubilizing microorganisms seems to be the least sensitive to the seasonal changes except for a slight reduction from late summer-I to the rainy season (Fig. 12).
11. The higher microbial population under the trees compared to the treeless control plots clearly implies the potential ability of these exotic tree species for improving the soil qualities when the beneficial microflora are taken as indices of soil productivity.

References

REFERENCES

Abbasi, M.K., Zafar, M., and Sultan, T. 2010. Changes in soil properties and microbial indices across various management sites in the mountain environments of Azad Jammu and Kashmir. *Commun. Soil Sci. Plant Anal.* 41(5-8): 768-782.

Adekunle, V.A.J., Dafiewhare, H.B., and Ajibode, O.F. 2005. Microbia population and diversity as influenced by soil pH and organic matter in different forest ecosystems. *Pakistan J. Biol. Sci.* 8(10): 1478-1484.

Alam S., Khalil, S., Ayub, N., and Rashid, M. 2002. In vitro solubilization of inorganic phosphate by phosphate solubilizing microorganism (PSM) from maize rhizosphere. *Intl. J. Agric. Biol.* 4: 454-458.

*Aleksandrov, V.G., Blagodyr, R.N., and Iiiev, I.P. 1967. Liberation of phosphoric acid from apatite by silicate bacteria. *Mikrobiyol Zh. (Kiev)*, 29: 111-114.

Alexander, M. 1977. *Introduction to Soil Microbiology*. John Wiley and Sons Inc., NewYork, 467p.

Aneesh, S. 2013. Biomass production and nutrient dynamics in multipurpose tree based black pepper production system. M.Sc. thesis (For.) submitted to Kerala Agricultural University, Vellanikkara, 124p.

Anino, E.O. 1992. Natural ecto-mycorrhiza of *Acacia mangium*. *Nitrogen Fixing Tree Res. Rep.* 10: 96.

Bakarr, M. I. and Janos, D. P. 1996. Mycorrhizal associations of tropical legume trees in Sierra Leone, West Africa. *For. Ecol. Manage.* 89(1/3): 89-92.

Balasubramanian, A. and Ravichandran, V.K. 1997. Biofertilizers - an alternative source of nutrients for sustainable productivity of trees. *J. Ecobiol.* 9(3): 203-206.

Balasubramanian, A. and Ravichardran, V.K. 2005. Productivity enhancement of few multipurpose tree species using biofertilizers. *Indian J. Agrofor.* 7(1): 41-43.

Banerjee, S.K., Mishra, T.K., Singh, A.K., Jain, A. 2004. Impact of plantation on ecosystem development in disturbed coal mine overburden spoils. *J. Trop. For. Sci.* 16(3): 294-307.

Barbaruah, B. and Baruah, P. 2012. Deuteromycetous Fungi in a Tropical Rainforest Ecosystem of the Upper Brahmaputra Valley. *Indian For.* 138(12) 1164-1169.

Bardgett, R.D., Bowman, W.D., Kaufmann, R., and Schmidt, S.K. 2005. A temporal approach to linking aboveground and belowground ecology. *Trends Ecol. Evol.* 20: 634-641.

Bauhus, J., Pare, D., and Cote, L. 1998. Effects of tree species, stand age and soil type on soil microbial biomass and its activity in a southern boreal forest. *Soil Biol. Biochem.* 30: 1077-1089.

*Begon, M., Harper, J.L., and Townsend, C.R. 1990. Ecology: Individuals, Populations and Communities (2nd Ed.). Blackwell Scientific Publications USA.

Bento, R.A., Saggin-Júnior, O.J., Pitard, R.M., Straliotto, R., Silva, E.M.R. da, Tavares, S.R. de L., Landa, F.H.T.G. de, Martins, L.F., and Volpon, A.G.T. 2012. Selection of leguminous trees associated with symbiont microorganisms for phytoremediation of petroleum-contaminated soil. *Water, Air, and Soil Pollut.* 223(9): 5659-5671.

Berg, G., Zachow, C., Lottmann, J., Gotz, M., Costa, R., and Smalla, K. 2005. Impact of plant species and site on rhizosphere-associated fungi antagonistic to *Verticillium dahliae* Kleb. *Appl. Environ. Microbiol.* 71: 4203-4213.

Bertsch, P.M. and Thomas, G.W. 1985. Potassium status of temperature region soils. In: Munson, R.D. (Ed.), *Potassium in Agriculture*. ASA, CSSA and SSSP, Madison, WI, pp. 131-162.

Bhat, A.K. 1990. Effect of afforestation and deforestation on forest floor microbial activities. *Adv. Plant Sci.* 3(2): 326-328.

Binkley, D. 1994. The influence of tree species on forest soils: processes and patterns. In: Mead, D.J. and Cornforth, I.S. (ed.), *Proceedings of the Trees and Soil Workshop,* Canterbury, New Zealand, 28 Feb.-2 Mar. Lincoln University Press, Canterbury, New Zealand, pp. 1-33.

Binkley, D., and Giardina, C. 1998. Why do species affect soils? The warp and woof of tree–soil interactions. *Biogeochemistry* 42: 89-106.

Binkley, D., and Valentine, D. 1991. Fifty-year biogeochemical effects of green ash, white pine and Norway spruce in a replicated experiment. *For. Ecol. Manage.* 40: 13-25.

Biswas, D.R. and Basak, B.B. 2009. Influence of potassium solubilizing microorganism (*Bacillus mucilaginosus*) and waste mica on potassium uptake dynamics by sudan grass (*Sorghum vulgare*) grown under two Alfisols. *Plant Soil Environ. J.* 317: 235-255.

Bowen, G.D. and Rovira, A.D. 1991. The rhizosphere, the hidden half of the hidden half. In: Waisel, Y. and Kafka, U. (ed.), *Plant Roots*. The Hidden Half Marcel Dekker, New York, pp. 641-649.

Bowen, G.D., Sanginga, N., and Danso, S.K.A. 1990. Biological nitrogen fixation in agroforestry - an overview. In: *Transactions 14th International Congress of Soil Science;* August, 1990, Kyoto, Japan. Volume III pp. 170-175.

Brockett, B.F.W., Prescott, C.E., and Grayston, S.J., 2012. Patterns in forest soil microbial community composition across a range of regional climates in western Canada. *Soil Biol. Biochem.* 44: 9-20.

Brunck, F., Colonna, J.P., Dommergues, Y., Ducousso, M., Galiana, A., Prin, Y., Roederer, Y., and Sougoufara, B. 1990. Control of inoculation of trees with root symbionts. A synthesis of a selection of trials in the tropics. *Bois et Forêts des Tropiques* 223: 24-42.

Buckley, D.H. and Schmidt, T.M. 2003. Diversity and dynamics of microbial communities in soils from agro-ecosystems. *Environ. Microbiol.* 5: 441-452.

Buvaneswaran, C., Saravanan, S., and Jambulingam, R. 2003. Role of tree stands in the rehabilitation of degraded lands of Auroville, India. *Indian J. For.* 26(4): 333-338.

Buyer, J.S., Roberts, D.P., Millner, P. and Russek-Cohen, E. 2001. Analysis of fungal communities by sole carbon source utilization profiles. *J. Microbiol. Meth.* 45: 53-60.

Calvaruso, C., N'Dira, V., and Turpault, M.P. 2011. Impact of common European tree species and Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco) on the physicochemical properties of the rhizosphere. *Plant Soil* 342: 469-480.

Chang, K.P., Hu, H.T., and Kao, P.C. 1986. Effect of endomycorrhizal fungi and *Rhizobium* inoculation on growth of *Acacia auriculiformis* A. Cunn. ex Benth. *Nitrogen Fixing Tree Res. Rep.* 4: 40-41.

ChaoMei, P., Feng, Y., PeiLing, L., and YouJu, L. 1998. Characteristics of soil microbes in south subtropical lateritic red earth under artificial forests. *J. Trop. Subtrop. Bot.* 6(2): 158-165.

ChaoMei, P., Feng, Y., PeiLing, L., and YouJu, L. 1998. Characteristics of soil microbes in south subtropical lateritic red earth under artificial forests. *J. Trop. Subtrop. Bot.* 6(2): 158-165.

Chaukiyal, S.P., Singh, K.C.H., and Pokhriyal, T.C. 1999. Effects of seasonal variations on nodulation and nitrogen fixation behaviour in some Acacia species. *Ann. For.* 7(1) 112-119.

Chavan, K.N., Kenjale, R.Y., and Chavan, A.S. 1995. Effect of forest tree species on properties of lateritic soil. *J. Indian Soc. Soil Sci.* 43(1): 43-46.

Chen, C.R., Condron, L. M., Davis, M. R., Sherlock, R.R. 2003. Seasonal changes in soil phosphorus and associated microbial properties under adjacent grassland and forest in New Zealand. *For. Ecol. Manage.* 177: 539-557.

Chen, Y. P., Rekha, P.D., Arunshen, A.B., Lai, W.A., and Young, C.C. 2006. Phosphate solubilizing bacteria from subtropical soil and their tricalcium phosphate solubilizing abilities. *Appl. Soil Ecol.* 34: 33-41.

Chong, W., Yong, Z., Ni, M., and ChongLu, Z. 2012. Response characteristics of *Casuarina equisetifolia* inoculated with mycorrhizal fungi under low temperature stress. *Acta Botanica Boreali-Occidentalia Sinica* 32(10): 2068-2074.

ChongLu, Z., MingQin, G., Yu, C., and FengZhen, W. 1995. Inoculation of Casuarina with ectomycorrhizal fungi, vesiculararbuscular mycorrhizal fungi and Frankia. In: Brundett, M., Dell, B., Malajczuk, N., and MingQin, G. (eds), *Mycorrhizas for plantation forestry in Asia*: Proceedings of an international symposium and workshop, Kaiping, Guangdong Province, P.R. China, pp. 122-126.

Cocking, E.C. 2003. Endophytic colonization of plant roots by nitrogen-fixing bacteria. *Plant Soil* 252: 169-175.

Combalicer, M.S., DonKoo, L., SuYoung, W., PilSun, P., KiWoong, L., Tolentino, E.L., Combalicer, E.A., YongKwon, L., and YeongDae, P. 2011. Aboveground biomass and productivity of nitrogen-fixing tree species in the Philippines. *Sci. Res. Essays.* 6(27): 5820-5836.

Cooke, R.C. and Rayner, A.D.M. 1984. Ecology of Saprotrophic Fungi. Longman, London.

Cruz, R. E. dela; Manalo, M.Q., Aggangan, N.S., Tambalo, J.D. 1988. Growth of three legume trees inoculated with VA mycorrhizal fungi and Rhizobium. *Plant Soil* 108(1): 111-115.

CunYu, Z. 2006. Effect of different leaffall decomposition on soil microorganisms. *J. Hubei Inst. Nationalities – Nat. Sci. Ed.* 24(4): 335-338.

Das, P., Roy, A., Debnath, A., Bhattacharjee, S., Sinha, S., Saha, A.K. 2013. Fungal diversity in the rhizosphere of *Acacia auriculiformis* A. Cunn. ex Benth and *Bambusa balcooa* Roxb. growing in Suryamaninagar, Tripura, Northeast India. *Indian J. Fundamental Appl. Life Sci.* 3(1): 123-127.

Das, S., De, M., Ray, R., Chowdhury, C., Jana, T.K., and De, T.K. 2012. Microbial ecosystem in sunderban mangrove forest sediment, north-east coast of Bay of Bengal, India. *Geomicrobiol. J.* 29(7): 656-666.

Deka, H.K. and Mishra, R.R. 1984. Distribution of soil microflora in jhum fallows in north-east India. *Acta Botanica Indica* 12(2): 180-184.

Dhaneshkumar, P., Ashokan, P.K., and Balasundaran, M. 2001. Nodulation behaviour of mangium (*Acacia mangium* Willd.) in Kerala and seedling response to Rhizobium inoculation. In: Varma, R.V., Bhat, K.V., Muralidharan, E.M., and Sharma, J.K. (eds), *Tropical forestry research: challenges in the new millennium*. Proceedings of the International Symposium, Peechi, India, pp. 142-146.

Dhar, P.P. and Mridha, M.A.U. 2006. Biodiversity of arbuscular mycorrhizal fungi in different trees of madhupur forest, Bangladesh. *J. For. Res.* 17(3): 201-205.

Díaz-Raviña, M., Acea, M.J., Carballas, T. 1993. Seasonal fluctuations in microbial populations and available nutrients in forest soils. *Biol. Fertil. Soils* 16(3): 205-210.

DiCello, F., Bevivino, A., Chiarini, L., Fani, R., Paffetti, D., Tabacchioni, S., and Dalmastri, C. 1997. Biodiversity of a *Burkholderia cepacia* population

isolated from the maize rhizosphere at different plant growth stages. *Appl. Environ. Microbiol.* 63: 4485-4493.

Diem, H.G., Gueye, I., Gianinazzi-Pearson, V., Fortin, J.A., and Dommergues, Y.R. 1981. Ecology of VA mycorrhizae in the tropics: the semi-arid zone of Senegal. *Acta OEcologica, OEcologia Plantarum* 2(16): 53-62.

Dilly, O., Bach, H.J., Buscot, F., Eschenbach, C., Kutsch, W.L., Middelhoff, U., Pritsch, K., and Munch, J.C. 2000. Characteristics and energetic strategies of the rhizosphere in ecosystems of the Bornhöved Lake district. *Appl. Soil Ecol.* 15: 201-210.

Dimbleby, G.W. 1952. Soil regeneration on the North-East Yorkshire moors. *J. Ecol.* 40: 331-341.

Diouf, D., Duponnois, R., Ba, A.T., Neyra, M., and Lesueur, D. 2005. Symbiosis of *Acacia auriculiformis* and *Acacia mangium* with vmycorrhizal fungi and *Bradyrhizobium* spp. improves salt tolerance in greenhouse conditions. *Funct. Plant Biol.* 32(12): 1143-1152.

Dommergues, Y.R. 1995. Nitrogen fixation by trees in relation to soil nitrogen economy. *Fertil. Res.* 42(1/3): 215-230.

Dommergues, Y.R. 1996. Nitrogen fixation in actinorhizal plants and its applications. *Acta Botanica Gallica* 143(7): 663-679.

Dreyfus, B.L. and Dommergues, Y.R. 1981. Nodulation of *Acacia* species by fast and slow growing tropical strains of *Rhizobium*. *Appl. Environ. Bacteriol.* 41: 97-99.

Dunfield, K.E. and Germida, J.J. 2003. Seasonal changes in the rhizosphere microbial communities associated with field-grown genetically modified canola (*Brassica napus*). *Appl. Environ. Microbiol.* 69: 7310-7318.

Duponnois, R., Kisa, M., and Plenchette, C. 2006. Phosphate solubilizing potential of the nematofungus *Arthrobotrys oligospora*. *J. Plant Nutr. Soil Sci.* 169: 280-282.

Ekelund, F., Ronn, R., Christensen, S. 2001. Distribution with depth of protozoa, bacteria and fungi in soil profiles from three Danish forest sites. *Soil Biol. Biochem.* 33: 475-481.

Ehrlich, H.L. 1990. Mikrobiologische and biochemische Verfahrenstechnik. In: Einsele, A., Finn, R.K., and Samhaber, W. (eds), *Geomicrobiology* (2nd Ed.). Weinheim: VCH Verlagsgesellschaft.

El-Lakany, M.H. 1987. Contribution of Casuarina to soil fertility in Egypt. In: *Les arbres fixateurs d'azote. L'amélioration biologique de la fertilité du sol;* 17-25 mars, 1987, Actes des séminaires, Dakar, Sénégal, pp. 287-293.

Elsas, J.D. van, Speksnijder, A.J., and Overbeek, L.S. van 2008. A procedure for the metagenomics exploration of disease-suppressive soils. *J. Microbiol. Methods* 75: 515-522.

Ettema, C.H. 1998. Soil nematode diversity: species coexistence and ecosystem function. *J. Nematology* 30: 159-169.

Ezawa, T., Smith, S.E. and Smith, F.A. 2002. P metabolism and transport in AM fungi. *Plant Soil* 244: 221-230.

FaMing, W., ZhiAn, L., HanPing, X., Bi, Z., NingYu, L., Jin, L., and WeiXing, Z. 2010. Effects of nitrogen-fixing and non-nitrogen-fixing tree species on soil properties and nitrogen transformation during forest restoration in southern China. *Soil Sci. Plant Nutr.* 56(2): 297-306.

Federle, T.W., Dobbins, D.C., Thorntonmanning, J.R., and Jones, D.D. 1986. Microbial biomass, activity, and community structure in subsurface soils. *Groundw.* 24: 365-374.

Fierer, N. and Jackson, R.B., 2006. The diversity and biogeography of soil bacterial communities. *Proc. Nat. Acad. Sci.* 103: 626-631.

Fierer, N., Schimel, J.P., and Holden, P.A. 2003. Variations in microbial community composition through two soil depth profiles. *Soil Biol. Biochem.* 35: 167-176.

Fierer, N., Strickland, M.S., Liptzin, D., Bradford, M.A., and Cleveland, C.C., 2009. Global patterns in belowground communities. *Ecol. Lett.* 12: 1238-1249.

Filion, M., St-Arnaud, M. and Fortin, J.A. 1999. Direct interaction between the arbuscular mycorrhizal fungus glomus intraradices and different rhizosphere microorganisms. *New Phytol.* 141: 525-533.

Florence, E.J.M., Balasundaran, M., and Sankaran, K.V. 2001. Microbial diversity of the sholas of Munnar and Wayanad. In: Nair, K.K.N., Khanduri, S.K., and Balasubramanyan, K. (eds), *Shola forests of Kerala: Environment and Biodiversity* pp. 137-150.

Frankland, J.C., Magan, N., and Gadd, G.M. 1995. Fungi and Environmental Change. Cambridge University Press, Cambridge.

Fritze, H., Pietikainen, J., and Pennanen, T. 2000. Distribution of microbial biomass and phospholipid fatty acids in Podzol profiles under coniferous forest. *Eur. J. Soil Sci.* 51: 565-573.

Frossard, E., Condron, L.M., Oberson, A., Sinaj, S., and Fardeau, J.C. 2000. Processes governing phosphorus availability in temperate soils. *J. Environ. Qual.* 29: 15-23.

Fyles, J.W. and Cote, B. 1994. Forest floor and soil nutrient status under Norway spruce and red pine in a plantation in southern Quebec. *Can. J. Soil Sci.* 74: 387-392.

Galiana, A. 1991. Nitrogen fixation of *Acacia mangium*/Rhizobium. In: *La symbiose fixatrice d'azote chez Acacia mangium- Rhizobium.* 246p.

Galiana, A., Chaumont, J., Diem, H.G., and Dommergues, Y.R. 1990. Nitrogen-fixing potential of *Acacia mangium* and *Acacia auriculiformis* seedlings inoculated with *Bradyrhizobium* and *Rhizobium* spp. *Biol. Fertil. Soils* 9(3): 261-267.

Galiana, A., Gnahoua, G.M., Chaumont, J., Lesueur, D., Prin, Y., and Mallet, B. 1998. Improvement of nitrogen fixation in Acacia mangium through inoculation with rhizobium. *Agrofor. Syst.* 40(3): 297-307.

Ganry, F. and Dommergues, Y.R. 1995. Nitrogen fixing trees: a research area. *Agric. et Dév.* 7: 38-55.

Gauthier, D., Diem, H.G., Dommergues, Y.R., and Ganry, F. 1985. Assessment of N2 fixation by *Casuarina equisetifolia* inoculated with Frankia ORS021001 using 15N methods. *J. Soil Biol. Biochem.* 17(3): 375-379.

George, E., Marschner, H. and Jakobsen, I. 1995. Role of arbuscular mycorrhizal fungi in uptake of phosphorous and nitrogen from soil. *Crit. Rev. Biotechnol.* 15: 257-270.

George, S.J. and Kumar, B.M. 1998. Litter dynamics and cumulative soil fertility changes in silvopastoral systems of a humid tropical region in central Kerala, India. *Int. Tree Crops J.* 9(4): 267-282.

Gessner, M.O., Swan, C.M., Dang, C.K., McKie, B.G., Bardgett, R.D., Wall, D.H., and Hättenschwiler, S. 2010. Diversity meets decomposition. *Trends Ecol. Evol.* 25: 372-380.

Giller, K.E. 2001. *Nitrogen Fixation in Tropical Cropping Systems.* CABI Publishing CAB International Wallingford Oxon OX10 8DE UK, 409p.

Giri, B., Kapoor, R., Agarwal, L., and Mukerji, K.G. 2004. Preinoculation with Arbuscular Mycorrhizae Helps *Acacia Auriculiformis* Grow in Degraded Indian Wasteland Soil. *Commun. Soil Sci. Plant Anal.* 35(1-2): 193-204.

Girvan, M.S., Bullimore, J., Pretty, J.N., Osborn, A.M., and Ball, A.S. 2003. Soil type is the primary determinant of the composition of the total and active bacterial communities in arable soils. *Appl. Environ. Microbiol.* 69: 1800-1809.

Gleixner, G., Kramer, C., Hahn, V., and Sachse, D. 2005. The effect of biodiversity on C storage in soils. In: Scherer-Lorenzen, M., Körner, C., and Schulze, E.D. (Eds), *Forest Diversity and Function: Temperate and Boreal Systems*. Springer, Berlin, Heidelberg, New York, pp. 165-183.

Goldstein, A.H. 1986. Bacterial solubilization of mineral phosphates: historical perspective and future prospects. *Am. J. Altern. Agric.* 1: 51-7.

Golinska, P. and Dahm, H. 2011. Occurrence of actinomycetes in forest soil. *Dendrobiology* 66: 3-13.

Gower, S.T. and Son, Y. 1992. Differences in soil and leaf litterfall nitrogen dynamics for five forest plantations. *Soil Sci. Soc. of Am. J.* 56: 1959-1966.

Grayston, S.J. and Prescott, C.E. 2005. Microbial communities in forest floors under four tree species in coastal British Columbia. *Soil Biol. Biochem.* 37: 1157-1167.

Grayston, S.J., Vaughan, D., and Jones, D. 1997. Rhizosphere carbon flow in trees, in comparison with annual plants: the importance of root exudation and its impact on microbial activity and nutrient availability. *Appl. Soil Ecol.* 5: 29-56.

Grayston, S.J., Wang, S., Campbell, C.D., and Edwards, A.C. 1998. Selective influence of plant species on microbial diversity in the rhizosphere. *Soil Biol. Biochem.* 30: 369-378.

Gueye, M. and Ndoye, I. 1998. Genetic diversity and nitrogen fixation of acacias. In: Campa, C., Grignon, C., Gueye, M., and Hamon, S. (eds), *L'acacia au Sénégal. Actes de la réunion thématique sur l'acacia au Sénégal.* Dakar, Sénégal, pp. 351-355, 464-465.

Guo, L.B. and Gifford, R.M. 2002. Soil carbon stocks and land use change: a meta-analysis. *Glob. Change Biol.* 8(4): 345-360.

*Hamdan, H., Weller, D.M., and Thomashow. L.S. 1991. Relative importance of fluorescent siderophores and other factors in biological-control of *Gaeumannomyces graminis* var tritici by *Pseudomonas fluorescens* 2-79 and M4-80r. *Appl. Environ. Microbiol.* 57: 3270-3277.

Hansen, R.A. 2000. Effects of habitat complexity and composition on a diverse litter microarthropod assemblage. *Ecol.* 81: 1120-1132.

Hättenschwiler, S., Aeschlimann, B., Coûteaux, M.-M., Roy, J., and Bonal, D. 2008. High variation in foliage and leaf litter chemistry among 45 tree species of a neotropical rainforest community. *New Phytologist* 179: 165-175.

Hobbie, S.E. 1992. Effects of plant species on nutrient cycling. *Trends Ecol. Evol.* 7: 336-339.

Hong, M., WenXiang, H., XiaoMing, L., GuoBin, L., and Xiang, Y. 2007. Evaluative feature of soil microbial population under plant restored process in loess regions. *Acta Botanica Boreali-Occidentalia Sinica* 27(3): 588-593.

Hu, H.T. and Chang, K.P. 1983. *Pure culture synthesis of nodules by Rhizobium sp. on Acacia auriculiformis Cunn. ex Benth. and its morphology.* Technical Bulletin, Experimental Forest, National Taiwan University No. 145, i+ 6p.

Igual, J.M., Valverde, A., Cervantes, E., and Velázquez, E. 2001. Phosphate-solubilizing bacteria as inoculants for agriculture: use of updated molecular techniques in their study. *Agron.* 21: 561-568.

Inagaki, M. and Ishizuka, S. 2011. Ecological impact on Nitrogen and phosphorus cycling of a widespread fast-growing leguminous tropical Forest plantation tree species, *Acacia mangium*. *Diversity* 3(4): 712-720.

Jackson, M.L. 1958. *Soil Chemical Analysis*. Prentice Hall of India private ltd., New Delhi, 498p.

Jacob, M., Weland, N., Platner, C., Schaefer, M., Leuschner, C., and Thomas, F.M. 2009. Nutrient release from decomposing leaf litter of temperate deciduous forest trees along a gradient of increasing tree species diversity. *Soil Biol Biochem.* 41: 2122-2130.

Jamaluddin, Chandra, K.K. 1997. Distribution of VAM fungi in bauxite mine overburden plantation of Amarkantak (Madhya Pradesh). *Indian For.* 123(5): 412-418.

Jayakumar, P. and Tan, T.K. 2005. Growth performance and nodulation response of *Acacia mangium* co-inoculated with *Bradyrhizobium* sp. and *Pisolithus tinctorius*. *Symbiosis* 40: 109-114.

Jennifer, L.K., Beaudette, A.L., Hartb, H., Moutoglis, P., Klironomos, N.J., Lee, H. and Trevors, J.T. 2004. Methods of studying soil microbial diversity. *J. Microbiol. Methods.* 58: 169-188.

Johnson, L.F. and Curl, E.A. 1972. Isolation of groups of microorganisms from soil. Methods for research on the ecology of soil borne plant pathogens. Burgees Publishing Company, New York, pp 6-13.

Johnson, M.J., Lee, K.Y., and Scow, K.M. 2003. DNA fingerprinting reveals links among agricultural crops, soil properties, and the composition of soil microbial communities. *Geoderma* 114: 279-303.

Kang, S.C., Hat, C.G., Lee, T.G., and Maheshwari, D.K. 2002. Solubilization of insoluble inorganic phosphates by a soil-inhabiting fungus Fomitopsis sp. PS 102. *Curr. Sci.* 82: 439- 442.

Kara, O. and Bolat, I. 2009. Short-term effects of wildfire on microbial biomass and abundance in black pine plantation soils in Turkey. *J. Ecological Indicators* 9: 1151-1155.

Karthikeyan, A, Chandrasekaran, K, Geetha, M and Kalaiselvi, R 2013a. Growth response of *Casuarina equisetifolia* Forst. rooted stem cuttings to Frankia in nursery and field conditions. *J. Biosci.* 38 741–747

Karthikeyan, A., Geetha, M., and Chandrasekaran, K. 2013b. Nodulation in rooted stem cuttings of *Acacia auriculiformis* A. Cunn. ex. Benth. *Indian For.* 139(11): 1046-1047.

Kasongo, R.K., Ranst, V.E., Verdoodt, A., Kanyankagote, P., and Baert, G. 2009. Impact of *Acacia auriculiformis* on the Chemical Fertility of Sandy Soils on the Bateke Plateau, D.R. Congo. *Soil Use Manage.* 25 (1): 21-27.

Katznelson, H., Peterson, E.A., and Rovatt, J.W. 1962. Phosphate dissolving microorganisms on seed and in the root zone of plants. *Can. J. Bot.* 40: 1181-1186.

Kayode, J. and Franco, A.A. 2002. Response of *Acacia mangium* to rhizobia and arbuscular mycorrhizal fungi. *Trop. Sci.* 42(3): 116-119.

Khan, A.A., Jilani, G., Akhtar, M.S., Naqvi, S.M.S., and Rasheed, M. 2009. Phosphorus Solubilizing Bacteria: Occurrence, mechanisms and their role in crop production. *J. Agric. Biol. Sci.* 1(1): 48-58.

Khan, M.S., Zaidi, A., and Wani, P.A. 2007. Role of phosphate-solubilizing microorganisms in sustainable agriculture - A review. *Agron. Sustain. Dev.* 27: 29-43.

Khanna, P.K. 1998. Nutrient cycling under mixed-species tree systems in Southeast Asia. *Agrofor. Syst.* 38: 99-120.

Kucey, R.M.N., Janzen, H.H., and Legget, M.E. 1989. Microbial mediated increases in plant available phosphorus. *Adv. Agron.* 42: 199-228.

Kumar, A. and Gurumurthi, K. 1999. Effect of Frankia on growth and nodulation in *Casuarina equisetifolia*. *Indian For.* 125(5): 490-495.

Kumar, R.V., Reddy, B.V.P., and Mohan, V. 1999. Distribution of ectomycorrhizal fungi in forest tree species of Andhra Pradesh, southern India - a new record. *Indian For.* 125(5): 496-502.

Kunhamu, T.K., Kumar, B.M., and Syam, V. 2011. Tree allometry, volume and aboveground biomass yield in a seven-year-old *Acacia mangium*. Willd stand at Thiruvazhamkunnu, India. In: Kumar, B.M. and Kunhamu, T.K. (eds), *Quarter Century of Agroforestry Research in Kerala: A Compendium of Research Publications*. Kerala Agricultural University, Thrissur, Kerala, pp. 158-164.

Lajudie, P. de, Willems, A., Nick, G., Moreira, F., Molouba, F., Torck, U., Neyra, M., Collins, M.D., Lindström, K., Dreyfus, B. and Gillis, M. 1998. Characterization of tropical tree rhizobia and description of *Mesorhizobium plurifarium* sp. nov. *Int. J. Syst. Bacteriol.* 48: 369-382.

Lajudie, P. de, Willems, A., Pot, B., Dewettinck, D., Maestrojuan, G., Neyra, M., Collins, M.D., Dreyfus, B., Kersters, K. and Gillis, M. 1994. Polyphasic taxonomy of rhizobia: emendation of the genus *Sinorhizobium* and description of *Sinorhizobium meliloti* comb. nov., *Sinorhizobium saheli* sp. nov. and *Sinorhizobium teranga* sp. nov. *Int. J. Syst. Bacteriol.* 44: 715-733.

Leckie, S.E., Prescott, C.E. and Grayston, S.J. 2004. Forest floor microbial community response to tree species and fertilization of regenerating coniferous forests. *Can. J. For. Res.* 34: 1426-1435.

LiXia, Z., WeiMin, Y., ZhiGang, Y., ZhiAn, L., and MingMao, D. 2004. Soil microbial characteristics in rehabilitation process of degraded ecosystems in Heshan. *J. of Trop. and Subtrop. Bot.* 12(3): 202-206.

Marschner, P., Yang, C.H., Lieberei, R., and Crowley, D.E. 2001. Soil and plant specific effects on bacterial community composition in the rhizosphere. *Soil Biol. Biochem.* 33: 14371-445.

Meliani, A., Bensoltane, A., and Mederbel, K. 2012. Microbial diversity and abundance in soil: related to plant soil type. *Am. J. Plant Nutr. Fertilization Technol.* 2(1): 10-18.

Ming, N., Han, M., Ke, L., JiaRong, W., ZheXue, Q., ChangMing, F., JiaKuan, C., and Bo, L. 2012. Comparison of bacterial and fungal communities between natural and planted pine forests in subtropical China. *Curr. Microbiol.* 64(1): 34-42.

Muntz, A. 1890. Sur La decomposition des rockes et al formation de la terrarable. Compt. Rend. *Akad. Sci.* Paris, 110: 1370-1372.

Myers, R.T., Zak, D.R., White, D.C., and Peacock, A. 2001. Land scape level patterns of microbial community composition and substrate use in upland forest ecosystems. *Soil Sci. Soc. Am. J.* 65: 359-367.

Nga, D.T. 1994. Rhizobial inoculation on *A. mangium* and *A. auriculiformis*. *For. Res. Newsl.* 5: 12-14.

Nick, G., de Lajudie, P., Eardly, B.D., Suomalainen, S., Paulin, L., Zhang, X., Gillis, M. and Lindström, K. 1999. *Sinorhizobium arboris* sp. nov. and *Sinorhizobium kostiense* sp. nov., two new species isolated from leguminous trees in Sudan and Kenya. *Int. J. Syst. Bacteriol.* 49: 1359-1368.

Nieto, K.F. and Frankenberger, W.T. 1989. Biosynthesis of cytokinins in soil. *Soil Sci. Soc. Am. J.* 53: 735-740.

O'Donnell, A.G., Seasman, M., Macrae, A., Waite, I. and Davies, J.T. 2001. Plants and fertilisers as drivers of change in microbial community structure and function in soils. *Plant Soil.* 232: 135-145.

Ohtake, H., Wu, H., Imazu, K., Ambe, Y., Kato, J., and Kuroda, A. 1996. Bacterial phosphonate degradation, phosphite oxidation and polyphosphate accumulation. *A Res. Conserv. Recycling* 18: 125-34.

Oren, A. and Steinberger, Y. 2008. Catabolic profiles of soil fungal communities along a geographic climatic gradient in Israel. *Soil Biol. Biochem.* 40: 2578-2587.

Osonubi, O. and Mulongoy, K. 1991. Response of two Acacia species to drought and inoculation with an ectomycorrhizal fungus. *Beltsville Symposia Agric. Res.* 14: 375.

Oyun, M.B., Akharayi, F.C., and Adetuyi, F.C. 2006. Microbial population in decompsing legume litter of differing quality. *Am. J. Agric. Biol. Sci.* 1(1): 22-26.

Panda, T. 2010. Role of fungi in litter decomposition associated with *Casuarina equisetifolia* L. plantations in coastal sand dunes, Orissa, India. *Int. J. Biodivers. Sci. Manage.* 6(1/2): 52-60.

Patil S.J., Patil, H.Y., Mutanal, S.M., and Shahapurmath, G. 2012. Growth and productivity of *Acacia mangium* clones on shallow red soil. *Karnataka J. Agric. Sci.* 25(1): 94-95.

Perera, P.K.P., Amarasekera, H.S., and Weerawardena, N.D.R. 2012. Effect of growth rate on wood specific gravity of three alternative timber species in Sri Lanka; *Swietenia macrophylla, Khaya senegalensis* and *Paulownia fortune. J. Trop. For. Environ.* 2(1): 26-35.

Pradhan, N. and Sukla, L.B. 2005. Solubilization of inorganic phosphate by fungi isolated from agriculture soil. *Afr. J. Biotechnol.* 5: 850-854.

Prescott, C.E., and Grayston, S.J. 2013. Tree species influence on microbial communities in litter and soil: Current knowledge and research needs. *For. Ecol. Manage.* 309: 19-27.

Priha, O. and Smolander, A. 1999. Nitrogen transformations in soil under *Pinus sylvestris, Picea abies* and *Betula pendula* at originally similar field afforestation sites. *Biol. Fertil. Soils* 24: 45-51.

Priha, O., Grayston, S.J., Hiukka, R., Pennanen, T., and Smolander, A. 2001. Microbial community structure and characteristics of the organic matter in soils under *Pinus sylvestris, Picea abies* and *Betula pendula* seedlings at two forest sites. *Biol. Fertil. Soils* 33: 17-24.

Pritchett, W.L. 1979. Properties and management of forest soils. In: *Properties and Management of Forest Soils*. Publisher – John Wiley and Sons, New York, 500p.

Raghu, K. and MacRae, I.C. 1966. Occurrence of phosphate-dissolving microorganisms in the rhizosphere of rice plants and in submerged soils. *J. Appl. Bacteriol.* 29: 582-6.

Rahman, G.M.M., Nara, K., and Hogetsu, T. 2000. Assay of host specificities of rhizobial strains on *Acacia mangium* from different provenances and different Acacia species. Bulletin of the Tokyo University Forests 103: 333-337.

Rajendran, K. and Devaraj, P. 2004. Biomass and nutrient distribution and their return of *Casuarina equisetifolia* inoculated with biofertilizers in farm land. *Biomass Bioenergy* 26: 235-249.

Rajendran, K., Sugavanam, V., and Devaraj, P. 2000. Influence of biofertilizers on the biomass production of *Casuarina equisetifolia* in farm forestry. *Bangladesh J.For. Sci.* 29(1): 26-36.

Rao, S.W.V.B. and Sinha, M.K. 1963. Phosphate dissolving organisms in the soil and rhizosphere. *Indian J. Agric. Sci.* 33: 272-278.

Rathod, R. and Devar, K.V. 2004. Available nutrient status of soil under different plant communities. *Karnataka J. Agric. Sci.* 17(1): 132-133.

Ravichandran, V.K. and Balasubramanian, T.N. 1999. Growth response of *Casuarina equisetifolia* seedlings to dual inoculation of Frankia and VAM (*Glomus fasciculatum*). *J. Ecobiol.* 11(3): 175-179.

Reddell, P. 1990. Increasing productivity in plantings of *Casuarina* by inoculation with Frankia. In: El-Lakany, M.H., Turnbull, J.W., and Brewbaker, J.L. (eds), *Advances in Casuarina Research and Utilization*. Proceedings of the Second International *Casuarina* Workshop, Cairo, Egypt, pp. 133-140.

Reddell, P., Rosbrook, P.A., Bowen, G.O., and Gnale, D. 1988. Growth response in *Casuarina cunnighamiana* plantings inoculation with Frankia. *Plant Soil* 108: 76-86.

Ricklefs, R.E. and Matthew, K.K. 1982. Chemical characteristics of the foliage of some deciduous trees in southeastern Ontario. *Can. J. Bot.* 60: 2037-2045.

Rodrigues, H.J.B., Sá, L.D. de A., Ruivo, M. de L.P., Costa, A.C.L. da, Silva, R.B. da, Moura, Q.L. de, and Mello, I.F. de 2011. Quantitative microbial population variability associated with the miçroclimate conditions observed in tropical rainforest soil. *Revista Brasileira de Meteorologia* 26(4): 629-638.

Rodríguez, H. and Fraga, R. 1999. Phosphate solubilizing bacteria and their role in plant growth promotion. *Biotechnol. Adv.* 17: 319-339.

Rousk, J., Baath, E., Brookes, P.C., Lauber, C.L., Lozupone, C., Caporaso, J.G., Knight, R., and Fierer, N. 2010. Soil bacterial and fungal communities across a pH gradient in an arable soil. *ISME J.* 4: 1340-1351.

Rousk, J., Brookes, P.C., and Baath, E. 2009. Contrasting soil pH effects on fungal and bacterial growth suggest functional redundancy in carbon mineralization. *Appl. Environ. Microbiol.* 75(6): 1589-1596.

Royer-Tardif, S., Bradley, R.L. and Parsons, W.F.J. 2010. Evidence that plant diversity and site productivity confer stability to forest floor microbial biomass. *Soil Biol. Biochem.* 42: 813-821.

Saadoun I., Gharaibeh R. 2003. The Streptomyces flora of Badia region of Jordan and its potential as a source of antibiotics active against antibiotic-resistant bacteria. *J. Arid Environ.* 53: 365-371.

Sanginga, N., Vanlauwe, B., and Danso, S.K.A. 1995. Management of biological N2 fixation in alley cropping systems: estimation and contribution to N balance. *Plant Soil* 174(1/2): 119-141.

Sankaran, K.V. and Balasundaran, M. 2001. Soil microflora of the sholas of Eravikulam National Park, Idukki District. In: Nair, K.K.N., Khanduri, S.K., and Balasubramanyan, K. (eds), Shola forests of Kerala: environment and biodiversity pp. 151-178.

Sarkar, K. 2010. Evaluation of nitrogen fixing potential of indigenous tree legume rhizobia under acid stress condition of lateritic soil in West Bengal. *Environ. Ecol.* 28(2A): 1149-1155.

Sassi, M.B., Dollingera, J., Renault, P., Tlili, A., and Bérard A. 2012. The FungiResp method: An application of the MicroResp method to assess fungi in microbial communities as soil biological indicators. *Ecol. Indicators* 23: 482-490.

Scherer-Lorenzen, M., Körner, C., and Schulze, E.D. 2005. The functional significance of forest diversity: a synthesis. In: Scherer-Lorenzen, M., Körner, C., and Schulze, E.D. (Eds), *Forest Diversity and Function: Temperate and Boreal Systems*. Springer, Berlin, Heidelberg, New York, pp. 377-389.

Schiavo, J.A., Busato, J.G., Martins, M.A., and Canellas, L.P. 2009. Recovery of degraded areas revegeted with *Acacia mangium* and Eucalyptus with special reference to organic matter humification. *Scientia Agricola* 66(3): 353-360.

*Schlegel H. 2000. Mikrobiologia ogólna. Warszawa: PWN.

Selvi, K.S.T., Mohan, V., and Udaiyan, K. 2008. Study on the status of rhizobial nodulation in *Acacia auriculiformis* and *A. mangium*. *Indian For.* 134(11): 1512-1520.

Sempavalan, J., Santhanakrishnan, P., and Kumutha, K. 2001. Effect of Frankia strains associated with VA Mycorrhiza on *Casuarina equisetifolia*. *Madras Agric. J.* 88(7/9): 519-521.

Shah, S.K., Shah, R.P., Xu, H.L., and Aryal, U.K. 2006. Biofertilizers: an alternative source of nutrients for sustainable production of tree crops. *J. Sustain. Agric.* 29(2): 85-95.

ShangShyng, Y., HsiaoYun, F., ChiunKai, Y., and IChien, L. 2003. Microbial population of spruce soil in Tatachia mountain of Taiwan. *Chemosphere* 52(9): 1489-1498.

ShangShyng, Y., ShuHsien, T., HsiaoYun, F., ChiunKai, Y., WeiLan, H., and ShineTsern, C. 2006. Seasonal variation of microbial ecology in hemlock soil of Tatachia Mountain, Taiwan. *J. Microbiol. Immunol. Infection* 39(3): 195-205.

Shantharam, S. and Mattoo, A.K. 1997. Enhancing biological nitrogen fixation: an appraisal of amount and alternative technologies for N input into plants. *Plant Soil* 194: 205-216.

Sharma, B.K., Sarma, H.K., Shukla, A.K., and Tiwari, S.C. 2009. Impact of seabuckthorn stands on rhizospheric and soil microbial population. *Indian J. For.* 32(2): 263-268.

Sharma, J.K., Sankaran, K.V., Balasundaran, M., and Sankar, S. 1996. *Use of mycorrhizal and nitrogen fixing symbionts in reforestation of degraded acid soils of Kerala*. KFRI Research Report, 51p.

Sidhu, O.P., Behl, H.M., Gupta, M.L., and Janardhanan, K.K. 1990. Occurrence of vesicular-arbuscular mycorrhiza of *Casuarina equisetifolia* L. *Curr. Sci.* 59(8): 422-423.

Silva, R.G., Jorgensen, E.E., Holub, S.M., and Gonsoulin, M.E. 2005. Relationships between culturable soil microbial populations and gross nitrogen transformation processes in a clay loam soil across ecosystems. *Nutr. Cycling Agroecosyst.* 71(3): 259-270.

Singh, A.K., Ashutosh, S., Pandey, D.K., Lal, R.B., and Banerjee, S.K. 1994. Nitrogen enrichment of bhata soil and nutrient uptake by some Acacia species at nursery stage. *Indian Agric.* 38(2): 113-119.

Singh, K.S.D., Arifin, A., Radziah, O., Shamshuddin, J., Hazandy, A.H., Majid, N.M., Aiza-Shaliha, J., Rui, T. X., and Keeren, S. R. 2013. Status of soil microbial population, enzymatic activity and biomass of selected natural, secondary and rehabilitated forests. *Am. J. Environ. Sci.* 9(4): 301-309.

Smalla, K., Wieland, G., Buchner, A., Zock, A., Parzy, J., Kaiser, S., Roskot, N., Heuer, H., and Berg, G. 2001. Bulk and rhizosphere soil bacterial communities studied by denaturing gradient gel electrophoresis: plant-dependent enrichment and seasonal shifts revealed. *Appl. Environ. Microbiol.* 67: 4742-4751.

Smith, K.P. and Goodman, R.M. 1999. Host variation for interactions with beneficial plant-associated microbes. *Annu Rev. Phytopathol.* 37: 473-491.

Sparks and Huang, P.M., 1985. Physical chemistry of soil potassium. In Potassium in agriculture. *Am. Soc. Agron. J.* pp.201-276.

Sperberg, J.I. 1958. The incidence of apatite solubilizing organisms in the rhizosphere and soil. *Aust. J. Agric. Resour. Econ.* 9: 778.

Sprent, J.I. 1984. Effects of drought and salinity on heterotrophic nitrogen fixing bacteria and on infection of legumes by rhizobia. In: Veeger, C. and Newton, W.E. (eds), *Advances in Nitrogen Fixation Research*. Martinus Nijhoff/Dr W. Junk, The Hague, pp. 295-302.

Sprent, J.I. and Parsons, R. 2000. Nitrogen fixation in legume and non-legume trees. *Field Crops Res.* 65: 183-196.

Steenwerth, K.L., Drenovsky, R.E., Lambert, J.J., Kluepfel, D.A., Scow, K.M., and Smart, D.R. 2008. Soil morphology, depth and grapevine root frequency influence microbial communities in a Pinot noir vineyard. *Soil Biol. Biochem.* 40: 1330-1340.

Strickland, M.S. and Rousk, J. 2010. Considering fungal: bacterial dominance in soils methods controls, and ecosystem implications. *Soil Biol. Biochem.* 42: 1385-1395.

Subbarao, N.S. 1988. Phosphate solubilizing micro-organism. In: Biofertilizer in agriculture and forestry. Regional Biofert. Dev. Centre, Hissar, India. pp. 133-142.

Tamilsselvi, K.S., Mohan, V., and Udaiyan, K. 2010. Effect of soil properties on the distribution of AM fungi in Acacia ecosystems. *Plant Arch.* 10(1): 33-35.

Tangjang, S., Arunachalam, K., Arunachalam, A., and Shukla, A.K. 2009. Microbial population dynamics of soil under traditional agroforestry systems in northeast India. *Res. J. Soil Biol.* 1(1): 1-7.

Taylor, J.P., Wilson, B., Mills, M.S., and Burns, R.G. 2002. Comparison of microbial numbers and enzymatic activities in surface soils and sub soils using various techniques. *Soil Biol. Biochem.* 34: 387-401.

Thomas, K.D., and Prescott, C.E., 2000. Nitrogen availability in forest floors of three tree species on the same site: the role of litter quality. *Can. J. For. Res.* 30: 1698-1706.

Thoms, C. and Gleixner, G. 2013. Seasonal differences in tree species' influence on soil microbial communities. *Soil Biol. Biochem.* 66: 239-248.

Tilki, F. and Fisher, R. F. 1998. Tropical leguminous species for acid soils: studies on plant form and growth in Costa Rica. *For. Ecol. Manage.* 108: 175-192.

Timonen, S., Finlay, R.D., Olsson, S., and Soderstrom, B. 1996. Dynamics of phosphorous translocation in intact ectomycorrhizal systems: non-destructive monitoring using a B-scanner. *FEMS Microbial. Ecol.* 19: 171-180.

Tiwari, S.C. 1998. Influence of *Casuarina equisetifolia* plantation on soil properties raised in Arunachal Pradesh. *Mycorrhiza News* 10(2): 13-14.

Treseder, K.K. 2005. Nutrient acquisition strategies of fungi and their relation to elevated atmospheric CO2. In: Dighton, J., White, J.F., and Oudemans, P. (eds), *The Fungal Community* (3rd Ed.). Taylor & Francis, New York, pp. 713-731.

Turk, D., and Keyser, H.H. 1992. Rhizobia that nodulate tree legumes: specificity of the host for nodulation and effectiveness. *Can. J. Microbiol.* 38(6): 451-460.

Turner, D.P., Sollins, P., Leuking, M., and Rudd, N. 1993. Availability and uptake of inorganic nitrogen in mixed old-growth coniferous forest. *Plant Soil* 148: 163-174.

Uroz, S., Calvaruso, C., Turpaul, M.P., Pierrat, J.C., Mustin, C., and Frey-Klett, P. 2007. Effect of the mycorrhizosphere on the genotypic and metabolic diversity of the bacterial communities involved in mineral weathering in a forest soil. *Appl. Environ. Microbiol.* 73: 3019-3027.

Valdes, M., Rodrigo, C.A., Leyva, M.A., and Camacho, A.D. 2004. Promotion of *Casuarina equisetifolia* (L.) growth in the nursery by symbiotic microorganisms. *Terra* 22(2): 207-215.

Vessey, J.k. 2003. Plant growth promoting rhizobacteria as bio-fertilizers. *Plant Soil* 255: 571-586.

Vieira, F.C.S. and Nahas, E. 2005. Comparison of microbial numbers in soils by using various culture media and temperatures. *Microbiol. Res.* 160(2): 197-202.

Wahab, A.A.M. 1980. Nitrogen-fixing nonlegumes in Egypt. I. Nodulation and N_2 (C_2H_2) fixation by *Casuarina equisetifolia*. *Zeitschrift fur Allgemeine Mikrobiologie* 20(1) 3-12.

Walkley, A.J. and Black, J.A. 1934. Estimation of soil organic carbon by chromic acid titration method. *Soil Sci.* 31: 29-38.

Wall, D.H. and Virginia, R.A. 1999. Controls on soil biodiversity: insights from extreme environments. *Appl. Soil Ecol.* 13: 137-150.

Wardle, D.A. 1992. A comparative assessment of factors which influence microbial biomass carbon and nitrogen levels in soil. *Biol. Rev.* 67: 321-358.

Wardle, D.A. 2002. *Communities and Ecosystems: Linking the Aboveground and Belowground Components*. Princeton University Press, Princeton, 408p.

Wardle, D.A., Yeates, G.W., Barker, G.M., and Bonner, K.I. 2006. The influence of plant litter diversity on decomposer abundance and diversity. *Soil Biol. Biochem.* 38: 1052-1062.

Whitelaw, M. A. 2000. Growth promotion of plants inoculated with phosphate solubilizing fungi. *Adv. Agron.* 69:99-151.

Whitman, W.B., Coleman, D.C., and Wiebe, W.J. 1998. Procariote the unseen majority. *Proc. Natl. Acad. Sci.* 95: 6578-6583.

Wieland, G., Neumann, R., and Backhaus, H. 2001. Variation of microbial communities in soil, rhizosphere, and rhizoplane in response to crop species, soil type, and crop development. *Appl. Environ. Microbiol.* 67: 5849-5854.

Wright, S.F. and Upadhyaya, A. 1998. A survey of soils for aggregate stability and glomalin, a glycoprotein produced by hyphae of arbuscular mycorrhizal fungi. *Plant Soil.* 198: 97-107.

XinTao, M., Yong, L., QiangJun, L., MinWe, G., and ChunGen. P. 2010. Analysis of microbial flora and dominant populations in three types of *Pinus massoniana* forests in Yunyang County of the Three Gorges Reservoir

Area: I. Bacteria, Bacillus and fungi species in forest land soil. *For. Res. Beijing* 23(4): 560-566.

Yamashita, N., Ohta, S., and Hardjono, A. 2008. Soil changes induced by *Acacia mangium* plantation establishment: Comparison with secondary forest and *Imperata cylindrica* grassland soils in South Sumatra, Indonesia. *For. Ecol. Manage.* 254: 362-370.

Yao, H., He, Z., Wilson, M.J., and Campbell, C.D. 2000. Microbial biomass and community structure in a sequence of soils with increasing fertility and changing land use. *Microb. Ecol.* 40: 223-237.

YongKwon, L. and SuYoung, W. 2012. Changes in litter, decomposition, nitrogen mineralization and microclimate in *Acacia mangium* and *Acacia auriculiformis* plantation in Mount Makiling, Philippines. *Int. J. of Phys. Sci.* 7(12): 1976-1985.

Young, C.C. 1990. Effects of phosphorus-solubilizing bacteria and vesiculararbuscular mycorrhizal fungi on the growth of tree species in subtropical-tropical soils. *Soil Sci. Plant Nutr.* 36(2): 225-231.

Zak, D.R., Holmes, W.E., White, D.C., Peacock, A.D., and Tilman, D. 2003. Plant diversity, soil microbial communities, and ecosystem function: are there any links? *Ecol.* 84: 2042-2050.

Zhang, Y., Zhong, C.L., Chen, Y., Chen, Z., Jiang, Q.B., Wu, C., and Pinyopusarerk, K. 2010. Improving drought tolerance of *Casuarina equisetifolia* seedlings by arbuscular mycorrhizas under glasshouse conditions. *New For.* 40(3): 261-271.

* Original not seen

SOIL PRODUCTIVITY CHANGES UNDER SELECTED EXOTIC FOREST TREE SPECIES WITH SPECIAL REFERENCE TO BENEFICIAL MICROFLORA

By

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ABSTRACT OF THE THESIS

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ABSTRACT

A field investigation was carried out with four exotic tree species (*Acacia auriculiformis, A. mangium, Casuarina equisetifolia* and *Swietenia macrophylla*) planted at 2 m × 2 m spacing and of about 30 years age at Kerala Forest Research Institute sub-centre Nilambur during 2013-2014. The specific objective of the study was to examine the variations in soil productivity, with special reference to the beneficial microflora, due to long term occupancy of these trees. The rhizosphere soils were collected for isolation and enumeration of soil microflora like actinomycetes, bacteria, fungi, N-fixing bacteria, P-solubilises and K-solubilising bacteria population at quarterly interval for a period of one year. The soil physico-chemical properties under the trees were also assessed.

It was found that, over the years, the tree species influenced the soil physico-chemical properties. The lowest bulk density and pH were associated with tree plots compared to the treeless plots. However, the soil moisture content was not significantly different. The soil organic carbon, total nitrogen and exchangeable potassium were significantly higher (2.15%, 0.13% and 80.15 kg ha^{-1} respectively) in *S. macrophylla* and the lowest (1.38%, 0.07% and 52.34 kg ha^{-1} respectively) in treeless control plot. Available nitrogen and available phosphorus were significantly higher (71.6 kg ha^{-1} and 4.42 kg ha^{-1} respectively) in *A. mangium* and the lowest (39.05 kg ha^{-1} and 4.08 kg ha^{-1}) in treeless plot.

Tree species greatly influenced the soil microflora population. In general, microflora population was higher in tree plots than the treeless control. During the entire period of study, *A. auriculiformis* had highest mean bacteria, fungi and nitrogen fixing bacteria population while the highest population of phosphorus solubilizing microorganism and potash solubilizing bacteria was recorded in *A. mangium*. The highest mean population of actinomycetes was associated with *C. equisetifolia*.

Seasonal variation in microflora population was obvious. Actinomycetes population was, generally, the lowest during rainy season and the peak population

during early summer season and late summer-II. The bacterial population was the maximum during rainy season and the lowest during early summer season. The fungal population was more in both the late summer (2013 and 2014) seasons and the lowest in the winter season. Nitrogen fixing bacteria population was highest in the late summer-I and found to decrease through the rainy season and winter season. The populations of phosphate solubilizers and potash solubilizing bacteria were highest in late summer-I season and lowest in the rainy season (phosphate solubilizer) and winter season (potash solubilising bacteria).

A. mangium had the maximum height (19.90 m) followed by *C. equisetifolia, A. auriculiformis* and the lowest was for *S. macrophylla.* Diameter at breast height was also highest in *A. mangium* (24.31 cm) followed by S. *macrophylla, A. auriculiformis* and *C. equisetifolia*

The present study highlighted the influence of tree species on microflora population. Microflora population was found to be significantly higher in tree species compared to nearby treeless control plot and was found to be varying according to seasons. All the tree species have shown higher soil nutrient content than treeless plot. These four exotic tree species in the present study is seen to take part actively in the improvement of soil quality and soil health which are the major determinants of sustainable soil productivity.