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Review Article

Restoration of Mine Spoil in a Dry Tropical Region: A Review

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Surface mining extensively alters the physical, chemical and biological characteristics of the soil, and therefore, the re-vegetation of mine spoil through natural process takes a very long time and poses a major problem because nutritionally it is a recalcitrant medium for plant growth. We review important studies on the restoration of mine spoils in the tropical dry region of India. Through this communication, we suggest that the microbial biomass of soil is a critical factor in the recovery of mine spoils because it plays a major role in the re-establishment of nutrient cycling. The levels of microbial biomass C, N and P can be treated as functional indexes for soil re-development. Tree plantations have been reported to significantly accelerate the re-development process. Ground seeding of the mine spoils with suitable tree and grass species together with NPK fertilization has been reported to promote growth, and consequently leads to increase in biomass production. Species-specific variations are reported to occur in the response to fertilization. Relatively, greater variation has been reported for non-leguminous, rather than for leguminous species. Furthermore, leguminous species exhibit higher growth rates as compared to non-leguminous species. Our review also suggests that the microsite conditions on the mine spoils exhibit differences and should be given more consideration for accelerating the process of re-vegetation and fulfilling the post-mining land use objectives.

Keywords: Restoration; Mine Spoil; Microbial Biomass; Fertilization; Revegetation

Introduction

Rapid expansion of human population, together with development in technology and economy has significantly altered the terrestrial biosphere by processes such as environmental pollution and forest degradation (Singh and Jha, 1993; Bradshaw, 1997; Parrotta and Knowles, 2001; Chaturvedi *et al.*, 2017a; Chaturvedi *et al.*, 2017b). One of the processes associated with the economic development is surface mining, which leads to drastic alteration in biological, physical and chemical properties of the soil, and therefore, natural recovery of these altered systems is generally a slow process (Croxton, 1928; Down, 1975; Bradshaw and Chadwick, 1980; Roberts *et al.*, 1981; Marrs *et al.*, 1981; Ahirwal *et al.*, 2017a), and resembles the primary succession on natural materials (Bradshaw, 1983; Wali, 1987). Establishment of natural vegetation on the mine spoil through the natural process of succession and recuperation of soil quality to a stage similar to un-degraded natural forest may take a long time (50-100 years) due to the adverse soil conditions for plant growth (Bradshaw, 1997). Several reports have suggested that the slow recovery of mine spoil is largely due to constraints in microbial growth (Lindermann *et al.*, 1984; Smejkalova *et al.*, 2003; Kavamura and Esposito, 2010), and the vegetation succession (Jha and Singh, 1991; Singh *et al.*, 2002; Tordoff *et al.*, 2000; Pandey and Maiti, 2008). Mining eliminates plants, removes soil by excavation, alters microbial communities, reshapes landforms, and disrupts surface and subsurface hydrologic regimes (Herath *et al.*, 2009; Sheoran *et al.*, 2010; Shrestha and Lal, 2011). Mining indeed is one of the most notable forms of human-caused ecosystem degradation. According to Ghose (2001)

**Author for Correspondence: E-mail: ravikantchaturvedi10@gmail.com; ravi@xtbg.ac.cn* and Maiti (2012), more than 90% of coal in India has been mined through open strip mining methods making massive degradation of forest land inevitable. When the desired material is removed, original soils are lost in the process, or they are deeply buried by wastes. In the open cast coal mining huge amount of infertile overburden material is dumped on the nearby unmined land; creating a major problem in rehabilitation of such heavily disturbed ecosystem. Overburden dumps are characterised by such factors as increased bioavailability of metals, more sand content, lack of sufficient moisture, increased bulk density, and relatively low soil organic matter (Sheoran *et al.*, 2010). Acidic dumps can release salt or may contain sulphidic material, which can generate acid-mine-drainage (Ghose, 2005). There are multiple effects of mine wastes: geo-environmental disasters, pollution of water and air, soil erosion, toxicity, biodiversity loss, which ultimately leads to economic loss of the country (Wong, 2003; Sheoran *et al.*, 2008). The physico-chemical characteristics of mine spoils are unfavourable, containing low organic matter content, thereby creating rigorous conditions for the growth of microbes and plants (Jha and Singh, 1993; Singh *et al.*, 1995; Singh *et al.*, 2002; Singh *et al.*, 1996; Singh and Singh, 1999). Sometimes the mine spoil conditions become highly variable, both within and among sites, and similarly the vegetation is also found extremely variable (Gibson, 1982). In the mine spoil microbial diversity and nutrients are very poor and biologically it is toxic (Wali, 1975; Singh and Jha, 1993), therefore, to prevent the contamination of adjoining agricultural lands and rivers from the harmful leachates, stabilization of mine spoils is needed.

Weathering and oxidisation of rock fragments can lead to rapid changes in the pH of a given mine soil (Sheoran *et al.*, 2010). pH is abruptly lowered when Pyritic minerals (FeS_2) oxidize into sulfuric acid, while the pH becomes high when carbonate ($Ca/MgCO_3$) rocks and minerals weather and dissolve. Maiti and Ghose (2005) have reported a pH of 4.9 to 5.3 in the dumping site of a coal mine situated in Central Coalfield Limited's (CCL), North Karanpura, Ranchi district, India which indicates the acidic nature of the dump. At pH lower than 5, Maiti (2003) has observed increased bio-availability of toxic metals such as cadmium, nickel and lead. The three major macronutrients, N, P and K are generally deficient in overburden dumps (Coppin and Bradshaw, 1982; Sheoran *et al.*, 2008). The stone content in overburden dumps may be rather high and range between 35%-65%, with an average value of 55% (Maiti and Ghose, 2005). The content of coarse particles (larger than 2 mm) in a typical mine spoil varies between less than 30 to more than 70% and depends on the hardness of rock, blasting techniques, and process of spoil handling (Sheoran *et al.*, 2010). Ghose (2005) reported 66% sand content and only 8.6% clay in a mined soil. Singh *et al.* (2004a) and Singh and Singh (2006) reported 80% sand and only 11% clay at the Singrauli Coal field India. It is known that compared to the fine textured soils, sandy mine soils hold less nutrients and water.

Soil aggregation controls soil hydrology, affects soil diffusion and nutrient availability (Lindemann *et al.*, 1984; Heras, 2009), reduces erosion potential (Elkins *et al.*, 1984), and induces stabilization of organic carbon and long-term sequestration (Six *et al.*, 2004). When mining begins and the naturally existing soil layers are removed and stockpiled at another place, aggregate structure breaks down and the newly formed soil becomes compact reducing aeration and water holding capacity. Micro-aggregates are more stable and resilient than macro-aggregates, as the organic matter involved in binding the soil particles together occupy the pores which are too small for microorganisms to reside (Gregorich *et al.*, 1989). Several factors such as; the sampling time, dump height, presence of stone, organic carbon concentration, and the litter layer texture and thickness on the dump surface influence moisture content in a dump (Donahue *et al.*, 1990). The moisture content in the overburden dumps, during the peak summer season (May-June), has been reported as low as 2-3% (Maiti *et al.*, 2002). Further, mine spoils are generally compact and are characterised by high bulk density, because of which plant growth is limited since most species are unable to extend roots effectively to deeper layers (Maiti and Ghose, 2005).

The primary objective of re-vegetation of mine spoils is to control erosion through plant cover in the short-term and development of a self-sustaining community through re-colonization of native plants in the long-term. Reclamation is argued to be an effective way to improve soil quality in mining areas (Tripathi *et al.*, 2016). The mine spoils lack most of the physical, chemical and biological characteristics of normal soils, and the results of the changes in soil structure and nutrient accumulation during ecosystem re-development are observable in terms of changes in biomass levels and in species composition (Bradshaw, 1983). Successful reclamation can be evaluated in many ways, but soil quality is among the most important indicators of restoring functional ecosystems. Maharana and Patel (2013) followed the soil reclamation process over a period of 10 years in the Basundhara (west) open cast colliery of Mahanadi Coalfields Limited (MCL), Sundargarh, Odisha and reported a progressive increase in clay content, water holding capacity and soil organic carbon, and estimated that the mine spoil at their study site shall take approximately 28 years for the soil features to become similar to adjoining native forest soil through the process of reclamation. Tripathi *et al.* (2016) reported significant increase in soil organic carbon and microbial biomass carbon (MBC) with increasing age of re-vegetation: between 2009 and 2011 above-ground biomass increased 23 times and below-ground biomass 26 times.

Long-term mine spoil restoration requires the establishment of stable nutrient cycles aided by plant growth and microbial processes (Singh *et al.*, 2002; Sheoran *et al.*, 2010). Soil development on reclaimed mine site depends on mineral weathering, and properties of the reclaimed soil may differ substantially from those of the original soils (Sencindiver and Ammons, 2000). Litterfall and decomposition is the starting point of development of soil organic carbon and nutrient stocks, therefore the surface horizon of mined land can be used as a proxy to determine the progress and success of restoration (Akala and Lal, 2000). Crocker and Major (1955), Dancer *et al.* (1977) and Roberts *et al.* (1981) have reported nutrient accumulation as an important process of ecosystem development in naturally colonized spoils. Soil is the basis of vegetation restoration in post-mining lands, and determines the direction of land use after reclamation. Therefore, knowledge about soil dynamics during reclamation and recovery is particularly significant to guide the future ecological restoration (Dutta and Agrawal, 2003; Courtney *et al.*, 2009; Ahirwal *et al.*, 2017a). Importance of nutrient dynamics in the development of mine soil and its role in global climate change has been recently highlighted (Shrestha and Lal, 2011; Mukhopadhyay and Maiti, 2014; Mukhopadhyay *et al.*, 2016).

As already mentioned, natural restoration is a slow process (Iverson and Wali, 1982; Jha and Singh, 1991; Jha and Singh, 1992), but it can be accelerated by planting trees and herbaceous species. This two-tiered vegetation elevates the mine spoil bio-diversity and biological fertility (Singh *et al.*, 1996). To overcome the problem of nutritional deficiency, fertilizers are often applied. Several studies have reported increase in biomass and productivity of herbaceous species after fertilization (Schoenholtz *et al.*, 1992; Piha *et al.*, 1995; Singh *et al.*, 1996). However, fertilization exhibits variable effect on the growth of woody species planted on mined land (Vogel, 1981).

For the long-term sustainability, restoration process at a mining area is aimed to develop an ecosystem which is native to the area (Chambers *et al.*, 1994). In the ecological restoration process, major focus is given towards the species persistence through natural recruitment and survival, functioning of food webs, and system-wide conservation of nutrients via interactions among animals, plants and the detritivore community (Jackson *et al.*, 1995). After the removal of top soil, soil seed-bank and root stocks are eliminated and soil profile is disturbed, which ultimately slows down the process of natural succession on mine spoils (Parrotta, 1992). But it has been reported that the rehabilitation process may be enhanced by planting suitable indigenous species together with ground seeding of herbaceous flora (Singh *et al.*, 1995; Singh *et al.*, 1996). Plantations can play a major role in the rehabilitation of spoils (Singh *et al*., 2002). On the severely degraded sites, plantations have exhibited marked catalytic effects on the development (succession) of native forest, compared to the sites which are left unplanted (Parrotta *et al.*, 1997; Parrotta and Knowles, 2001). Possessing variable growth characteristics, species vary in their stabilizing and nutrient enriching capacity. Trees and shrubs usually provide a permanent vegetation cover on mined sites with little or no aftercare. Trees can help maintain or increase the soil organic matter, nitrogen fixation, or decrease the erosion rate, and improve soil physico-chemical and biological properties (Jha and Singh, 1991; Frouz *et al.*, 2009). However, impact of trees on soil fertility will depend on their nutrient cycling characteristics, for example litter chemistry and decomposition (Byard *et al.*, 1996). Since not all the tree species are equally capable of developing in a harsh mining environment, selection of species that can tolerate a wide range of climatic conditions such as drought, high temperature, and nutrient-poor condition is important for restoration effort (Ahirwal *et al.*, 2017b). Those tree species which are able to grow under nutrient-poor conditions and accumulate high biomass are suitable for re-vegetaion of mine spoil (Singh *et al.*, 2006; Mukhopadhyay *et al.*, 2013; Mukhopadhyay *et al.*, 2014). Grasses (*Pennisetum pedicellatum, Cymbopogon citratus*) and legumes (*Stylosanthes humilis, S. hamata, Sesbania sesban*, and *Crotalaria juncea*) effectively control erosion in early stages of mine spoil restoration (Maiti and Saxena, 1998; Maiti and Maiti, 2015). On the mine lands, grasses play both positive and negative role as besides stabilizing the soils they also compete with the regenerating woody species. Particularly, C_4 grasses have ability to tolerate drought, low soil nutrients and many other climatic stresses. Fibrous roots of grasses can slow erosion, stabilize soil, conserve soil moisture and can result in the formation of a layer of organic soil. Since, the initial plant cover mainly constitutes grasses, they support the development of self-sustaining diverse plant communities (Shu *et al.*, 2002; Singh *et al.*, 2002; Hao *et al.*, 2004).

Vegetation contributes to the accumulation of soil organic matter and plant nutrients. Development of a sufficient organic matter pool to serve as N source and sufficient N-mineralization potential, resulting into nutrient release rates that are adequate for plant growth are essential for sustaining vegetation at an acceptable level of production (Bradshaw *et al.*, 1986). Microorganisms contribute to the re-establishment of biogeochemical processes, and play an important role in soil re-development and in the maintenance of soil fertility. The importance of microorganisms in soil formation and revegetation through their activities as decomposers and nutrient cyclers, N_2-fixers and mycorrhizal symbionts has been widely recognized. Soil microbial biomass (a living part of the soil organic matter) is an agent for transformation of added and native organic matter and a reservoir for N, P and S (Jenkinson and Ladd, 1981). In general, plants serve as an important carbon source for the microbial community and in turn microbes provide nutrients for plant growth through mineralization. Recognition of the importance of soil microorganisms in functioning of ecosystems has attracted considerable interest towards the measurement of nutrients held in the microbial biomass (Jenkinson and Powlson, 1976; Brookes *et al.*, 1982; Brookes *et al.*, 1984; Brookes *et al.*, 1985; Powlson *et al.*, 1987; Srivastava and Singh, 1988; Srivastava and Singh, 1989; Singh *et al.*, 1989).

According to Moreno-de las Heras *et al.* (2008), analysis of the spatial distribution patterns of afforested plants on restored mine spoils may provide information which can be used to test for the underlying restoration measures. Zhao *et al.* (2012) argued that the processes and spatial patterns of afforested plants are important for examining whether or not the implemented reclamation measures have been able to develop sustainable plant communities and to provide theoretical evidence for improving ecological recovery techniques. Zhao *et al.* (2015) have reported on the changes in the population structure, size class structure, and spatial distribution patterns of *Robinia pseudoacacia* (ROPS) and *Pinus tabuliformis* (PITA) mixed forests after a 17-year succession, in the Pingshuo opencast mine spoil located in Shuozhou city, northern Shanxi Province, north-western China and provided basic information on relevant ecological research and conduction in the vegetation restoration of opencast coal mines.

Restored site has a large potential to sequester atmospheric C that may vary with the climatic conditions and the plant species used for reclamation (Lal, 2005; Pietrzykowski and Daniels, 2014). The development of vegetation cover and improvement in soil properties on reclaimed sites can result in sequestering more atmospheric CO_2 with an increase in the age of reclamation (Amichev *et al.*, 2008). However, the root and microbial respiration also results in emission of CO_2 from soil surface into the atmosphere (Kutsch *et al.*, 2009). Soil respiration is the main source of CO_2 released from the soil and it varies with the climatic conditions, ecosystem type and soil organic carbon (SOC) concentration (Rastogi *et al.*, 2002; Vodnik *et al.*, 2009; Ota and Yamazawa, 2010). Ahirwal *et al.* (2017b) have assessed the impact of reclamation on soil properties, accretion of soil C and N stock, changes in ecosystem C pool and soil CO_2 flux in Rohini open strip mining project located at the south of the river Damodar in Burmu block of Ranchi district, Central Coal fields limited (CCL)

Jharkhand. These authors reported that the fertility of reclaimed mine soil increased with the age of reclamation: after 7 to 11 years of reclamation, soil C and N stocks increased two times, C sequestration rate was 1.71 Mg C ha^{-1} yr^{-1} and the total ecosystem C pool increased at 3.72 Mg C ha^{-1} yr^{-1}. After 11 years of reclamation, soil CO_2 flux (2.36 ± 0.95 μmol $m^{-2}s^{-1}$) was four times higher than that of the natural forest soil. Thus, these authors found that reclaimed mine soil acted both as a sink and source of CO_2 in the terrestrial ecosystem.

In this article, we review important findings on the restoration of mine spoils in the dry tropical environment, with particular reference to India, based on the studies conducted by our group at the Banaras Hindu University. Further, we have used the terms restoration, rehabilitation and reclamation as synonyms.

Changes in Soil Biomass C, N and P During Restoration

Very few studies have appeared in the literature which define the effects of severe soil disturbance, caused by surface mining, on general microbiological activities and related soil microbial biomass. In the coal mine areas, Wilson (1965) investigated microbiology of non-vegetated, vegetated and undisturbed sites and observed an increase in the numbers of actinomycetes and bacteria in mine spoils as vegetation became established. Lawrey (1977a) and Lawrey (1977b) collected fungal samples from strip-mined habitat (non-vegetated, re-vegetated) and from undisturbed sites, and observed very low number of fungal genera in the non-vegetated habitat, due to complete absence of plant litter. Stroo and Jenks (1982) measured the microbial respiration and activities of soil enzyme in mine spoil in the initial stages of soil formation and compared the measurements with those from native soils. They observed less respiratory activity in barren mine spoils compared to native soils. On accumulation of organic matter and nitrogen in the mine spoils, the activity of microbes slowly recovered. The study showed the importance of the association between vegetation and the microbial development in the disturbed mine lands. Hershman and Temple (1978) estimated adenosine triphosphate (ATP) as a factor for the characterization of microbial status in the coal strip mine spoils and found greater levels of ATP in native range soils than the spoils. Jurgensen (1978) and Cundell (1977) emphasized the importance of soil microflora in ensuring satisfactory plant growth and subsequent formation of soil organic matter during re-vegetation of strip-mined land. Srivastava *et al.* (1989) examined the levels of microbial biomass C, N and P of an age-series of coal mine spoils in a dry tropical environment. They studied five mine spoils with different ages (5, 10, 12, 16 and 20 yr old), one deforested unmined site and another natural forest site. All sites are located within a radius of 5 km in Jhingurda block, north-eastern part of Singrauli coal field (24º10'20"-24º12'31" N lat., 82º42'-82º44'30" E long, and 350-450 m altitude) in Madhya Pradesh, India. Opencast coal mining in the area started after 1965, but before that it had picturesque surroundings, with a high hill in the background with steep southern slopes covered with dense forest vegetation and a foreground, covered with good cultivated lands cut by the Jhingurda stream and its large number of feeder streams (Tripathi and Dutta, 1967).

The physico-chemical characteristics of the soils reported by Srivastava *et al.* (1989) for mine spoils, the native forest and deforested soils are given in Table 1. Soil organic C contents for the native forest and deforested sites were 3.01 and 1.98%, respectively. Total N in the 5-yr-old spoil was only 23% of that in the native forest soil. Microbial C, N and P in the soil ranged from 209 to 867 μg C g^{-1}, 20-75 μg N g^{-1} and 7-29 μg P g^{-1} soil, respectively. The observed values were greatest in native forest soil and lowest in the 5-yr-old spoil (Table 2). The biomass C, N and P were about four times greater in native forest soil than in the 5-yr-old spoil.

Soil organic C reflected in the microbial biomass (soil microbial biomass C) was 2.9 and 2.l% in native forest and deforested soils, respectively (Srivastava *et al.*, 1989). These authors could not estimate the organic C value for the spoils due to coal particle contamination. However, when C:N ratio for mine spoil is assumed as 10.5 (like that of native forest and deforested soils), the mean value for soil organic C reflected in biomass would be 4%, which compares with the range given in literature for other soils (Jenkinson and Ladd, 1981; Srivastava and Singh, 1988). Microbial biomass N (MBN) accounted for 2.2-4.2% of the total soil N and the N concentration in dry biomass, calculated as MB-N/2 MBC (by

Table 1: Some properties of the mine spoils, the native forest and deforested soils. WHC, water holding capacity; TSN, Total soil N. (Source: Srivastava *et al.*, 1989)

Site	Root biomass ($g\,m^{-2}$)	pH	WHC (%)	Gravimetric soil water (%)	TSN (%)	Mineral N ($\mu g\,g^{-1}$)	$NaHCO_3$-Pi ($\mu g\,g^{-1}$)
Forest soil	-†	6.4	52	8.6	0.291	16.4	15.0
Deforested soil	-	7.3	46	2.9	0.186	14.8	9.2
5 yr old spoil	284	7.7	52	4.6	0.068	5.8	5.0
10 yr old spoil	342	7.9	45	2.9	0.074	7.6	7.3
12 yr old spoil	537	8.1	46	4.2	0.077	7.9	7.0
16 yr old spoil	485	8.1	48	2.6	0.082	9.9	8.4
20 yr old spoil	553	7.9	50	5.4	0.086	15.6	8.9

†- not determined

Table 2: Microbial biomass C, N and P contents of mine spoils, native forest and deforested soils. MBN, Microbial biomass N; TSN, Total Soil N. (Source: Srivastava *et al.*, 1989)

Site	C ($\mu g\,g^{-1}$)	N ($\mu g\,g^{-1}$)	P ($\mu g\,g^{-1}$)	C:N	C:P	N in microbial biomass (%)	P in microbial biomass (%)	MBN/TSN (%)
Forest soil	867	75	29	11.6	29.9	4.3	1.7	2.6
Deforested soil	422	40	15	10.6	28.1	4.7	1.8	2.1
5-yr-old spoil	209	20	07	10.5	29.9	4.8	1.7	2.9
10-yr-old spoil	276	23	10	12.0	27.6	4.2	1.8	3.1
12-yr-old spoil	356	28	12	12.7	29.7	3.9	1.7	3.6
16-yr-old spoil	360	32	13	11.3	27.7	4.4	1.8	3.9
20-yr-old spoil	496	36	16	13.8	31.0	3.6	1.6	4.2

assuming that dry biomass contains 50% C (Brookes *et al.*, 1984), ranged from 3.6-4.8% (Table 2). Variability in the total soil N explained 89.7% of the variance in biomass N (Table 3). This compares with 80% obtained by Brookes *et al.* (1985) for a similar relationship involving 20 arable soils. Microbial biomass N was also positively related with biomass C and mineral N (Table 3). No data on the N concentration in biomass and total soil N reflected in the biomass for mine spoils are available in the literature. However, for sandy soils under continuous cropping in the U.K., 2-6% of the total soil N was found as biomass N (Brookes *et al.*, 1985). The values reported in the study by Srivastava *et al.* (1989) are within this range.

In these soils, the concentration of P in the biomass, calculated as MBP/2MBC by Srivastava *et al.* (1989), ranged from 1.6 to 1.8% (C:P ratio from 27.6 to 31.0, X = 29.1). This range is narrow compared to other reports (Brookes *et al.*, 1984; Sarathchandra *et al.*, 1984) and may indicate that the quality of the biomass was similar across sites. Biomass P in the study of Srivastava *et al.* (1989) was positively related with biomass C, biomass N and bicarbonate soluble Pi in the soils (Table 3). MBC ($\mu g\ g^{-1}$) can be predicted with some confidence ($R^2 = 0.993$, $P < 0.01$) from the more easily measurable MBP ($\mu g\ g^{-1}$) using the following regression:

$$MBC = -17.49 + 30.47\ (\pm\ 1.06)\ MBP$$

In the study of Srivastava *et al.* (1989), while inorganic N explained only 62.7% variability in the biomass N, inorganic P explained 97.8% vaiability in the biomass P. Significant relation was however, not observed between P concentration in biomass and $NaHCO_3$-Pi in the soil. Brookes *et al.* (1984) also found no relationship between P concentration in biomass and bicarbonate soluble Pi and suggested that factors other than soil $NaHCO_3$-Pi determine the concentration of P in the biomass. The soil microbial biomass can be characterized by a mean C:N:P ratio

Table 3: Regression equations ($Y = a \pm bX$) for relationships among microbial biomass C, N, P, min-N, $NaHCO_3$-Pi, TSN (total soil nitrogen) and root biomass. Values-for root biomass are in g m^{-2} and for spoil age in yr. All other values are in μg g^{-1} soil. (Source: Srivastava *et al.*, 1989)

Y	*X*	*a*	*b*	SE	R^2
Biomass C	Root biomass	-14.84	0.80	0.222	0.814*
Biomass C	Spoil age	111.34	18.10	0.878	0.929
Biomass N	Biomass C	0.45	0.08	0.007	0.966
Biomass N	TSN	10.38	0.02	0.003	0.897
Biomass N	Mineral N	-1.04	3.35	1.155	0.627*
Biomass N	Spoil age	13.72	1.12	0.112	0.970
Biomass P	Biomass C	0.49	0.03	0.001	0.993
Biomass P	Biomass N	0.86	0.38	0.023	0.980
Biomass P	$NaHCO_3$-Pi	-4.78	2.23	0.148	0.978
Biomass P	Spoil age	4.29	0.58	0.049	0.979
TSN	Spoil age	620.53	12.18	0.039	0.993

*Significant at $P < 0.05$. All other R^2 values are significant at $P < 0.01$

of 29:3:1 and is determined largely by total soil N (TSN) and $NaHCO_3$-Pi ($R^2 = 0.976$, $P < 0.005$) according to the following equation:

$$MBC = -167.10 + 69.83\ Pi - 104.35\ TSN$$

where, MBC and Pi are in μg g^{-1} and TSN is in %.

All the three parameters of soil microbial biomass (C, N and P) were greater in the native forest soil as compared to the mine spoils (Srivastava *et al.*, 1989). The reduction in microbial nutrients in the mine spoils are commonly due to the lack of (i) a topsoil layer and its associated plant components, (ii) favorable nutrient levels and (iii) active microbial system (Visser *et al.* 1983). Hendrick and Wilson (1956) have also reported CO_2 efflux rate lower in strip mined spoils as compared to undisturbed soils and argued that this may be due to lack of sufficient N in mine spoils.

In the spoils studied by Srivastava *et al.* (1989), the root biomass ranged from 284 to 553 g m^{-2} being highest in the 20-yr-old and lowest in the 5-yr-old spoil (Table 1). Root biomass directly provides carbon and nutrients for the development of soil microbial population through secretions of organic compounds and upon mortality. Therefore, the relationship between root biomass and MB-C was positive (Table 3). Wilson (1965), in a study involving a number of years on general microbiological characteristics of a number of different mine spoils under re-vegetation, reported increasing number of actinomycete and bacterial population in mine spoils as vegetation established. Vegetated spoils had larger populations of important physiological groups of bacteria viz., ammonifiers, cellulose decomposers and denitrifiers as present in un-vegetated mine spoils. Stroo and Jenks (1982) reported that parameters such as organic matter and N in soil are good indexes of microbial activity in the areas which are re-vegetated. They observed that after twenty years of re-vegetation, microbial activity in the surface soil of re-vegetated mining sites was very close to levels found in undisturbed sites.

Srivastava *et al.* (1989) found positive association of total soil N and microbial C, N and P with the age of spoils (Table 3). The recovery of total soil N during the 20 yr of spoil age in the study of Srivastava *et al.* (1989) was 0.0012% per yr. This rate is markedly faster as compared to the rates obtained by Woodmansee *et al.* (1980) who estimated that it will take 2160 yr for the soil N pool to reach the level of native soil for North American spoils. Microbial activity reflects the critical genetic process of organic matter and nutrient accumulation (Schafer *et al.*, 1980). Microbial biomass growth on residues increases turnover of soil organic matter by concurrent mineralization, immobilization and stabilization reactions (Voroney *et al.*, 1989). Powlson *et al.* (1987)

have emphasized that measurement of soil microbial biomass can provide an indication of changes in total soil organic matter long before the reliable detection of changes in total soil C and N. We suggest soil microbial biomass as a critical factor for the recovery of mine spoils as it helps in the nutrient cycling re-establishment. The levels of biomass C, N and P can be considered as functional indexes of soil re-development.

Impact of Post-mining Subsidence on Nitrogen Transformation

In India, the total annual coal production was estimated at 325 million tonnes during 1994-1995 and 417 million tonnes by 1999-2000, with the contribution of opencast at about 252 million tonnes (Banerjee, 1990). As a consequence of increased demand for coal in India, more and more coal is being obtained also from underground coal mining; this created a large amount of land subsidence which covered large area of farmland and also caused undulation of land surface. Subsidence may be described as movement of the ground surfaces due to re-adjustments of the overburden after the collapse or failure of underground mine workings. It is an abrupt depression of local ground surface, which results due to sudden collapses of the overburden into an underground void. Subsidence can occur due to pillar, roof, or floor failure, particularly in older mines (Bauer *et al.*, 1995).

Effects of subsidence have been reported on agriculture land in Illinois (Darmody *et al.*, 1989), United Kingdom (Selman, 1986), China (Hu and Gu, 1995), South Africa (ven der Merwe, 1992), and Australia (Holla and Bailey, 1990). These effects include soil erosion, disruption of surface and subsurface drainage, wet or ponded areas, and reduction of crop yields. Large cracks mostly develop at the surface of soil after subsidence, which can create a hazard and can considerably alter soil hydrology. The disturbances created by subsidence have also been observed to alter N availability. For example, higher rates of N mineralization and nitrification have been observed in the intact tropical forests compared to agricultural sites (Piccolo *et al.*, 1994; Reiners *et al.*, 1994; Neill *et al.*, 1995; Neill *et al.*, 1997), which suggests that N availability is maximum (Nadelhoffer *et al.*, 1983), where there is low anthropogenic disturbance.

Tripathi *et al.* (2009) assessed the impact of underground mining subsidence on the soil characteristics with emphasis on nitrogen transformation, microbial biomass N (MBN), fine root biomass and root tips counts. The study sites (5B incline Mine spread over an area of 2.85 km^2) are located in Singareni Coalfields of Singareni Collieries Company Ltd. (SCCL), Kothagudem (Andhra Pradesh, India) at 17º32' N latitude and 80º42' E longitude. In their study design, they selected one plot, 100 x 100 m in size, in undisturbed forest (undisturbed microsite) and one plot, 10 x 10 m in size, each, in the adjacent slope and depressed microsites of the subsided panel area. They collected five soil samples at random, from upper 0-10 cm, from each of the undisturbed microsite and adjacent slope and depression microsites for rainy season (August), for winter season (December) and for summer season (May) during 2004-2005.

The study by Tripathi *et al.* (2009) showed substantial changes in the major physico-chemical characters of soil as affected by subsidence, which was demonstrated by differences among the undisturbed and the two subsided microsites. For example, compared to the undisturbed microsite, soil moisture, WHC (water holding capacity), proportion of finer soil particles (silt + clay), soil organic C, total N and P were lower in slope microsite and higher in depression microsite, and the BD (bulk density) was higher in slope microsite and lower in depression microsite (Table 4). Due to formation of cracks along the edge of the panel surface water infiltration increases due to subsidence. In a study by Smart (2003), the soil drainage improved after subsidence. The subsided panel contains maximum soil moisture in the centre of the panel compared to the microsites which are undisturbed (CMLR, 2001) (Table 5). Tripathi *et al.* (2009), argued that the greater C and N contents observed in the depression microsites maybe partly due to accumulation of plant parts including leaves and litter from the drying trees tilted towards depression microsite and surface run off organic matter. Besides, the plants uprooted in the slope microsite add dead roots, dried stems and leaves which increase the amount of organic matter ultimately getting accumulated in depression microsite. Higher clay content in depression microsites increases the WHC and promotes accumulation of organic C and

Table 4: Physico-chemical characteristics of undisturbed, slope and depression microsite soils in the coal mine spoil located in Singareni Coalfields of Singareni Collieries Company Ltd. (SCCL), Kothagudem (Andhra Pradesh, India). (Source: Tripathi *et al.*, 2009)

S.No.	Parameters	Undisturbed microsite	Subsided slope microsite	Subsided depression microsite
1.	pH	6.17	5.93	6.01
2.	Soil texture (%)			
	>0.2 mm	67.00	72.00	65.00
	0.2-0.1 mm	21.00	18.00	22.00
	<0.1 mm	12.00	10.00	13.00
3.	WHC (%)	32.24	28.64	34.50
4.	BD (g cm^{-3})	1.14	1.20	0.98
5.	Organic C (μg g^{-1})	18400.00	16800.00	20800.00
6.	Total N (μg g^{-1})	1530.00	1265.00	2140.00

Table 5: Mean seasonal and mean annual moisture contents (%) in undisturbed, slope and depression microsites in different panels. (Source: Tripathi *et al.*, 2009)

Season	Panels									Mean annual
	MK-4 A-19 5			B N-18			MK-4 Y-12			
	Rainy	Winter	Summer	Rainy	Winter	Summer	Rainy	Winter	Summer	
Undisturbed microsite	10.12	6.14	4.35	10.89	7.4	3.91	11.32	6.56	4.1	7.33
Subsided slope microsite	5.22	4.0	1.78	6.36	4.93	2.42	7.62	4.89	2.16	4.37
Subsided depression microsite	12.35	10.8	8.58	12.85	11.65	8.46	12.68	9.92	7.86	10.56

total N in soil.

Prescott *et al.* (2000) suggested that on coarse-textured soils, the already slower accumulation of organic matter, C and N is further constrained by slower N cycling. The reason behind presence of higher fine root biomass in subsided depression microsite could be the greater root proliferation due to higher soil moisture and maximum accumulation of organic matter run-off from the slope microsite. Conversely, the damage to fine roots is comparatively high in the slope microsite due to high tensile strain. Number of root tips in depression microsite was substantially higher than slope and undisturbed microsites presumably due to higher soil moisture and below ground biomass. Further, Tripathi *et al.* (2009) found a higher ground vegetation density on depression microsite also leading to higher density of root tips. For a dry tropical forest, Singh and Srivastava (1985) observed positive correlation of the root tip density with soil moisture and rainfall.

In the study of Tripathi *et al.* (2009), MBN was lower in slope microsite due to lower growth of plant roots, as exhibited by lesser number of root tips and lower fine root biomass. According to Garbeva *et al.* (2004), root tips and young roots are the main sites for microbial growth. Thus, young roots provide the highest amount of organic C available for microbial growth. Greater concentration of clay and more soil moisture in depression microsite may also be partly responsible for higher MBN in depression compared to slope microsite. Several studies have found a positive correlation between clay content and MBC (Poret-Peterson *et al.*, 2007; Merckx *et al.*, 1985; van Veen *et al.*, 1985; Kaiser *et al.*, 1992), presumably due to greater capacity of clay to retain organic matter in the form of substrate for microbial growth (Marshman and Marshall, 1981). Soil moisture strongly correlates with soil microbial biomass (Luizao *et al.*, 1992; Srivastava, 1992; Wardle, 1992). In the study by Tripathi *et al.* (2009), MBN was positively related to soil moisture, organic C, fine root biomass and root tips (Table 6).

Higher rates of nitrification and N-mineralization in depression microsite may be due to high organic C, fine root biomass, total N, microbial biomass and moisture content. Roots make a continuous contribution to soil organic matter through decay and their annual contribution to the organic pool can be as high as that from above-ground litter (Nadelhoffer *et al.*, 1985). Growing roots of plants release considerable amounts of organic carbon into the rhizosphere (Noble and Randall, 1998). High soil erosion could also lead to the lower rates of nitrification and N-mineralization in slope microsite. Jha *et al.*

(1996) emphasised that in erosional soil, the contact between plant residues and microbes is reduced causing lower decomposition rate, which results into reduced inputs and increased outputs of organic matter in the erosional soils. In the study by Tripathi *et al.* (2009), there was a positive relationship of N-mineralization with soil moisture, organic C, total N and microbial biomass (Table 6).

The post-mining land subsidence alters the soil physico-chemical characteristics, fine root biomass, nitrogen transformation rates and the microbial biomass on land surface. Although many studies show the detrimental impact of underground mine subsidence on the fertility of soil, microbial community and also plant biomass, a positive impact with respect to soil physico-chemical characteristics, plant available nutrients, fine root biomass and root tips count was found in the study of Tripathi *et al.* (2009). An increase in soil moisture enhances the production of fine root biomass, root tips and soil microbial biomass in subsided depression micro sites, which leads to an increased nutrient supply rate due to enhanced nitrification and N-mineralization. These positive changes in vegetation properties and soil characteristics directly reflect the influence of subsidence on dry tropical forest ecosystems.

Spoil Characteristics and Vegetation Development in Time

Time is important in succession because of its direct effect on species occurrence and abundance (Egler, 1954; Connell and Slatyer, 1977). Time-dependent changes in resource availability are argued to control succession (Christensen and Peet, 1984; Tilman, 1982; Tilman, 1985). Croxton (1928) and Bramble and Ashley (1955) noted that spoil characteristics affect the rate of development and composition of the community. The natural development of the vegetation communities on mine spoils may not exhibit a simple successional scheme, but may rather represent a vegetation complex responding individualistically to environmental conditions (Glenn-Lewin, 1980). Nevertheless in several situations an ordered development of soil and vegetation may occur (Roberts *et al.*, 1981; Marrs *et al.*, 1981). In some cases succession may stagnate at a given stage. Schafer and Nielsen (1979) found stagnated half-shrub/annual grass seral stage due to sandy soil texture on a 50-yr old spoil in southern Montana. Here we present the study conducted by Jha and Singh (1991), who assessed the changes in spoil characteristics, species composition and plant biomass in an age series of coal mine spoils in a dry tropical environment in India. The study area of Jha and Singh (1991) is located in Madhya Pradesh, India, at Jhingurda (24°10'20"-24°12'31" N lat. and 82°41'-82°44'30" E long.). In this study, an age series of coal mine spoils (5, 10, 12, 16 and 20-yr old) were selected as the study sites. Among the 5 sites, two sites 10 and 12-yr old were fenced in May 1987.

Influence of Age on Spoil Characteristics and Vegetation

The proportion of coarse particles (> 2.0 mm) was higher in mine spoils compared to native forest soil (Table 7). The proportion of coarse particles decreased with the age of mine spoils ($R = -0.943$, $P < 0.05$) and the proportion of 0.2-1.0 mm particles increased with age ($R = 0.957$, $P < 0.05$) (Tables 7, 8). Evidently,

Table 6: Correlation coefficients (*r*) between various selected soil parameters. (Source: Tripathi *et al.*, 2009)

	Moisture	Organic	Total C	Total N	Fine root P	Root tips biomass	NO_3^- count	NH_4^+	Nitrification	N-mineralization
Organic C	0.991*									
Total N	0.979*	0.992*								
Total P	0.935*	0.935*	0.956*							
Fine root biomass	0.932*	0.961*	0.986*	0.947*						
Root tips count	0.959*	0.963*	0.978*	0.993*	0.963*					
Nitrification	0.998*	0.982*	0.964*	0.922*	0.909*	0.946*	0.998*	0.983*		
N-mineralization	0.955*	0.981*	0.992*	0.926*	0.990*	0.953*	0.953*	0.984*	0.936*	
MBN	0.996*	0.996*	0.987*	0.925*	0.950*	0.954*	0.996*	0.998*	0.990*	0.975*

Table 7: Selected physico-chemical properties of native forest soil and mine spoils. (Source: Jha and Singh, 1991)

	Forest soil	Mine spoil (age in yr)				
		5	10	12	16	20
Soil texture (%)						
>2 mm	8	25	23	24	20	18
2-0.2 mm	64	61	63	58	56	60
0.2-0.1 mm	14	5	6	8	10	10
<0.1 mm	14	9	8	10	14	12
pH	6.4	6.3	6.2	6.3	6.5	6.8
Water holding capacity (%)	52	52	45	46	48	50
Gravimetric soil water (%)	8.6	4.6	2.9	4.2	2.6	5.4
Total soil N (%)	0.291	0.068	0.074	0.077	0.082	0.086
Mineral N (µg g^{-1})	16.4	5.8	7.6	7.9	9.9	15.6
$NaHCO_3$-Pi (µg g^{-1})	15	5.0	7.3	7.0	8.4	8.9
Exchangeable Na (µg g^{-1})	35	115	97	86	71	64
Exchangeable K (µg g^{-1})	264	35	49	54	63	74

Table 8: Regression equations ($Y = a + bX$) representing relationships between spoil age and spoil characteristics. Values for spoil age (X) are in yr, for particle size distribution in (%) and for all other characters in µg g^{-1} spoil. (Source: Jha and Singh, 1991)

Y	a	b	r
Coarse fragments (> 2.0 mm)	28.05	–0.4801	–0.943*
2.0-0.2 mm	62.26	–0.21	–0.449 NS
0.2-0.1 mm	2.106	0.436	0.957*
< 0.1 mm	7.573	0.256	0.643 NS
Total soil N	620.53	12.18	0.996**
Mineral N	1.621	0.6137	0.930*
$NaHCO_3$-extractable Pi	4.12	0.2533	0.959**
Exchangeable Na	130.00	–3.469	–0.989**
Exchangeable K	22.73	2.5609	0.991**

*Significant at $P < 0.05$, **Significant at $P < 0.01$, NS = Not significant

fragmentation, redistribution and aggregation of soil particles occurs gradually with the passage of time following the development of vegetation and soil processes.

Jha and Singh (1991) reported increase in total soil N, mineral N, $NaHCO_3$-extractable Pi and exchangeable K with the age of mine spoils ($R = 0.930$-0.996, $P < 0.05$-0.01, Table 8). Compared to the native forest soils, these parameters in mine spoils were lower even after 20 years of succession (Table 7). Exchangeable Na exhibited declining trend with the age of mine spoils ($R = -0.989$, $P < 0.01$, Table 8), however the value was greater compared to native forest soil even after 20 years of succession (Table 7). Sandoval and Gould (1978) observed that spoils of North Dakota and New Mexico contained high exchangeable Na which resulted in degeneration of soil structure, decreased infiltration and more crusting.

Srivastava *et al.* (1989) have reported an increase in microbial C, N and P in the spoils with age. Therefore, the biological and physicochemical properties of the spoil improved over time. Srivastava *et al.* (1989) found 26.5% increase in total soil N between 5 and 20 years of spoil age. In west Virginia coal mine spoils, Jencks *et al.* (1982) measured annual rates of N accumulation in mine spoil under black locust of 222 kg ha^{-1} at age 5-7 years, 146 kg ha^{-1} at 10-14 years and 171 kg ha^{-1} at 16-18 years; Vimmerstedt *et al.* (1989) observed increment in total N concentration upto 0.19 % for the 0-5 cm horizon of calcareous mine soils, and for the acidic mine spoil for the same horizon, they reported around 0.15% increment during 30 years. Dancer *et al.* (1977) have emphasised that the value of 700 kg ha^{-1} nitrogen content in the soil is appropriate for the development of a substantial self-sustaining ecosystem in degraded lands. In the study of Jha and Singh (1991), total soil N varied from 830 to 1049 kg ha^{-1} in the mine spoil of 5 to 20 year of age. Skeffington and Bradshaw (1981) observed that a pool of organic N together with a high rate of ammonification was important for sustainable development of vegetation and prevention of N immobilization. Marrs *et al.* (1981) found an increase in total soil nitrogen in the process of revegetation on naturally-colonized china clay wastes at Cornwall.

Plant Communities

Jha and Singh (1991), reported that on the mine spoils of different ages (i.e., sites), species with > 100 IVI were *Aristida adscensionis*, *Dactyloctenium aegyptium* and *Bothriochloa pertusa*. Arbitrarily, on the basis of IVI values, a total of four communities were identified:

(i) *Dactyloctenium aegyptium-Aristida adscensionis-Digitaria setigera*

(ii) *Aristida adscensionis-Bothriochloa pertusa-Dactyloctenium aegyptium*

(iii) *Aristida adscensionis-Bothriochloa pertusa-Eragrostis tenella*

(iv) *Bothriochloa pertusa-Aristida adscensionis*

Dactyloctenium aegyptium, *Aristida adscensionis* and *Digitaria setigera* were the early colonisers *Dactyloctenium aegyptium-Aristida adscensionis-Digitaria setigera* was the pioneer plant community observed on the 5-yr old mine spoil. On the 10-yr old spoil this community was replaced by *Aristida adscensionis-Bothriochloa pertusa-Dactyloctenium aegyptium* community. Thus. *Aristida adscensionis* became more important species and *Dactyloctenium aegyptium* went to the third position, while *Bothriochloa pertusa* became the second most important species. This same community, viz. *Aristida adscensionis-Bothriochloa pertusa-Dactyloctenium aegyptium* continued to occur on the 12-yr old spoil. On the 16-yr old spoil *Aristida adscensionis* gained further in importance and *Eragrostis tenella* replaced *Dactyloctenium aegyptium* in the third rank. *Bothriochloa pertusa* emerged as the most dominant species on the 20-yr old spoil, with *Aristida adscensionis* getting second rank in importance.

Aristida adscensionis was the most important species which contributed in the formation of all communities either as dominant or co-dominant. The IVI of *Aristida adscensionis* increased from 74.8 (on 5-yr old spoil) to 178.19 (on 16-yr old spoil) and then decreased to 82.14 (on 20-yr old spoil). The IVI of *Dactyloctenium aegyptium* and *Digitaria setigera* decreased with increase in age of the mine spoils. Participation of these species however was not observed in the community formation on older spoils. Increase in the IVI of *Bothriochloa pertusa* was observed from 64.74 on 10-yr old spoil to 102.23 on 20-yr old spoil. Thus, only a few species participated in community formation as dominants or co-dominants. The number of species contributing> 1% shoot biomass varied from 2 (16-yr old spoil) to 9 (5-yr old spoil). In total, three species contributed > 79% shoot biomass on 5 yr old spoil (*Dactyloctenium aegyptium*, *Aristida adscensionis*, *Digitaria setigera*), > 90% on 10 yr old spoil (*Aristida adscensionis*, *Bothriochloa pertusa*, *Dactyloctenium aegyptium*), and 12 yr old spoil (*Aristida adscensionis*, *Bothriochloa pertusa*, *Heteropogon contortus*), one species (*Aristida adscensionis*) >98% on 16-yr old spoil and three species > 95% (*Aristida adscensionis, Bothriochloa pertusa, Eragrostis tenella*) on 20 yr old spoil. This is illustrative of harsh environmental conditions both climatic and edaphic. MacMahon (1980) has argued that the combination of extreme values of environmental factors and the unpredictable variation taxes the adaptive suits of most organisms, with the result that only the existing species which have already adapted to these conditions participate in the succession on disturbed areas. Bradshaw (1983) indicated that once the propagules arrive, the species which adapt the special site conditions, or the species which show acclimatization to the extreme site conditions get selected in the flora which is very distinct on drastically degraded lands. *Bothriochloa pertusa* which is considered as a species of high successional order and grows under better soil conditions, contributes in the formation of community on mine spoils with *Aristida adscensionis*, which is a dominant species of degraded grasslands (Pandey and Singh, 1991). Thus re-vegetating the mine spoil with selected species of higher successional order is possible.

Jha and Singh (1991) observed that between

Table 9: Community coefficients calculated on the basis of presence or absence of plant species for mine spoils of different ages. (Source: Jha and Singh, 1991)

Mine spoil (age in yr)	5	10	12	16	20
5	100	41	37	37	29
10		100	41	35	31
12			100	38	35
16				100	35
20					100

pairs of plant communities, community coefficients exhibited a decreasing trend with increase in the age of mine spoil (Table 9). Plant communities developing on the younger aged mine spoils showed more similarity with each other compared to the plant communities developed on the older aged mine spoils. The turnover of communities reflects mainly the changes in the relative proportions of various taxa; most of the species which were recruited at the initial phase of succession, that is, on 5-yr old spoil were also found growing on the 20-yr old spoil. This indicates that succession process on these spoils occurs in accordance with 'initial floristic composition' hypothesis by Egler (1954) or 'tolerance model' of Connell and Slatyer (1977).

Community characteristics, viz. species richness, concentration of dominance, species diversity and evenness for the sites studied by Jha and Singh (1991) are summarized in Table 10. Here, species richness increased as the age of the mine spoil increased. Such a type of increase in species richness in the process of succession has also been reported by several other workers (Nicholson and Monk, 1974; Bazzaz, 1975; Pandey and Singh, 1985; Inouye *et al.*, 1987). Habitat improvement over time evidently, leads to enhanced species recruitment. Species evenness declined with age from 5-yr old to 16-yr old community with a slight increase in the 20-yr old community. The age pattern of species diversity was similar to that of evenness of species. Evidently evenness had a major influence on species diversity compared to species richness. On the other hand, during succession, several workers have observed a consistent increase in species diversity (Odum, 1969; Margalef, 1963; Monk, 1967; Reinners *et al.*, 1971). Since there is an inverse relationship between species diversity and concentration of dominance, the latter was found to increase upto 16-yr age and then declined in the 20-yr old community.

Table 10: Community characteristics of vegetation on mine spoil of different ages. (Source: Jha and Singh, 1991)

Spoil age (year)	Species richness*	Species evenness (Pielou's index)	*Shannon-Weiner diversity	*Concentration of dominance (Simpson's index)
5	2.26	0.708	2.087	0.192
10	2.37	0.623	2.005	0.247
12	2.48	0.582	1.852	0.333
16	2.67	0.548	1.742	0.370
20	4.32	0.597	2.188	0.208

*Using IVI value

Shoot biomass exhibited significant difference between the spoil ages, it was especially high in protected 10 and 12-yr old mine spoils. With increasing age, the area-weighted above ground plant biomass also increased except for that of *Xanthium strumarium* which declined (Table 11). The decline in the *Xanthium strumarium* biomass was due to the fact that size and number of *Xanthium strumarium* patches declined with age. The participation of *Xanthium strumarium* in the total area-weighted shoot biomass was consistent, which indicates that this plant could be an important natural factor for the improvement of habitat of mine spoils in this region.

Jha and Singh (1991) observed that in the adjoining grazed grasslands the peak shoot biomass varies from 59 to 113 g m^{-2} while in protected grasslands the range is from 511 to 700 g m^{-2} (Pandey

Table 11: Shoot and root biomass in mine spoils of different ages (g m^{-2}). (Source: Jha and Singh, 1991)

Spoil age	Shoot biomass		Total shoot biomass	Root biomass		Total root biomass	Total plant mass	Per cent root material
	Monospecific patches of *Xanthium strumarium*	Other vegetation		Monospecific patches of *Xanthium strumarium*	Other vegetation			
5	185	95	280	139	280	419	699	59.9
10	201	184	385	122	401	523	908	57.6
12	152	283	435	120	563	683	1118	61.1
16	148	154	302	119	473	592	894	66.2
20	141	190	331	89	554	643	979	65.6

and Singh, 1990). Thus the shoot biomass value for the mine spoils reported by Jha and Singh (1991), occurred between the grazed and protected native grasslands of the region. Roberts *et al.* (1980) have documented that on reclaimed china clay waste in Cornwall, biomass of plants increased with time; however even after seven years of growth the biomass values compared to the adjacent undisturbed sites were still lower. Marrs *et al.* (1981) also reported increase in root and shoot biomass with age in the naturally developed china clay waste at Cornwall. Fyles *et al.* (1985) reported that the 15-yr old naturally developed sites had low shoot biomass compared to the fertilized 2, 3, 5-yr old sites and protected native grassland in south eastern British Columbia coalmine spoil. Increasing spoil age consequently increased productivity, a direct relationship between the two has been reported for Northern Great Plains in USA (Schafer, 1984) but in some cases a drop in productivity may also occur (De Puit *et al.*, 1978).

The root biomass in *Xanthium strumarium* patches decreased with the age of mine spoil, whereas that in the other vegetation increased with age (Table 11). Contribution of *Xanthium strumarium* was reported from 14 to 33% to total area-weighted root biomass at the study sites. In adjoining native grasslands, the range of peak root biomass in 0-30 cm soil depth had been reported from 444 to 708 g m^{-2} for grazed and 1137 to 1639 g m^{-2} for ungrazed sites in an earlier study by Pandey and Singh (1990). The total plant mass including shoot mass and root mass on various mine spoils varied from 699 to 1118 g m^{-2} (Table 11). The total plant mass values in the protected native sites (10 and 12-yr old) were higher than the grazed sites.

The per cent root material (PRM) is considered as an index of the relative importance of plant component present below ground in relation to the total plant mass present in the system (Singh and Krishnamurthy, 1981). The percent root material in the study of Jha and Singh (1991) varied from 57.6 to 66.2% in the different aged mine spoils. Generally, the PRM values were lower in young spoils compared to the older spoils. Therefore, the organic matter allocation to below ground compartment showed increasing trend with the age of succession. In adjoining grazed grasslands. The root material varied from 86 to 88% and from 67 to 70% in the protected ungrazed grasslands (Pandey and Singh, 1990). The per cent root material values for the mine spoils reportedby Jha and Singh (1991) were lower as compared to the adjacent grazed and the protected ungrazed grasslands.

Jha and Singh (1991) subjected the data on spoil features, microbial biomass C, N and P; and shoot and root biomass, to Discriminant Analysis and identified four Discriminating Functions which in combination accounted for 100% variance in the data. They constructed a territorial map using the first two Discriminating Functions with group centroid means in Fig. 1. The scatter plot exhibited that the different aged mine spoils are separated from each other. The 10-yr old and 12-yr old spoils showed close association with each other, while the 5-yr old spoil and 20-yr old spoil were placed far apart. Thus the complex physico-chemical and biological properties of each spoil were characteristically different with a progressive trend of improvement.

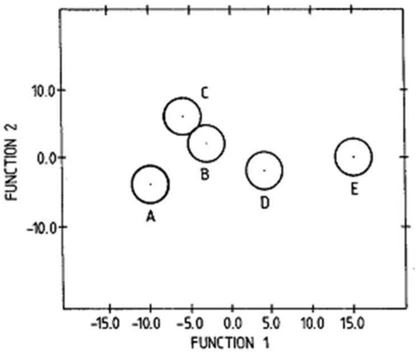

Fig. 1: Plot of group means as a function of the first two discriminant functions (DF 1 and DF 2) for spoil features, microbial C, N and P, and shoot and root biomass groups determined by discriminant analysis. A. **5-yr old spoil,** B. **10-yr old spoil,** C. **12-yr old spoil,** D. **16-yr old spoil, and** E. **20-yr old spoil (Source: Jha and Singh, 1991)**

Influence of Microsites and Seed Viability on Re-Development of Vegetation on Coalmine Spoil

The most important factors influencing vegetation development on mine spoils are micro-climate, spoil properties, surrounding flora and the propagule dissemination efficiency (Bramble and Ashley, 1955; Gibson *et al.*, 1985). The kind and quantities of available resources are generally determined by climatic and edaphic conditions of the site. The success of individual species and community composition are determined by local site variables. The conditions of substrate on individual mine spoils act as an environmental sieve (Hulst, 1978), such that the most favorable species are able to develop and become a significant component of the community. The process of natural re-vegetation on mine spoils is considered to be multi-factorial in nature (Glenn-Lewin, 1980; Gibson *et al.*, 1985), where partly it is autogenic and partly allogenic (Bradshaw, 1983). The process of succession may be accelerated by the introduction of selected species via moving intact seed banks, seedings, and by planting seedlings (Skoglund, 1992). Features of seed ecology including role of soil seed banks in succession, patterns of seed longevity and adaptive value of large seeds and germination have been documented especially for tropical rain forest species (see for example Whitmore, 1983; Foster, 1986; Vázquez-Yanes and Orozco-Segovia, 1993). We realise that knowledge of seed germination and establishment of seedlings is not enough for deciphering the community processes which includes plant recruitment and succession, but successful efforts of introduction, and re-introduction of species populations in restoration are needed. In forest conservation and management plans, the information about the ecological requirements at seed and seedling stages is rarely articulated.

Jha and Singh (1992) assessed the effect of different microsites of the mine spoil (slope, coal-patch margin, undulating surface and flat surface) on selected physical, chemical and biological features of the substrate, and on community composition and plant biomass levels, and Khurana and Singh (2001) reviewed the ecology of seed viability in dry tropical environment. Sites studied by Jha and Singh (1991) at Jhingurda are described earlier. They selected four microsites on each site, with a mean slope of 25%: coal-patch margin (margins of the dumps of low grade, unusable coal material on the spoil heaps), undulating surface, flat surface and slope usually, the coal-patch sites are devoid of vegetation, except for a very few herbaceous plants. The basal portions of the "coal-patch"constitute "coal-patch" margins containing fine coal particles and decomposed materials which are transported by rain water from infertile upper layer of the "coal-patches".

Across spoil ages, the average pH was maximum (6.8) for undulating surface and minimum for the microsite at the coal-patch margins (5.6). pH of the adjoining native forest soil was 6.4 [Fig. 2(a)]. Proportion of coarse particles (> 2.0 mm) was greatest (25%) on the "coal-patch" margin, and lowest on flat surfaces (19%). Values for coarse particles in all microsites were greater compared to the native forest soil (8%) [Fig. 2(b)]. The proportion of particle size 2.0-0.2 mm ranged from 56% (coal-patch margin) to 64% (slope), and fluctuated in all microsites across age [Fig. 2(c)]. The proportions of particle size 0.2-0.1 mm and < 0.1 mm increased with age in all microsites [Fig. 2(a) and (b)]. Bramble and Ashley

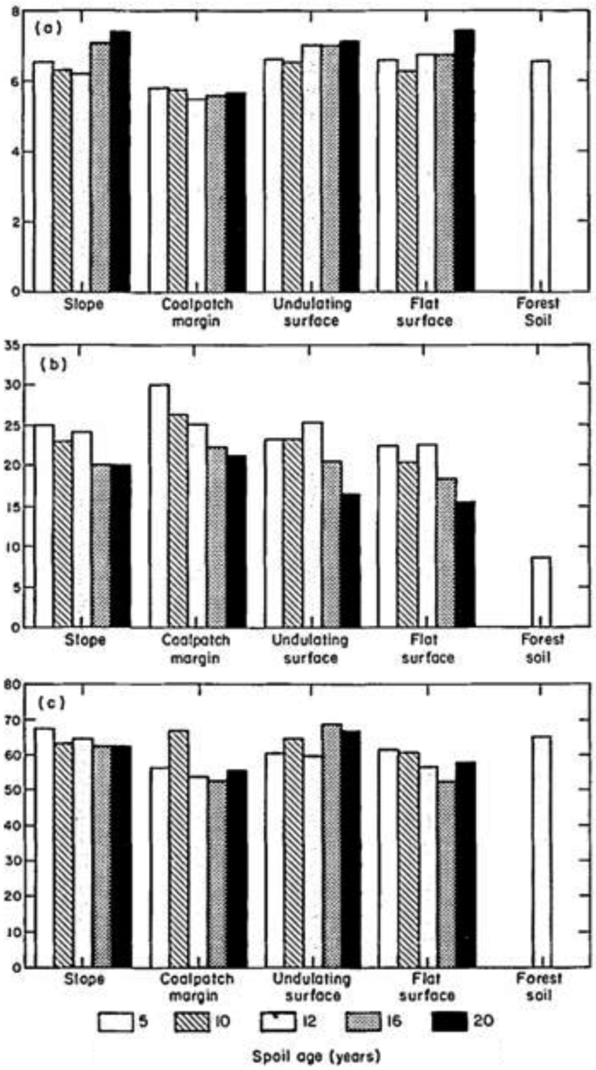

Fig. 2: pH and proportion of coarse particles in various microsites of mine spoils of different ages. (a) pH; (b) proportion of particle size > 2 mm; (c) proportion of particle size 2-0.2 mm. (Source: Jha and Singh, 1992)

(1955) argued that the proportion of fine earth particles (< 2 mm) of about 20% limits the growth and survival of plant on surface-mined lands.

The total soil N values were lower in mine spoils in all microsites compared to the native forest soil, and N increased as the age of mine spoil showed increment in all microsites [Fig. 3(c)]. There was decrease in exchangeable Na [Fig. 4(a)] and increase in exchangeable K [Fig. 4(b)] with the age of mine spoil. However, the average exchangeable Na was found greatest for the "coal-patch" margin microsite and lowest for the flat surface microsite. Less exchangeable K was observed in the "coal-patch" margin microsites compared to other microsites. The mine spoil exchangeable Na content was greater than the native forest soil, while the mine spoil exchangeable K was lower compared to the forest soil.

Jha and Singh (1992) reported lowest values of microbial biomass C, N and P for slope and greatest for coal-patch margin microsites [Fig. 4(c) and 5(a) and 5(b)]. In mine spoils, all three microbial parameters were lower in all microsites as compared to the native forest soil. With increasing age of the spoils, microbial C, N and P in all microsites also increased. Strong correlation of fine particles, total soil N and root biomass were observed with microbial C, N and P.

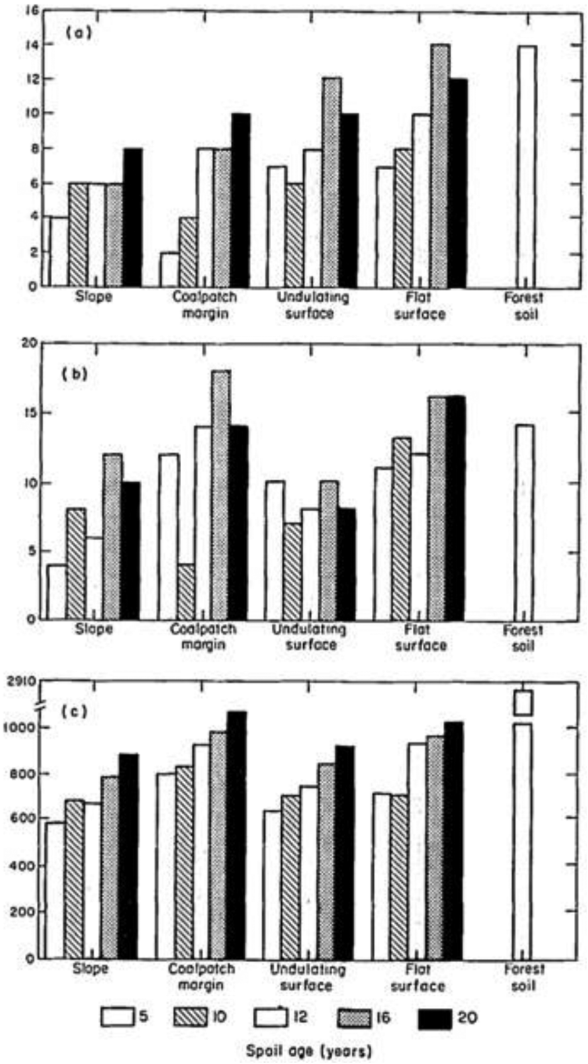

Fig. 3: Proportion of medium and fine soil particles and total soil N in various microsites of mine spoils of different ages. (a) Proportion of particle size 0.2-0.1 mm; (b) proportion of particle size < 0.1 mm; (c) total soil N (μgg^{-1}). (Source: Jha and Singh, 1992)

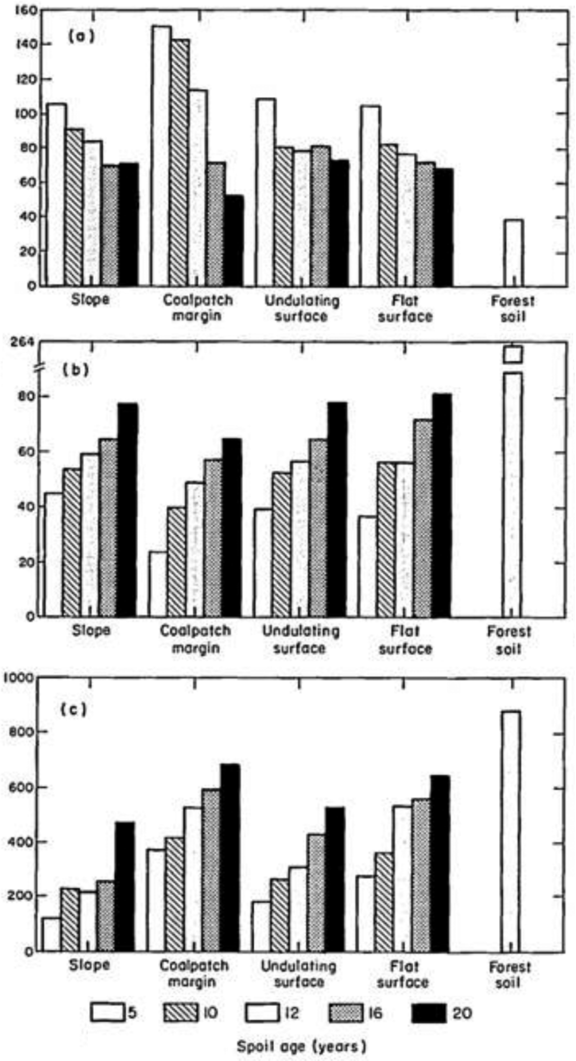

Fig. 4: Exchangeable Na, K and microbial C in various microsites of mine spoils of different ages. (a) exchangeable Na (μgg^{-1}); (b) exchangeable K (μgg^{-1}); (c) microbial C (μgg^{-1}). (Source: Jha and Singh, 1992)

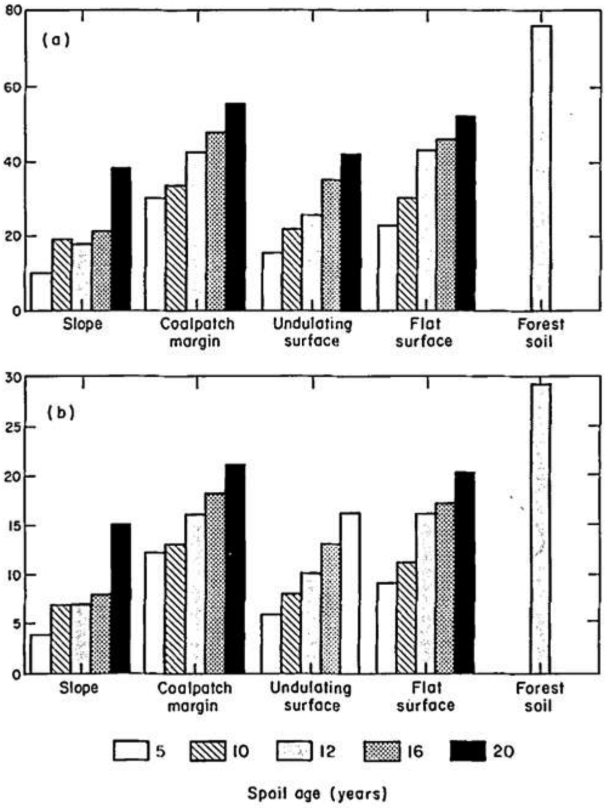

Fig. 5: Microbial N and P in various microsites of mine spoils of different ages. (a) microbial N (μgg^{-1}); (b) microbial P (μgg^{-1}). (Source: Jha and Singh, 1992)

Through organic secretions and decay, the root biomass directly adds C and nutrients to the soil microbial population. Therefore, the correlation between root biomass and microbial C, N and P was expected to be positive. Van Veen *et al.* (1984) argued that the composition of clay in soil influenc exits microbial preservation capacity. Similarly, West *et al.* (1988) also found that clay loam soil had maximum levels of microbial C and N-flush compared to the sandy soils.

On slopes, the species with ≥ 100 IVI were *Dactyloctenium aegyptium*, *Bothriochloa pertusa* and *Aristida adscensionis*. On coal-patch margins dominant species were *Aristida adscensionis* and *Eragrostis tenella*, on undulating surfaces *Aristida adscensionis* was common and *Dactyloctenium aegyptium* and *Aristida adscensionis* were frequent on flat surface microsites (Jha and Singh, 1992). On the basis of IVI values, these authors identified nine plant communities (Table 12). The early colonization

Table 12: Plant communities on the basis of IVI in different microsites on coalmine spoils of different ages. (Source: Jha and Singh, 1992)

Microsites	Mine spoil age (years)				
	5	10	12	16	20
Slope	*Dactyloctenium aegyptium-Digitaria setigera*	*Bothriochloa pertusa-Cassia pumila*	*Aristida adscensionis-Dactyloctenium aegyptium*	*Aristida adscensionis-Bothriochloa pertusa*	*Aristida adscensionis-Bothriochloa pertusa*
Coal-patch margin	*Dactyloctenium aegyptium-Aristida adscensionis*	*Aristida adscensionis-Dactyloctenium aegyptium*	*Aristida adscensionis-Bothriochloa pertusa-Tridax procumbens*	*Aristida adscensionis-Eragrostis tenella*	*Eragrostis tenella-Aristida adscensionis*
Undulating surface	*Dactyloctenium aegyptium-Aristidaadscensionis*	*Aristida adscensionis-Bothriochloa pertusa*	*Aristida adscensionis-Bothriochloa pertusa*	*Aristida adscensionis-Bothriochloa pertusa*	*Aristida adscensionis-Bothriochloa pertusa*
Flat surface	*Dactyloctenium aegyptium-Aristidaadscensionis*	*Aristida adscensionis-Dactyloctenium aegyptium*	*Aristida adscensionis-Heteropogon contortus*	*Aristida adscensionis-Bothriochloa pertusa*	*Aristida adscensionis-Bothriochloa pertusa*

was started by *Dactyloctenium aegyptium-Digitaria setigera* community as observed on the 5-yr-old slope microsite. The *D. aegyptium-A. adscensionis* community occurred on 5- yr-old coal-patch margins, 5-yr-old undulating surfaces and 5-yr-old flat surface microsites (Table 12). On slopes, undulating surfaces and flat surfaces, *A. adscensionis- B. pertusa* was observed as the final community in the 20-yr succession, while *E. tenella-A.adscensionis* was the final community on coal-patch margins. Notwithstanding the changes in species composition, it was reported that only a few species contributed in the development of community as dominants or co-dominants.

The number of species contributing ≥ 1% shoot biomass varied from seven (12-yr-old) to 16 (20-yr-old) on slopes, eight (10-yr-old) to 13 (5-yr-old) on coal-patch margins, 10 (5-, 10-yr-old) to 16 (16-yr-old) on undulating surfaces and 6 (12-yr-old) to 14 (20-yr-old) on flat surface microsites. On slopes only four species (*A. adscensionis, D. aegyptium, D. setigera* and *B. pertusa*) contributed from > 64 to 81% shoot biomass; on coal-patch margins the contribution by only four species (*A. adscensionis, D. aegyptium, B. pertusa*, and *E. tenella*) was from > 59 to 77%; on undulating surfaces the contribution by only four species (*A. adscensionis, D. aegyptium, B. pertusa* and *H. contortus*) was from > 60 to 74%; and on flat surface microsites the contribution by only four species (*A. adscensionis, D. aegyptium, B. pertusa* and *H. contortus*) was from > 57 to 78%. This result illustrates the harsh climatic and edaphic environmental conditions.

Total species composition, diversity, equitability and richness for different microsites, reported by Jha and Singh (1992) are given in Table 13. The greatest number of herbaceous species (21) was observed on 20-yr-old flat surfaces and the lowest (9) on the 10-yr-old coal-patch margins. The species richness was observed to increase with age of mine spoil on all microsites, except for 5-yr-old slopes and coal-patch margin microsites. The species richness values were observed to be high on 5-yr-old slopes and coal-patch margin microsites due to the presence of some ephemeral plants. The average species richness was found low on coal patch margin microsites than other microsites.

Average species diversity (across ages) was greatest (2.62) for undulating surfaces and lowest (2.22) for slope microsites. Average species equitability (across ages) was greater on flat surface and undulating surface microsites compared to the other microsites, emphasising a more equitable distribution of resources between species on these microsites.

Table 13: Total species content, diversity index, equitability and species richness in different microsites on mine spoils of different ages. (Source: Jha and Singh, 1992)

Microsite		Mine spoil age (years)				
		5	10	12	16	20
Slope	Total species content	13.00	11.00	13.00	14.00	17.00
	Species diversity	2.75	1.687	1.647	1.950	3.093
	Equitability	2.47	1.620	1.480	1.700	2.510
	Species richness	1.76	1.380	1.550	1.860	2.260
Coal-patch margin	Total species content	13.00	9.00	10.00	11.00	14.00
	Species diversity	3.116	1.943	2.133	2.574	2.561
	Equitability	2.800	2.040	2.130	2.470	2.230
	Species richness	1.890	1.120	1.150	1.400	1.740
Undulating surface	Total species content	10.00	13.00	15.00	16.00	18.00
	Species diversity	3.020	2.368	2.184	3.116	2.425
	Equitability	3.020	2.130	1.860	2.590	1.930
	Species richness	1.450	1.630	1.770	2.040	2.290
Flat surface	Total species content	10.00	14.00	17.00	19.00	21.00
	Species diversity	2.086	1.561	2.006	3.046	2.923
	Equitability	2.090	1.360	1.630	2.380	2.210
	Species richness	1.350	1.680	2.000	2.430	2.640

Mean shoot biomass was lowest for the slope and greatest for the flat surface microsites. Shoot biomass varied from 59 to 113 g m^{-2} in the adjoining grazed grasslands, and from 511 to 700 g m^{-2} in protected grasslands (Pandey and Singh, 1990). Therefore, the shoot biomass values for the mine spoils studied by Jha and Singh (1992) were within the range reported for the grazed and protected native grasslands. Sindelar (1979) indicated that older mined sites containing sandy loam spoil exposed to heavier grazing are considered less successionally advanced compared to the mine spoil with more silt and clay. Johnson *et al.* (1982) observed that older sites with high Ca and N had greater biomass than the sites with less favourable conditions.

Root biomass exhibited significant differences between microsites as well as between the ages of spoils. Significant interaction was also observed between microsite and age, and total area-weighted plant mass and percent root material. The minimum value (541 g m^{-2}) for total area-weighted plant mass was observed for 5-yr-old undulating surfaces and the maximum value (1386 g m^{-2}) observed was for 12-yr-old flat surface microsites. The range of per cent root material was 57-78, 67-77, 58-74 and 61-72% on slope, coalpatch margin, undulating surface and flat surface microsites, respectively. Generally, with increase in the age of the mine spoil, per cent root material also increased. More older sites (16- and 20-yr-old sites) exhibited more than 70% values for per cent root material in all microsites. According to Pandey and Singh (1990), the range of per cent root material in native grasslands was 86 to 88% for grazed and 67 to 70% for ungrazed grassland sites.

Importance of Microsites

Significant differences in spoil characteristics, plant biomass and plant communities highlight the importance of microsites. A discriminant analysis was performed using the spoil properties, microbial C, N and P and root and shoot biomass values. A territorial map was constructed with the group centroid means by using the two discriminating functions (Fig. 6). The scatter plot showed that the microsites were quite separate from each other, although some closeness was observed between undulating surface and flat surface microsites. Compared to other microsites, the slope and coal-patch margin microsites were very distinct. This analysis pointed that microsites remain important factor throughout the 20 years of succession and they should be considered in any plan of re-vegetation. The coalpatch margin microsites would take more time to become more habitable for plants as compared to other microsites. It is emphasised that the structure of spoil dumps should be so modified as to have greater proportions of flat surface and undulating surface microsites. On such microsites, a re-vegetation plan should be started for better results. On 12-yr-old flat surface microsites 24 species among 30 plant species of grasses, leguminous forbs, leguminous trees, non-leguminous trees and crops seeded exhibited satisfactory growth performance (Jha and Singh, 1990). For slopes, *Stylosanthes hamata* was found particularly suitable.

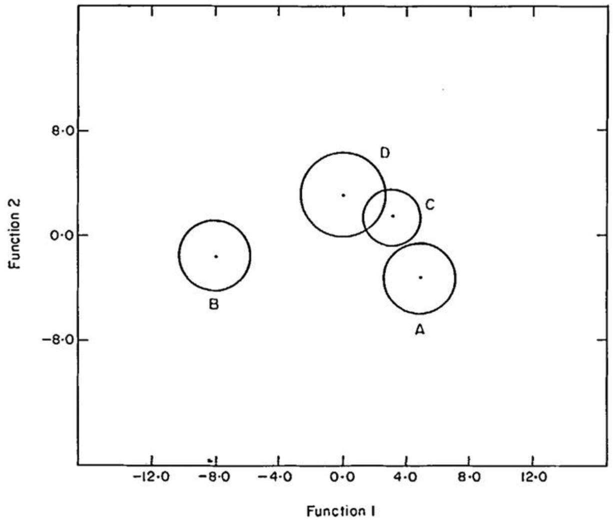

Fig. 6: Plot of group means against the first two discriminant functions (DFI and DF2) for spoil features. A, slope; B, coal-patch margin; C, undulating surface; D, flat surface microsites. (Source: Jha and Singh, 1992)

Importance of Seed Viability

Khurana and Singh (2001) emphasised the importance of seed viability and storage conditions for revegetation. In a seed stock, the proportion of viable seeds might vary due to the time of seed collection. For example, seeds of *Dalbergia sissoo* collected during the period November to July, yielded highest numbers of viable seeds (Bangarwa *et al.*, 1996). The temperature conditions and types of storage container best suitable for retaining maximum seed viability are known for certain Indian dry tropical

Table 14 : Reported optimal temperatures and storage container to maintain maximum seed viability of certain dry tropical species. For most species optimal moisture content was 7-8%. (Source: Khurana and Singh, 2001)

Optimal temperature (ºC)	Species	Storage container
3–5	*Albizia lebbeck*	Paper packet
	Albizia procera	Glass stoppered transparent bottle
	Bauhinia variegata	Paper packet
	Cassia siamea	Glass stoppered transparent bottle
	Ceiba pentandra	Air tight polyethylene bags
	Dendrocalamus strictus	Silica gel or anhydrous $CaCl_2$ in desiccator
	Peltophorum ferrugineum	Glass stoppered
15	*Azadirachta indica*	Perforated polyethylene bags
	Bambusa tulda	Sealed polyethylene bags
	Eucalyptus deglubta	Closed container
	Eucalyptus microtheca	Closed container
	Flindersia brayleyana	Closed container
20-25	*Dalbergia sissoo*	Tin
	Shorea robusta	Non sealed polyethylene bags
	Shorea talura	Non sealed polyethylene bags
15-35	*Acacia auriculiformis*	Glass stoppered bottle
	Cassia glauca	Air tight polyethylene bags
30	*Holoptelea integrifolia*	Sealed container with silica gel

species (Table 14). While a number of species such as *Albizia lebbeck* and *A. procera* need low temperatures (3-5°C), others, including *Azadirachta indica* and *Dalbergia sissoo*, require higher temperatures (15-25°C) (Table 14).

Evaluation of Direct Seeding of Tree Species as a Means of Re-Vegetation of Coal Mine Spoils

Reclamation efforts for the establishment of acceptable long-term plant cover with low maintenance requirements need proper identification of species suitable for revegetation. Direct seeding for re-vegetating mine spoils may be considered because it is easier and cost-effective compared to planting (Davidson, 1980). Particularly, the approach of direct seeding of tree species on normal sites could be successful but careful after care is essential. Direct seeding leads to better occupation of the site. Selection of suitable timing with respect to precipitation regime and conditions of temperature for seeding is important for successful development of mono and mixed stands of different tree and grass species (Singh *et al.*, 1995). Favourable results of seeding of grasses and leguminous forbs simultaneously with tree seedling have been observed in terms of survival and growth.

Jha and Singh (1993) have evaluated the growth performance of directly seeded leguminous trees, non-leguminous trees, leguminous forbs, grasses and crops on a 12-yr-old flat surface coal mine spoil at Jhingurda colliery, Northern Coalfields Limited, Singrauli. They observed that out of thirty plant species, twenty four species exhibited satisfactory growth performance after one year of seeding. Jha *et al.* (2000) investigated the feasibility of direct seeding as a means of revegetating coal mine spoils on large scale. The study site of Jha *et al.* (2000) is located at Jayant Colliery, Northern Coal Fields Ltd., Singrauli (23º47' –24º12' N lat., 81º48'-82º52' E long.), Madhya Pradesh, India. Experiments were set up in June 1993, on fresh mine spoils, in rain fed conditions, in about 1.5 ha area, on flat surface, and in about 3 ha area on slopes. On the flat surface area for each tree species, 20 x 20 m plots with three replicates were set up. On the slopy area in 20 m vertical strips seeding of tree species was done. Important results of the study are discussed below.

On the flat surface area maximum height was obtained by *Leucaena leucocephala* followed by *Zizyphus jujuba, Pongamia pinnata, Acacia catechu, Acacia nilotica* and *Azadirachta indica*. *Terminalia arjuna* obtained minimum height growth. In terms of diameter growth *Syzygium cumini* was the best species, and was followed by *Acacia catechu, Acacia nilotica* and *Pongamia pinnata*. Minimum diameter growth was realized by *Terminalia arjuna*.

Jha *et al.* (2000) observed that on slopes of mine spoil, *A. indica* was the fastest growing species in terms of height growth followed by *Leucaena leucocephala, T. arjuna, P. pinnata, A. catechu* and *Madhuca indica*. *T. bellirica* attained minimum height growth. The fast growing species in terms of diameter growth were *T. bellirica* and *T. arjuna* followed by *Madhuca indica, A. indica, A. catechu* and *P. pinnata*. *Leucaena leucocephala* attained minimum diameter growth.

On flat area, height/diameter ratio observed by Jha *et al.* (2000) was minimum for *S. cumini* and maximum for *Z. jujuba*, whereas on slopy area, it was minimum for *T. bellirica* and maximum for *L. leucocephala*. On flat surface area, maximum tree volume was recorded for *A. catechu* followed by *S. cumini, P. pinnata* and *A. nilotica*, and it was minimum for *T. arjuna*. On slopy area, the value for tree volume was maximum for *T. arjuna* followed by *A. indica, T. bellirica* and *M. indica*. Minimum tree volume was recorded for *S. cumini* on slopy area. Thus species vary in performance according to the surface conditions of the spoil.

Jha *et al.* (2000) also observed that the presence of leguminous forb, *Stylosanthes hamata*, and grasses *Pennisetum pedicellatum* and *Heteropogon contortus* in the experimental plots on flat and slopy areas enhanced the natural colonization of a large number of plant species. (a) Trees and shrubs: *Butea monosperma, Melia azedarach, Woodfordia fruticosa, Grevea* sp., and *Calotropis procera*, (b) Herbs and Grasses: *Hyptis suaveolens, Clitoria* sp., *Alternanthera sessilis, Ageratum conyzoides, Blumea oxyodonta, Desmodium triflorum, Apluda mutica, Abutilon graveolens, Sonchus oleraceus, Tephrosia purpurea, Alysicarpus longifolius, Phyllanthus varigatus, Aristida adscensionsis, Aristida cynatha, Vernonia cinerea, Launaea nudicaulis, Eragrostis tenella, Cynodon dactylon, Bothriochloa pertusa, Cyperus compressus, Evolvulus alsinoides, Tridax procumbens, Echinops echinatus, Aneilema nudiflorum, Saccharam munja*, etc.

Thus, the study by Jha *et al.* (2000) suggests that direct seeding of tree species along with grasses and leguminous forbs can accelerate the natural plant succession. Ground seeding of grasses will serve as a nurse crop and will act as trap for air-blown seeds. Large areas can be seeded in less time with less manpower, and seeding can be accomplished where planting is not feasible. These advantages are greatest with broadcast seeding. Plantations of nursery raised seedlings on slopes are difficult, and their growth and survival is low. Direct seeding of tree species with ground seeding of grasses and leguminous forbs is a suitable technique for checking erosion and for developing plant cover in slopy areas.

Ecological Restoration of Coal Mine Spoils Using Native Trees

As stated earlier, the natural recovery in mine spoils takes a very long time, for example, Srivastava *et al.* (1989) found that the recovery of total nitrogen pool in a mine spoil to the level of native forest soil, may take about 200 yrs of natural succession. For the successful restoration programme attempts should be given to speed up the natural recovery processes for restoration of soil fertility and enhancement of biological diversity (Dobson *et al.*, 1997; Singh and Singh, 2001). The initial step in any restoration programme should be towards the protection of the disturbed habitat and communities from being further wasted (Singh and Jha, 1993). Then attempts to accelerate the re-vegetation process for increasing bio-diversity and stabilizing nutrient cycling are to be made (Singh *et al.*, 1995). If we are able to accelerate the process of natural succession by planting a desirable plant species on mine spoil, we could develop a self-sustaining ecosystem in a short period. Another strategy in re-vegetation programme is the direct seeding of selected plant species including grasses on slopes of mine soil. Singh and Singh (2006) performed a series of experiments for the rehabilitation of mine spoil in a dry tropical region of India and evaluated the suitability of tree species for plantation, growth performance of selected indigenous species in monoculture and impact of the plantations on the restoration of biological fertility of soil. Experiments by Singh and Singh (2006) were performed in polyethylene pots with 17 indigenous species at Jayant coal mine located in Singrauli coalfield region (23°47'-24°12' N lat. and 81°48'-82°52' E long.) in 1993-1994. The treatments were: (a) mine spoil only (control); (b) mine spoil + 5 cm of forest top soil; (c) mine spoil + full dose of NPK; (d) mine spoil + 1/2 dose of NPK; and (e) forest top soil only. They maintained sixteen replicate polyethylene pots for each treatment for each species. After one year, the three replicate polyethylene pots were selected at random in each treatment for each species and were harvested. Quantification of biomass values were done for root, stem and leaves. The fresh weight of each plant component (root, stem and leaves) was recorded at the nursery. The sub-samples were brought to the laboratory for determination of dry weights. Important findings of the study are discussed below.

The 17 native tree seedling species investigated by Singh and Singh (2006) responded differently to the potting medium. However, all 17 species could be potentially grown on mine spoil and the growth performance of a majority of them could be improved by the application of NPK to the mine spoil. Singh *et al.* (2000) and Singh and Singh (2001) have reported the effect of NPK fertilization on the growth performance of 10 native tree species planted on mine spoil. All the 10 tropical tree species studied by them showed response to NPK fertilization; however the impact of fertilization on non-leguminous tree species was more compared to that on the leguminous tree species. In fertilized plots, the higher growth was also accompanied by higher foliar N and P concentrations in all species. Singh and Singh (2001) observed a positive relationship between growth rates (height, diameter and volume increments) and foliar N and P concentrations. However, the full dose application of NPK, weakened these relationships, indicating that fertilization brings more homogeneity among the growth of individuals (i.e. it eliminates the nutrient poverty in suppressed individuals) (Singh and Singh, 2001).

Eight tree species investigated by Singh and Singh (2006) for the direct seeding on the mine spoil exhibited satisfactory growth performance, although difference was detected in the amount of growth. Earlier, Jha and Singh (1993) studied the growth performance of directly seeded leguminous trees, non-leguminous trees, leguminous forbs, grasses and crops on 12-yr old flat surface at Jhingurda coalmine spoil and observed that out of 30 plant species tested, 24 species exhibited satisfactory growth. Therefore, direct seeding of species is suggested to be a cost-effective technique for the re-vegetation of mine spoil, in terms of low labour utilization and land recovery feasibility where the nursery-raised seedlings plantations are not easy.

In the study of Singh and Singh (2006), 5-yr-old plantations of the two non-pioneer species (*Shorea robusta* and *Tectona grandis*) on the mine spoil exhibited minimum biomass accumulation. The biomass range of 7.2-74.7 t ha^{-1} observed in the study by Singh and Singh (2006) compares with 24.4-73.3 t ha^{-1} total biomass (Singh and Singh, 1991a) in natural deciduous forests in the adjacent areas and the range reported for the subtropical forests 40-140 t ha^{-1} (Jung, 1969; Murphy and Lugo, 1986; Vyas *et al.*, 1977). The plantations of eight native tree species selected by Singh and Singh (2006) supported more vegetation mass than that was observed on naturally vegetated same aged mine spoil in the same area where the average total stand biomass was only 7 t ha^{-1} (Jha and Singh, 1991). On the naturally recovering mine spoil of the age 5-yr, the major species (all grasses) present were *Dactyloctenium aegyptium*, *Digitaria setigera* and *Aristida adscensionis* (Jha and Singh, 1992). Therefore, the biomass accumulation on the mine spoil was potentially accelerated due to tree plantations.

Several studies have reported that the above ground net production of the natural forests as well as plantations in the tropical zone ranged between 1.5 and 32.6 t ha^{-1}yr^{-1} (Faruqui, 1972; Singh and Singh, 1991a; Bargali *et al.*, 1992; Karmacharya and Singh, 1992; Singh and Toky, 1995; Veblen *et al.*, 1980; Taylor and Zisheng, 1987; Singh and Yadava, 1994; Tripathi and Singh, 1996; Chaturvedi *et al.*, 2011; Chaturvedi *et al.*, 2012; Chaturvedi and Raghubanshi, 2015; Chaturvedi *et al.*, 2017a), which compares with the range 2.7-24.7 t ha^{-1} yr^{-1}observed by Singh and Singh (2006) for the 5-yr old plantations raised on the mine spoil. Results of the study by Singh and Singh (2006), thus, highlighted that an early vegetation cover and high biomass production can be achieved through proper selection and plantation of pioneer native tree species in particular, because such species are able to survive under impoverished soil conditions and their long term maintenance cost is comparatively less.

Microbial biomass C in the mine spoil plantation soils in the study conducted by Singh and Singh (2006) represented 4.74-8.67% total organic C. The microbial biomass C observed for the adjacent forest ecosystem is 1.6-3.6% of organic C (Srivastava and Singh, 1989), and for U.K. soil samples, the reported range is 0.54-4.5% (Jenkinson and Oades, 1979; Oades and Jenkinson, 1979). In 26 agricultural soils, Anderson and Domsch (1980) observed that the microbial biomass contained between 0.27 and 4.8% total soil C (mean = 2.5%). Therefore, the carbon immobilization levels by microbial biomass were higher in the mine spoils as reported for the natural forest or agricultural soils. In nutrient cycling, soil microbial activity as well as level of soil microbial biomass plays an important role. Soil biomass is a critically important factor in the recovery of heavily disturbed sites as it supports the re-establishment of nutrient cycle (Srivastava *et al.*, 1989).

Tree foliage is a key component, which plays a very important role in primary production. Singh and Singh (2006) found a significant linear relationship between biomass of foliage and net primary production of the tree layer, when data were pooled across replicates for the plantations of four species (*Albizia lebbeck*, *Albizia procera*, *Tectona grandis*, and *Dendrocalamus strictus*) at 5-yr age (Fig. 7a). This relationship indicated that NPP (net primary production) was directly associated with the amount of foliage especially in the young plantations. Webb *et al.* (1983) also reported a positive relationship between above ground NPP and the standing biomass of foliage of forests, grasslands and desert sites.

Earlier, in the same plantations, Singh *et al.* (1999) studied litter fall and N deposition through litter fall. As reported by Singh and Singh (2006), the litter fall in 5-yr old plantations was 10.4, 8.8, 11.0 and 2.8 t ha^{-1} respectively, in *Albizia lebbeck, A. procera, Dendrocalamus strictus* and *Tectona grandis*. The corresponding values for N deposition were 6.8, 7.2, 11.0 and 3.1 kg ha^{-1}. They also found a positive relationship between soil organic C and litter fall which indicates that soil organic C is a function of the amount of dry matter deposited in the form of litter (Fig. 7b). The non-linear nature of relationship shows that after a few years, soil organic C might attain equilibrium and further increase in litter fall may not exhibit a net change; the litter fall itself may achieve equilibrium when the trees become mature. Similarly, a relationship found between the soil N and the quantity of litter fall N deposition suggests that soil N is particularly a function of N which is returned to the soil by the vegetation (Fig. 7c). Evidently, the species allocating a higher proportion of biomass to foliage and producing N-rich litter will accelerate the soil fertility restoration.

The study by Singh and Singh (2006) also exhibited an exponential relationship between microbial biomass C and soil organic C (Fig. 7d). Soil nutrient status is supposed to affect directly the biomass of microbes and development of specific microbial populations (Helal and Sauerbeck, 1986; Merckx and Martin, 1987). Ruess and McNaughton (1987) also reported a direct relationship between microbial biomass C and soil organic C. Diaz-Ravina *et al.* (1988) explained the differences in biomass C levels according to the differences in total soil C and N. A positive non-linear relationship observed between

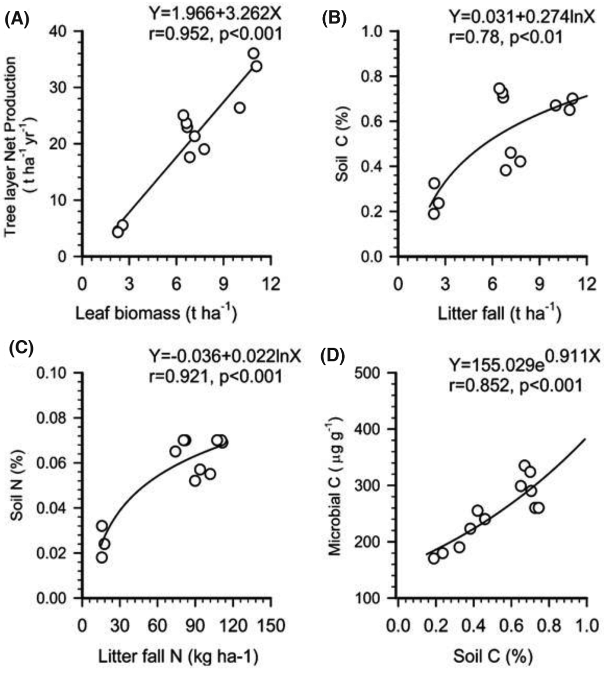

Fig. 7: Relationships between tree layer net production and leaf biomass (a), soil C with litterfall (b), soil N with litter fall N (c) and microbial biomass C with soil C (d) in 5-yr old plantations of four tree species on coal mine spoil. (Source: Singh and Singh, 2006)

the soil's organic C and microbial biomass C suggests that the two factors mirror each other during initial phase of soil re-development, and the exponential relationship indicates that biomass C might be an early indicator for the development of soil organic matter. Therefore, the study by Singh and Singh (2006) suggests that the measurement of microbial biomass could be an important parameter for monitoring the restoration of fertility of the soil, especially at the initial phase of soil re-development.

Comparative Growth Behaviour and Leaf Nutrient Status of Native Trees Planted on Mine Spoil With and Without Nutrient Amendment

Tree architecture (i.e., height-diameter, crown mass-trunk relationships) is considered important for selecting species for mine spoil plantations. The species selected by Singh and Singh (2001) for their study differed markedly in architectural traits, which also exhibited response by nutrient amendment. The slope (G) of log transformed height: diameter relationships observed by Singh and Singh (2001) for the first sampling ranged from 0.365 to 0.989 and for the second sampling, it varied from 0.355 to 0.972 (Table 15). These results are similar to the range 0.597 to 0.736 observed for the mature trees of eight neotropical tree species of Barro Colorado Island, Panama (O'Brien *et al.*, 1995). The analysis by Singh and Singh (2001) emphasised that the legumes *A. catechu* and *D. sissoo* and the non-legumes *A. indica* and *G. arborea* followed the elastic similarity tree growth model.

Rich (1986) suggested that when the scaling exponent b between stem diameter and height becomes equal to 0.67, the tree is considered to maintain elastic similarity through ontogeny. Usually, the elastic similarity model is followed by the large arborescent growth forms (Norberg, 1988). Alternately, the other model of tree growth is constant stress, where $b = 0.5$. This model assumes that trunk tapers in such a way that the wind pressure stress along the stem is equalized (Dean and Long, 1986). Singh and Singh (2001) reported that the legume *P. pinnata* and the non-legume *P. emblica* in their study followed this constant stress model of growth. Niklas (1992) argued that the constant stress model is the most commonly applicable model in the windy habitat. The third model is geometric similarity model, where $b = 1.0$, which presumes that the tree proportions remain constant throughout the whole life. This model is best followed by the smaller growth forms (from mosses to small trees) (Norberg, 1988). In the study of Singh and Singh (2001), the only tree species exhibiting geometric similarity model was *T. grandis*. Singh and Singh (2001) observed that in *A. lebbeck* and *T. bellirica*, were not fitting in any of the above three growth models and their b-values were < 0.5 (Table 15). It was found that relative to their diameter, height of these two species was shorter suggesting a greater safety margin against buckling compared to other species. In some species, the nutrient enrichment has considerable influence on the height diameter relationship. For example, after nutrient enrichment, b for *T. bellirica* increased from < 0.5 (constant stress) to about 1.0 (geometric similarity) and b for *G. arborea*, declined from about 0.7 (elastic similarity) to < 0.5 (Table 15).

During the tree growth, it is generally expected that the crown mass to trunk mass ratio will remain constant, therefore, the slope of regression between the proxy variables which represent crown mass and trunk mass should not show significant difference from unity (O'Brien *et al.*, 1995). In the study by Singh and Singh (2001), the slope value was found around unity in *A. indica*, *D. sissoo*, *G. arborea*, *P. emblica*, *T. grandis* and *T. bellirica* which suggests a constant ratio of crown mass to trunk mass (Table 16). However, in *A. catechu* and *A. lebbeck*, the slope value was observed below unity, indicating that in these species biomass allocation favoured trunk mass more than the crown mass (Table 16). These two species might be highly tolerant to wind action but only at the cost of photosynthetic tissue. Application of NPK increased the slope value towards unity in *A. catechu* and *A. lebbeck* and beyond unity in *A. indica*, *T. grandis* and *T. bellirica* (Table 16). Therefore, fertilizer application resulted in larger crowns in these species. Hulm and Killham (1990) reported a similar pattern after fertilizer amendment in Sitka spruce. Trees with larger crowns will be more prone to wind action, particularly on a newly formed loose substratum such as mine spoil. In *D. sissoo* and *G. arborea*, Singh and Singh (2001) found that fertilizer application did not cause any prominent shift in allocation between support and the systems involved in photosynthesis (Table 16).

Table 15: Regression of $\log_{10}$ height (m) and $\log_{10}$ diameter (cm) for nine tree species of two different ages grown on mine spoil under two levels of NPK and a control. (Source: Singh and Singh, 2001)

Species	Treatment	33 months after plantation				53 months after plantation			
		Intercept	Slope	R^2	*P*	Intercept	Slope	R^2	*P*
Legumes									
Acacia catechu	Control	–0.070	0.605	0.73	0.000	0.145	0.612	0.74	0.000
	Half NPK	–0.070	0.619	0.57	0.000	0.170	0.609	0.56	0.001
	Full NPK	–0.224	0.717	0.52	0.002	-0.011	0.702	0.53	0.002
Albizia lebbeck	Control	0.522	0.365	0.49	0.003	0.741	0.355	0.47	0.004
	Half NPK	0.310	0.493	0.71	0.000	0.470	0.487	0.71	0.000
	Full NPK	0.350	0.477	0.59	0.000	0.530	0.470	0.57	0.001
Dalbergia sissoo	Control	–0.010	0.745	0.67	0.000	0.168	0.734	0.68	0.000
	Half NPK	–4.480	0.800	0.53	0.002	0.118	0.807	0.53	0.001
	Full NPK	–0.075	0.751	0.60	0.000	0.089	0.742	0.60	0.000
Pongamia pinnata	Control	0.255	0.517	0.70	0.000	0.495	0.506	0.68	0.000
	Half NPK	0.355	0.478	0.62	0.000	0.561	0.464	0.60	0.000
	Full NPK	–0.130	0.726	0.72	0.000	-0.049	0.739	0.71	0.000
Non-legumes									
Azadirachta indica	Control	–0.038	0.632	0.57	0.001	0.0641	0.626	0.57	0.001
	Half NPK	0.104	0.578	0.50	0.003	0.266	0.567	0.48	0.003
	Full NPK	0.069	0.572	0.61	0.000	0.228	0.571	0.61	0.000
Gmelina arborea	Control	–0.212	0.720	0.65	0.000	-0.155	0.733	0.64	0.000
	Half NPK	–4.066	0.598	0.75	0.000	0.153	0.595	0.74	0.000
	Full NPK	0.606	0.367	0.56	0.001	0.897	0.358	0.54	0.001
Phyllanthus emblica	Control	0.091	0.568	0.75	0.000	0.201	0.556	0.73	0.000
	Half NPK	0.108	0.539	0.62	0.000	0.232	0.537	0.62	0.000
	Full NPK	0.111	0.518	0.65	0.000	0.277	0.496	0.66	0.000
Tectona grandis	Control	–0.698	0.910	0.60	0.000	-0.592	0.903	0.60	0.000
	Half NPK	–0.377	0.768	0.76	0.000	-0.214	0.762	0.75	0.000
	Full NPK	–0.721	0.989	0.81	0.000	-0.623	0.972	0.80	0.000
Terminalia bellirica	Control	–0.054	0.406	0.57	0.001	0.110	0.410	0.57	0.001
	Half NPK	–0.786	0.932	0.79	0.000	-0.751	0.935	0.79	0.000
	Full NPK	–0.938	0.948	0.63	0.000	-0.962	0.954	0.62	0.000

Singh and Singh (2001) found greater average height, diameter and volume increments for leguminous species as compared to those for non-leguminous species, which indicates that the leguminous species have a higher capacity for growth in habitats which are nutrient-poor. This might be due to the ability of fixing nitrogen in the leguminous species. Their study also emphasised higher foliar N concentration in leguminous species compared to that of non-leguminous species.

Singh and Singh (2001) reported a large degree of difference in tree volume (d^2h) (Table 17), which generally figures as a proxy parameter for biomass (Zavitkovski and Stevens, 1972; De Bell *et al.*, 1989). In the study of Singh and Singh (2001), this variability was higher among legumes than non-legumes (Table 17). When all species were considered together, full dose of NPK enhanced tree volume by 15±211 % at the first year of sampling and from 32 to 215 % at the second year of sampling. Nambiar and Fife (1987)

Table 16: Regression of crown mass (proxy variable: $\log_{10}$ crown area in m^2) to trunk mass [proxy variable: (d^2 in cm^2) (h in cm)] for nine tree species grown on mine spoil under two levels of NPK and a control. (Source: Singh and Singh, 2001)

Species	Treatment	Intercept	Slope	R^2	*P*
Legumes					
Acacia catechu	Control	–4.83	0.79	0.77	0.000
	Half NPK	–7.47	1.05	0.69	0.000
	Full NPK	–7.84	1.11	0.75	0.000
Albizia lebbeck	Control	–3.23	0.67	0.59	0.000
	Half NPK	–4.87	0.80	0.73	0.000
	Full NPK	–6.63	0.97	0.76	0.000
Dalbergia sissoo	Control	–4.94	0.89	0.42	0.009
	Half NPK	–7.07	1.10	0.66	0.000
	Full NPK	–7.93	1.19	0.61	0.000
Pongamia pinnata	Control	–5.85	0.98	0.49	0.003
	Half NPK	–3.34	0.73	0.30	0.032
	Full NPK	–9.82	1.35	0.62	0.000
Non-legumes					
Azadirachta indica	Control	–8.19	1.16	0.66	0.000
	Half NPK	–10.91	1.44	0.82	0.000
	Full NPK	–10.42	1.39	0.91	0.000
Gmelina arborea	Control	–6.99	1.05	0.73	0.000
	Half NPK	–5.79	0.91	0.66	0.000
	Full NPK	–5.03	0.86	0.62	0.000
Phyllanthus emblica	Control	–4.55	0.88	0.74	0.000
	Half NPK	–2.78	0.68	0.36	0.018
	Full NPK	–5.06	0.93	0.79	0.000
Tectona grandis	Control	–9.61	1.18	0.79	0.000
	Half NPK	–10.29	1.28	0.83	0.000
	Full NPK	–12.26	1.49	0.89	0.000
Terminalia bellirica	Control	–6.54	0.84	0.59	0.000
	Half NPK	–11.21	1.34	0.85	0.000
	Full NPK	–13.18	1.48	0.75	0.000

observed that after 2 years of planting, stem volume recorded in fertilized *Pinus radiata* trees was 71 % higher compared to control trees, and after 3.8 years of age, stem volume and biomass of N fertilized trees were observed two times more than controls. According to Singh and Singh (2001), in *A. catechu* and *G. arborea*, the effect of fertilization on the growth of height, diameter and volume was higher at the second sampling as observed in the first sampling, indicating age as a variable interacting with growth response. Similarly, Nommik and Moller (1981) reported a greater growth response to fertilization after 5 years of fertilizer application in Scots pine.

In the study by Singh and Singh (2001), the higher plant growth in fertilized plots was followed by enhanced N and P concentrations in the foliage. In their study they observed a positive relationship between the increments in height, diameter and volume, and foliar N and P concentrations (Fig. 8). Evidently, higher leaf nutrient status enhanced photosynthetic efficiency, mostly in trees on nutrient-

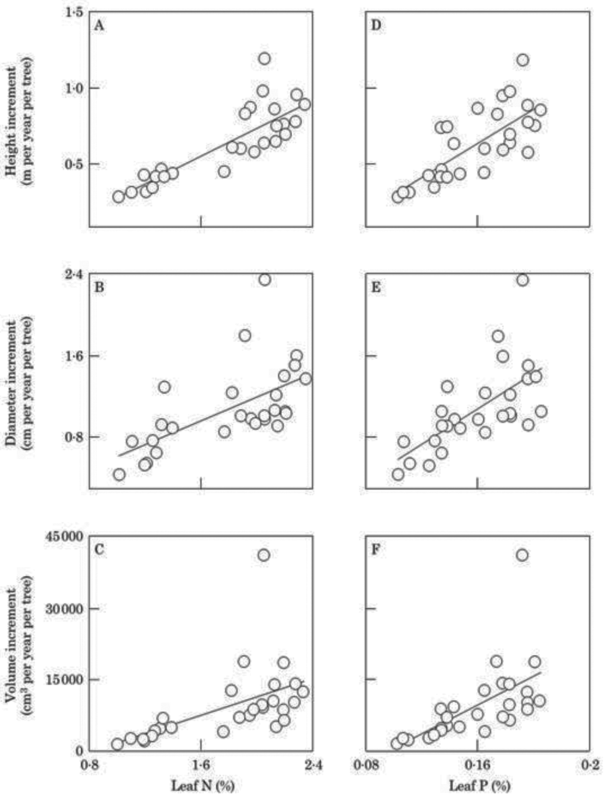

Fig. 8: Relationships between leaf nutrient status and growth parameters for trees planted on mine spoil. Regression equations are (A) $y = -1.73 + 0.554x$ ($R^2 = 0.697$, $P < 0.01$); (B) $y = 0.027 + 0.587x$ ($R^2 = 0.376$, $P < 0.01$); (C) $y = -7823.003 + 9530.92x$ ($R^2 = 0.273$, $P < 0.01$); (D) $y = -2.55 + 5.625x$ ($R^2 = 0.554$, $P < 0.01$); (E) $y = -0.31 + 8.725x$ ($R^2 = 0.431$, $P < 0.01$); and (F) $y = -14.958 + 152.040x$ ($R^2 = 0.360$, $P < 0.01$). Data are treatment means for all the nine species ($n = 9 \times 3 = 27$). (Source: Singh and Singh, 2001)

poor soils. N supply could influence plant growth and productivity by altering both leaf surface area and photosynthetic capacity (Sinclair, 1990; Frederick and Camberato, 1995). N content in leaves is related to the photosynthetic capacity, primarily because major amount of leaf N is represented by the enzymes of the Calvin cycle (Evans, 1989). Fahey *et al.* (1998) observed an enhancement in foliar nutrient concentrations (N, P and K) after NPK fertilization in five northern hardwood forest tree species. The study by Singh and Singh (2001) clearly pointed out that the tree species having lower foliar N concentration are affected more by N fertilization in terms of increasing foliar N concentration as compared to those with a greater foliar N concentration. A similar trend was reported for P concentration. This emphasises the fact that the initial foliar nutrient status of plants determine the response of foliar N and P concentrations to fertilization.

Singh and Singh (2001) observed positive relationships between the initial height and the subsequent height increment, and initial diameter and the subsequent diameter increment for trees growing on non-fertilized plots (Fig. 9). This emphasises that plants which are able to grow to a greater height and diameter at the initial phase will also continue to grow more rapidly. The amendment of full dose NPK, however, weakened these relationships, emphasising that fertilization results in more uniformity in growth

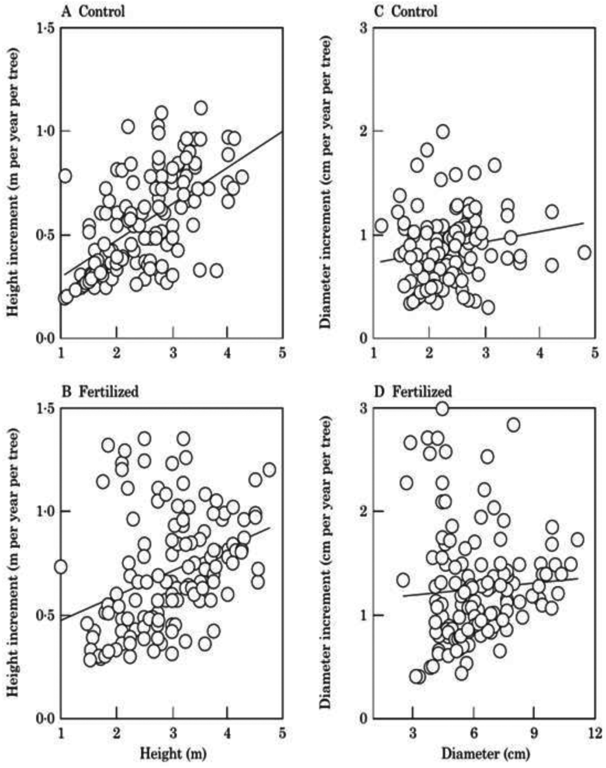

Fig. 9: Relationships between initial height (33 months after plantation) and subsequent annual height increment and between initial diameter and subsequent annual diameter increment for trees planted on mine spoil with and without fertilizer (full dose) application. Regression equations are (A) $y = 0.113 + 0.177x$ ($R^2 = 0.33$, $P < 0.01$); (B) $y = 0.353 + 0.119x$ ($R^2 = 0.121$, $P < 0.01$); (C) $y = 0.688 + 0.038x$ ($R^2 = 0.033$, $P < 0.05$); and (D) $y = 1.134 + 0.021x$ ($R^2 = 0.005$, $P > 0.05$). Data are for 135 (nine species x 15 individuals) trees each from control and fertilized (full dose) plots. (Source: Singh and Singh, 2001)

among the individuals (i.e. it removes the nutrient poverty of suppressed individuals). In saplings of *Banksia grandis* also Abbott (1985) observed a positive relationship between height and its increment.

Impact of Plantations of Native Trees on Mine Spoils

Tree plantations are considered to have the ability to restore soil fertility and improve micro-climatic conditions (Singh *et al.*, 2002). The ecological importance of tree plantations for revegetating damaged tropical lands has been documented by Lugo (1992), Lugo *et al.* (1993), and Parrotta (1992). However, each plant species possesses its own growth properties that characterises its value for stabilizing and enriching soil. Grasses and legumes prove to be more effective plant materials for preventing erosion in initial phase of reclamation. Tree and shrubs are efficient in providing a permanent cover on degraded areas with minimum additional after-care or maintenance. By having deep roots, trees could loosen the compacted soil to greater depth compared to grasses. Tree plantations are important nutrient and carbon sinks, leading to the enrichment of soil fertility and forest re-establishment within which native species can develop (Lugo, 1992). Trees can develop soils through processes including maintenance or enhancement of organic matter in soil, fixing biological nitrogen, nutrient uptake from below the reach of roots of under storey herbaceous vegetation, increased infiltration of water and storage, reduction in the nutrient loss by erosion and leaching, improving physical properties of soil, reduction of soil acidity and improving biological activity of soil (Young, 1997). In due course of time, trees are able to develop new self-sustaining topsoils (Filcheva *et al.*, 2000). However, influence of trees on the fertility of soil depends on their nutrient cycling properties such as litter chemistry and rate of decomposition (Montagnini *et al.*, 1995). Some plantation species show high nutrient use efficiency and thus contribute more as effective nutrient sinks as compared to other species (Lugo, 1992). In the temperate conditions, broad-leaved, slower growing native trees are considered more pleasant but have less efficiency for timber production (Filcheva *et al.*, 2000).

Singh *et al.* (2004a) studied the influence of young high-density plantations of the two native leguminous (*Albizia procera* and *A. lebbeck*) and one non-leguminous timber tree (*Tectona grandis*) species on the soil redevelopment process during the initial phase of mine spoil restoration. These experiments were performed at Jayant coal mine located in Singrauli coalfield region (23°47'–24°12' N lat. and 81°48'–82°52' E long.). This study focussed on young plantations of the above three native tree species planted on mine spoil in 1990. The stocking density during the time of plantation was 2500 individuals ha^{-1} for all the species. Among these, about 71-88% individuals were able to survive after 3 years. For this experiment, three permanent plots (each of 25 x 25 m for *A. lebbeck* and *A. procera* and 15 x 15 m for *T. grandis*) were established for each species plantation. From each plot using 15 x 15 x 10 cm monoliths, three soil samples were collected randomly in September of the year 1994, 1995 and 1996. The findings are discussed below.

Physico-chemical Characters

Singh *et al.* (2004a) reported a general improvement in the properties of soil due to plantation establishments. Across the plantations, there was an increase in soil WHC, decrease in bulk density and elevation in levels of soil organic C, total N, total P and exchangeable cations. Several studies have reported that due to tree plantations soil conditions are improved by increase in the organic matter mass and concentrations of available nutrients and by decline in the soil bulk density (Miller, 1984; Sanchez *et al.*, 1985; Bernhard-Reversat, 1988; Parrotta, 1992). However, the results are significantly influenced by the selection of planted species. Some species are able to accumulate mass and nutrients more compared to others, or they could influence the accumulation of any particular nutrient while others not. Probably, some species might not be able to affect the soil chemistry (Montagnini *et al.*, 1995).

Organic C is considered important for the sustainability of vegetation (Dragovich & Patterson, 1995). High levels of organic matter may improve capacity of aggregation and infiltration and enhance the availability of nutrients (NRC, 1981). In the study conducted by Singh *et al.* (2004a), maximum organic matter values were observed in *A. lebbeck* plantation and minimum in *T. grandis* plantation (Table 18), which

Table 17: Annual height, diameter and volume increments per tree species grown on mine spoil under two levels of NPK and a control. (Source: Singh and Singh, 2001)

Species	Treatment	Height (m)	Diameter (cm)	Volume (cm^3)
Legumes				
Acacia catechu	Control	0.74^{a}	1.05^{a}	8618^{a}
	Half NPK	0.95^{b}	1.60^{b}	$14\,016^{a}$
	Full NPK	0.89^{ab}	1.38^{b}	$12\,236^{a}$
Albizia lebbeck	Control	0.64^{a}	0.98^{a}	9020^{a}
	Half NPK	0.65^{a}	1.22^{b}	$13\,825^{ab}$
	Full NPK	0.76^{b}	1.4^{b}	18518^{b}
Dalbergia sissoo	Control	0.87^{a}	0.98^{a}	7514^{a}
	Half NPK	0.98^{a}	1.01^{a}	9587^{a}
	Full NPK	0.86^{a}	1.06^{a}	$10\,404^{a}$
Pongamia pinnata	Control	0.75^{a}	0.91^{a}	5116^{a}
	Half NPK	0.70^{a}	1.04^{a}	6467^{a}
	Full NPK	0.78^{a}	1.51^{b}	$10\,149^{b}$
Non-legumes				
Azadirachta indica	Control	0.45^{a}	0.85^{a}	4004^{a}
	Half NPK	0.60^{b}	1.01^{b}	7012^{b}
	Full NPK	0.58^{b}	0.93^{ab}	8583^{b}
Gmelina arborea	Control	0.61^{a}	1.24^{a}	$12\,525^{a}$
	Half NPK	0.83^{b}	1.8^{b}	$18\,642^{a}$
	Full NPK	1.19^{c}	2.35^{b}	$40\,930^{b}$
Phyllanthus emblica	Control	0.32^{a}	0.55^{a}	2086^{a}
	Half NPK	0.47^{b}	0.92^{b}	4756^{b}
	Full NPK	0.44^{b}	0.89^{b}	4967^{b}
Tectona grandis	Control	0.29^{a}	0.44^{a}	1314^{a}
	Half NPK	0.43^{b}	0.53^{b}	2478^{b}
	Full NPK	0.43^{b}	0.65^{b}	4205^{b}
Terminalia bellirica	Control	0.32^{a}	0.76^{a}	2519^{a}
	Half NPK	0.35^{a}	0.77^{a}	3237^{a}
	Full NPK	0.42^{b}	1.3^{b}	6871^{b}

Values in a column for each species superscripted with different letters are significantly different from each other at $P<0.05$

corresponds to their respective primary productivity levels as reported in Singh (1999). Kaye *et al.* (2000) also reported that soil carbon exhibits linear increase with increasing percentage of *Albizia* in mixed plantations.

Most soils contain low organic carbon content; therefore N is the major limiting nutrient for the growth of plants (Mays and Bengston, 1978). The benefit of sustaining an adequate N supply to vegetation on coal mine spoil is well reported in literatures (Davison and Jefferies, 1966; Fitter and Bradshaw, 1974). Effect of trees on soil fertility is influenced by their litter chemistry and rate of decomposition (Filcheva *et al.*, 2000). In the study of Singh *et al.* (2004a), maximum N levels were observed in soil planted with *A. lebbeck*, a N-fixing plant (Table 18). Another N-fixer, *A. procera*, was not found much effective in improving N levels in the soils suggesting that all N-fixers might not be equally efficient in improving soil N levels. This may be due to slow litter decomposition and lower return of N through litterfall by *A. procera* as compared to *A. lebbeck* (Singh, 1999). *A. lebbeck* has greater decomposition rate (decay constant –1.19 ± 0.04 per year) due to its high quality leaf litter (C/N = 27; lignin/N = 9.9). However, the leaf litter of *A. procera* is slow decomposing (decay constant –0.830 ± 0.02 per year) due to its poor leaf litter quality (C/N = 34; lignin/N = 33:3). *T. grandis* has been observed to have intermediate decomposition rate (decay constant –0.910 ± 0.08 per year) due to moderate litter quality (C:N ratio = 65; lignin/N ratio = 24.33). Also, in the plantations studied by Singh *et al.* (2004a), N-fixing efficiency of *A. lebbeck* nodules was 19% greater compared to *A. procera* nodules, but the area-weighted nodule biomass, in their study was significantly greater for *A. procera* (0.8-19.7 g m^{-2})

Table 18: Soil organic C (SOC), total nitrogen (TN), total phosphorus (TP), ratios (C:N and C:P) and available nutrients (NH_4-N, NO_3-N and PO_4-Pi) in re-developing soil under plantations of three native species on mine spoil[a]. (Source: Singh *et al.*, 2004a)

Characteristics	*Albizia lebbeck*	*Albizia procera*	*Tectona grandis*
Organic C (mg kg^{-1})	7456^{a}	4211^{b}	2611^{c}
Total N (mg kg^{-1})	720^{a}	549^{b}	258^{c}
Total P (mg kg^{-1})	192^{a}	186^{a}	178^{b}
SOC:TN ratio	10.36^{a}	7.67^{b}	10.12^{ab}
SOC:TP ratio	38.83^{a}	22.64^{b}	14.67^{c}
NH_4-N ($\mu g\ g^{-1}$)	3.78^{a}	3.68^{a}	2.30^{b}
NO_3-N ($\mu g\ g^{-1}$)	1.67^{a}	1.25^{b}	1.13^{bc}
Mineral-N ($\mu g\ g^{-1}$)	5.45^{a}	4.93^{b}	3.43^{c}
PO_4-P ($\mu g\ g^{-1}$)	8.56^{a}	8.39^{a}	7.33^{a}

[a] The values are means across plantation age. Values in a row superscripted with different letters are significantly different from each other at $P<0.05$

compared to *A. lebbeck* (0.2-3.7 g m^{-2}) (Singh *et al.*, 1995).

Phosphorus is considered as an essential element for the growth of plants (Dragovich and Patterson, 1995) and in coal mine spoil sites, it is a limiting nutrient (Bloomfield *et al.*, 1982; Fitter and Bradshaw, 1974). In the study by Singh *et al.* (2004a), age-related trend in soil P was not significant, which indicates independent behaviour of P. Other studies have also reported least correlation of P, compared to other nutrients with vegetation parameters (Roberts *et al.*, 1988). In re-vegetated coastal dunes, Aarde *et al.* (1998) observed that P does not correspond with age-related trend, but rather fluctuates.

N-mineralization

A major problem in re-vegetating the land degraded by surface mining may be the lack of plant available N (Voos and Sabey, 1987). In order to increase N availability plantation of N-fixers has been suggested (Bradshaw, 1997). Singh *et al.* (2004a) observed that the plant available N levels and rates of N-mineralization were always greater in plantations of N-fixer species viz. *A. lebbeck* and *A. procera*. Singh *et al.* (2004a) also reported a general positive association between total soil N and the rate of N mineralization (Fig. 10), however, *T. grandis* plantations with poor soil N content had minimum rates of N mineralization (Table 19). In Hawaii plantations, Garcia-Montiel and Binkley (1998) also observed that the presence of *Albizia* enhances total N pool and N supply to the ecosystem. Parrotta (1992) observed that in *Albizia* plantations higher mineral N produced was in the form of NO_3-N, which is in agreement with the studies from other tropical forest soils (Wetselaar, 1980; Pereira, 1982). However, in the study by Singh *et al.* (2004a), greater proportion of the mineralized N remained as NH_4-N. Declining nitrification could prevent the loss of N from the higher aged plantations resulting into a tighter N circulation (Singh and Singh, 1999).

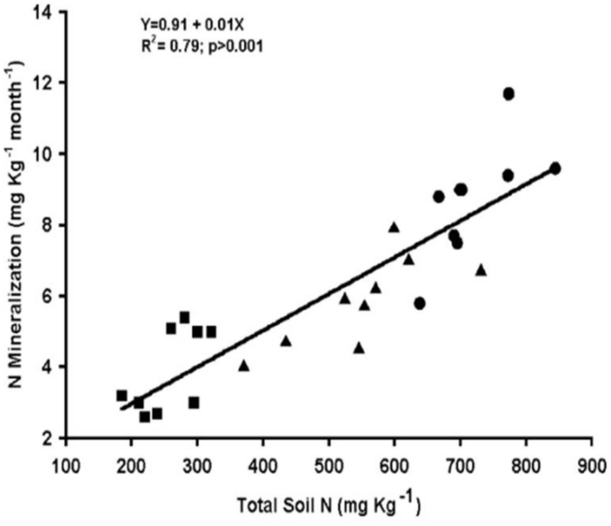

Fig. 10: Relationship between total soil N pool (X) and N mineralization rate (Y) across plantations of different age on mine spoil according to Y = 0.91 + 0.01X (R^2 = 0.79) (square: *T. grandis*; triangle: *A. procera*; circle: *A. lebbeck*). (Source: Singh *et al.*, 2004a)

Table 19: Nitrogen mineralization and nitrification rates in re-developing soil under plantations of three native species on mine spoil[a]. (Source: Singh *et al.*, 2004a)

Soil characters	*Albizia lebbeck*	*Albizia procera*	*Tectona grandis*
Nitrification ($\mu g\ g^{-1}$ per month)	2.46^{a}	1.59^{b}	1.22^{bc}
N-mineralization ($\mu g\ g^{-1}$ per month)	8.73^{a}	5.83^{b}	3.87^{c}

[a]The values are means across plantation age. Values in a row superscripted with different letters are significantly different from each other at P<0.05

Microbial Biomass

For developing a stable plant community on a degraded mined site, a functional soil microbe community is required (Corbett *et al.*, 1996). Microbial processes are very important for the revovery of ecosystems because the activity of micro-organisms could be used as an index of improvement of the soil genesis in mine spoils (Schafer *et al.*, 1980; Segaland Mancinelli, 1987). Microbial biomass measurements can provide one of the major satisfactory estimates for the restoration of microbial populations in soil (Ross *et al.*, 1990). A continuous increment in microbial biomass with mine spoils age in the study of Singh *et al.* (2004a) suggests continuous soil re-development on mine spoils. Also plantations of different species recorded different levels of microbial biomass, where the maximum values were observed in soil planted with N-fixers, *A. lebbeck* and *A. procera*. In this study, microbial biomass recovery was much faster compared to the recovery of total soil nutrient pools.

Bentham *et al.* (1992) reported that during soil recovery of lignite mining, after 5 years, microbial biomass exhibited more rapid increment than soil organic matter. In an earlier report, Hart *et al.* (1989) observed that after 10-25 years of recovery, populations of microbes and earthworms and the easily mineralized N pools had almost redeveloped in mined soil. However, total C and N were much slower to recover.

The microbial biomass C: total soil C ratio has been suggested as a measure of success in reclamation effort (Insam and Domsch, 1988). A continuous increase in microbial C: total C ratio was reported in the study of Singh *et al.* (2004a) in each plantation suggesting that steady state has not been achieved yet. A small variation in C/N ratio of microbial biomass across the age and almost similar situation across plantations of different species in 6-year-old plantations (Table 20) in the study of Singh *et al.* (2004a) suggests that C/N ratios of soil microbial biomass might reflect the physiology of the organisms growing with deficiencies of the external N supply (Jenkinson, 1988).

Table 20: Effect of age of plantation on soil microbial biomass (MB-C), microbial biomass N (MB-N), microbial biomass P (MB-P), and their contents (SOC, TN, and TP in MB-C, -N and -P) in re-developing soil of mine spoil[a]. (Source: Singh *et al.*, 2004a)

Soil characters	Age		
	4 years	5 years	6 years
MB-C (μg g^{-1})	129.34^{a}	229.79^{b}	363.17^{c}
MB-N (μg g^{-1})	20.03^{a}	30.48^{b}	43.09^{c}
MB-P (μg g^{-1})	10.11^{a}	13.92^{ab}	17.32^{b}
SOC in biomass C (%)	3.92^{a}	5.64^{b}	6.88^{bc}
Total N in biomass N (%)	5.06^{a}	7.24^{a}	8.20^{ab}
Total P in biomass P (%)	6.54^{a}	7.34^{a}	8.60^{a}
MB-C:MB-N	6.61^{a}	7.69^{a}	8.60^{ab}
MB-C:MB-P	13.16^{a}	17.09^{a}	21.66^{ab}

[a] The values are means across species. Values in a row superscripted with different letters are significantly different from each other at P<0.05

Accumulation of C and Nutrients

With increasing age, soil organic C and concentrations of Na, K, Ca, Mg and N increased in the study of Singh *et al.* (2004a). With soil development, organic matter accumulation and N increment takes place in the mined soil surface (Chichester and Hauser, 1991). The rates of accumulation of organic C in young soils have been observed to be 780 kg ha^{-1}yr^{-1} (Crocker and Major, 1955) and 1130 kg ha^{-1}yr^{-1} (Roberts *et al.*, 1981) and also as high as 1350 kg ha^{-1}yr^{-1} (Schafer *et al.*, 1980). In the study of Singh *et al.* (2004a), the rates of organic C accumulation in the soil were 1256, 1886 and 395 kg ha^{-1}yr^{-1} in *A. lebbeck*, *A. procera* and *T. grandis* plantations, respectively. In a study by Gonzalez-Sangregorio *et al.* (1991), total organic C content in mine soil exhibited increment from 0.2 to 1.4%, mostly after one year of seeding of lignite mine spoil in Spain. In the following years, C showed increasing trend, although at a lower rate, ultimately reaching a value of 2.3% at the end of the third year.

In the study by Singh *et al.* (2004a) the N accumulation rate in soil was 82.0, 109.9 and 22.5 kg N ha^{-1}yr^{-1} for *A. lebbeck, A. procera* and *T. grandis* plantations, respectively, exhibiting the role of N fixers in enhancing N accumulation in the soil. In China clay waste of Cornwall, UK, Roberts *et al.* (1981) observed 1966 kg ha^{-1} yr^{-1}accumulation rate for organic matter and 10.2 kg ha^{-1}yr^{-1} for N. Li and Daniels (1994) reported significant increase in total N in Appalachian coal mine soils due to accumulation of organic matter as the age of site increased. N accumulation was recorded mainly in the upper 0-5 cm soil layer in naturally vegetated mine soil and the N accumulation rate was 26.4 kg ha^{-1} yr^{-1}. Nitrogen fixing species generally accumulate 50-150 kg N ha^{-1}yr^{-1} (Bradshaw, 1983). Species-wise variations in organic matter and nutrients might be because of difference in litter input and the rate of decomposition in plantations. Both the nitrogen fixers had greater rates of litter fall and input of C, N and P to soil through litter.

The soil C/N ratio shows changes in the total organic C and total N (Chichester and Hauser, 1991). In the study of Singh *et al.* (2004a), soil C/N ratio in all the plantations increased with age which is similar to the observations in other studies suggesting that C/N ratio increases gradually with time in redeveloping ecosystems (Crocker and Dickson, 1957; Chichester and Hauser, 1991).

Values of soil C and N in the 6-yr old plantations on mine spoil in the study by Singh *et al.* (2004a) were much lower compared to that observed in nearby native forests (Roy and Singh, 1994). Several other studies have also reported that primary or young-growth forests store lower amounts of N, P, and K in the mineral soil as compared to the old growth forests (Entry and Emmingham, 1995). Schafer *et al.* (1980) observed that many properties of new mine soils approach levels as observed in natural soils in around tens of years. Many studies are available to suggest that the levels of organic matter are commonly lower on reclaimed mine sites than found in natural sites (Schafer *et al.*, 1980; Toy and Shay, 1987; Aarde *et al.*, 1998).

Comparative Performance and Restoration Potential of Two Species of Albizia Planted on Mine Spoil

Individual plant species could influence ecosystem processes and could affect nutrient dynamics by several mechanisms (Hooper and Vitousek, 1998; Singh and Singh, 1999). Therefore, the selection of plantation species might influence both the rate and the trajectory of re-vegetation processes (Parrotta, 1992). Desirable species for plantation on mine spoils should have properties such as (i) ability to grow on poor and dry soils, (ii) capable of developing the vegetation cover in minimum time period and could accumulate biomass rapidly, (iii) ability to bind soil for preventing soil erosion and nutrient loss, and (iv) ability to improve the soil organic matter and microbial biomass, leading to ample supply of plant available nutrients (Singh and Singh, 1999). Once soil fertility is enriched, the habitat becomes suitable for the development of more desirable species. As compared to non-leguminous species, N-fixing species are observed to have a characteristic effect on soil fertility by producing easily decomposable, nutrient-rich litter and fast turnover of fine roots as well as nodules (Bernhard-Reversat, 1988; Montagnini and Sancho, 1990). The principal way by which N accumulation in re-vegetating ecosystems can be increased is by the use of legumes (Bradshaw, 1997). However, according to Dobson *et al.* (1997), plantation of N-fixing species needs proper knowledge of their physiology and their soil preferences.

Albizia is considered a potential leguminous tree for plantation on vast areas of degraded lands, due to its adaptability to fairly arid conditions. *Albizia* trees are pioneers in forest re-growth and produce large amount of seeds and exhibit rapid growth (Parrotta, 1992). *Albizia lebbeck* is native tree of the Indian sub-continent, and nowadays, it has been cultivated in tropical and sub-tropical zones in America and Caribbean countries and also in south-east Asia (Kumar and Toky, 1994). *Albizia procera* commonly occurs in Africa, Asia, Australia, Caribbean, Central, North and South America. In India, the species is frequently distributed throughout the sub-Himalayan belt and is generally found in Assam, Bengal, Chota Nagpur, Western Ghats, Madhya Pradesh and Uttar Pradesh (Troup, 1921). These two species are moderate-sized, deciduous, nitrogen-fixing and endomycorrhizal trees (Singh *et al.*, 1995). Singh *et al.* (2004b) compared the performance and effect of young plantations of two indigenous *Albizia* species (*Albizia lebbeck* and *Albizia procera*) on the soil redevelopment processes during the early phase of mine spoil restoration. Experiments of Singh *et al.* (2004b) were executed at Jayant coal mine located in Singrauli coal-field region (23°47'–24°12' N lat. and 81°48'–82°52' E long.). Plantations of *A. lebbeck* and *A. procera* were developed in July-August 1990 by growing 7-8 months old seedlings raised in nursery in pits of 40 × 40 × 40 cm size at a spacing of 2 × 2m. About 200 g soil from adjacent forest was added to each pit as inoculant for rhizobia and mycorrhizal fungi. Three permanent plots, each 25 × 25 m in size, were randomly established in the plantations of both species in 1993. At the time of plantation, the stocking density was 2500 individual's ha^{-1}. About 88% individuals were found to survive after 3 years of plantation (Singh, 1999). In each plot, all individuals were measured for dbh (diameter at breast height) in 1993, and re-measurements were done each year up to 1996. Dinanath grass (*Pennisetum pedicellatum*) was sown (6 kg ha^{-1}) in these plantations on June 1994 for controlling soil erosion and nutrient loss due to run-off. Their findings are discussed below.

Biomass and Net Primary Production

The biomass per unit area is considered as the primary inventory data for understanding water and nutrients cycling in the ecosystem (Swank and Schreuder, 1974). Biomass accumulation results primarily from the balance of photosynthesis after subtracting loss due to respiration. The net assimilated C is allocated to supporting organs (coarse roots, stem wood, branches), leaves (light capturing) and nutrient-capturing parts (fine roots, root exudates, mycorrhizae), reproductive tissues (seeds and fruiting structure) and storage (carbohydrate in ray parenchyma cells, fine roots and foliage) (Ryan *et al.*, 1997). In the study by Singh *et al.* (2004b), the two leguminous species exhibited marked differences in biomass accumulation and allocation (Table 31).

A. lebbeck plantation attained a much higher tree layer and total vegetation biomass as compared to *A. procera*. However, *A. lebbeck* showed very poor performance on sodic soils at Banthra in India; 5-yr old plantation attained only 0.5 t ha^{-1} above ground biomass and thereafter was complete failure (Chaturvedi and Behl, 1996). A 5.5-yr old intensively managed *A. procera* plantation, growing on agricultural land, in Puerto Rico documented 124 t ha^{-1} above ground biomass, which resulted into net accumulation rate of 22.5 t ha^{-1}yr^{-1} (Lugo *et al.*, 1990), while in the study of Singh *et al.* (2004b), the net accumulation rate of 4.6 t ha^{-1}yr^{-1} was observed in the *A. procera* plantation on mine spoil. The *Albizia* plantations in the study of Singh *et al.* (2004b) recorded very high biomass compared to that found on 5-year-old naturally vegetated mine spoil in the same area, where the total stand biomass was observed only 7 t ha^{-1} (Jha and Singh, 1991).

Often allocation to large support roots is estimated by a simple allometric relationship, such as 20% of the total biomass of tree (Gower *et al.*, 1995). However, tree can change allocation pattern according to changes in both aerial and soil conditions (Sands and Mulligan, 1990). In the study by Singh *et al.* (2004b), below ground allocation was greater in *A. procera* (x = 40%) compared to *A. lebbeck* (x = 26%). Thērefore, the relative development of abōve and below-ground components on mine spoil was species-specific which is also reported by Sands and Mulligan (1990). Misra *et al.* (1998) for young plantation of *Eucalyptus nitens* in Australia reported that below ground biomass was mainly composed of coarse roots which increased as the size of trees increased. With increase in size of trees or production of biomass with increasing age of plantation, there is asymptotic decline in the contribution of leaves, fine and medium roots to total biomass, while that of stem, branches and coarse roots there is some increase.

The net primary production of the tree layer of *A. lebbeck* and *A. procera* plantations (17.0-25.4 and 10.8-19.3 t ha^{-1}yr^{-1}, respectively) reported by Singh *et al.* (2004b) (Table 31) was greater or similar to that of the adjoining native dry tropical forest (11.3-19.2 t ha^{-1}yrs^{-1}; Singh and Singh, 1991a; Chaturvedi *et al.*, 2011; Chaturvedi and Raghubanshi, 2015). Lugo *et al.* (1990) reported 6.0-32.2 t ha^{-1}yr^{-1} above ground net production for 5.5-yr old dense and intensively managed *A. procera* plantation in Peurto Rico. Singh *et al.* (2004b) measured the relative contributions of short-lived and long-lived components of tree to the tree biomass and NPP for the two plantations at 6 years age (Table 21). The contribution of foliage and small root (<5 mm diameter) to the biomass was very low compared to that to NPP (Table 21). On the other hand, they observed greater contribution of the long-lived component (stem) to biomass compared to NPP. Thus, the contribution of short-lived components was higher for the ecosystem function than long-lived components which exhibited higher contribution for the structure. In *A. procera* plantation, foliage contributed higher for structure and ecosystem function, while in *A. lebbeck* plantation contribution of stem was more. The two species recorded marked difference in allocational strategies. Because of the higher biomass allocation to foliage in *A. procera*, the biomass of foliage on per unit area was found similar for the two species.

Table 21 : Percentage contribution of different components to biomass and production of the 6-year-old plantation. (Source: Singh *et al.*, 2004b)

Components	*Albizia lebbeck*	*Albizia procera*
Foliage		
Biomass	12.4	20.1
Net primary productivity	33.2	50.7
Stem		
Biomass	63.0	47.7
Net primary productivity	40.9	31.0
Small root		
Biomass	1.6	2.1
Net primary productivity	4.2	5.1

Leaf Litter Decomposition and Nutrient Deposition on Plantation Floor

The quantity of leaf fall and the concentration of nutrients in the senesced leaves are considered as the most important attributes of nutrient cycling. The litter-mass accumulation and nutrient enrichment in plantations are also supposed to be important for controlling soil erosion and for assisting vegetation growth (Cuevas and Lugo, 1998). Fast foliage turnover (1 year) and its high share in NPP consequently lead to the deposition of a considerable amount of nutrients on the floor of the plantations. In the study by Singh *et al.* (2004b), higher amounts of N and P were deposited as the age of plantations increased. Total N deposition in *A. lebbeck* plantation was greater, compared to *A. procera*, mostly at ages of 5 and 6 years. This difference was due to higher nitrogen concentration in the leaf litter of *A. lebbeck*, since the total foliage biomass (i.e. total leaf fall) was statistically similar between the two species. P deposition did not exhibit significant difference between the two species.

Nutrients are released from the deposited litter for reusing by plants and the microbial community in soil after decomposition and this nutrient release depends on the rate of decomposition. Singh *et al.* (2004b) reported low decomposition rates on the mine spoil, which is in conformity with several other studies (Lawrey, 1977a; Carrel *et al.*, 1979; Wieder *et al.*, 1983; Singh and Singh, 1999). The rate of litter decomposition could act as an indicator of the recovery of soil ecosystems, because it mainly controls nutrient cycling (Miller and May, 1979). The litter decomposition rate was observed much faster for *A. lebbeck* compared to *A. procera*. The leaf litter of *A. lebbeck* shows 50% decomposition in 213 days and 95% decomposition in 922 days, while leaf litter of *A. procera* exhibit 50% decomposition in 307 days and 95% mass loss in more than 1000 days. The low decomposition rate of *A. procera* leaf litter might be because of lower N concentration and greater lignin concentration. The lignin content observed in the leaf litter of *A. lebbeck* was 16.6%, while in *A. procera*, it was 43.6% (Singh, 1999). Several studies have documented control of decomposition rate by lignin and polyphenol (Meentemeyer, 1978; Berg and Staaf, 1980; Taylor *et al.*, 1989; Mc Claugherty *et al.*, 1985; Mc Claugherty and Berg, 1987; Northup *et al.*, 1995). Thus, the release of nutrient, mainly N from leaf litter of *A. lebbeck* was also greater compared to the release of nutrient from the leaf litter of *A. procera*.

Impact of Plantation on Soil Fertility

Organic C is an important soil nutrient for the vegetation sustainability (Dragovich and Patterson, 1995). When the level of organic matter in mine spoil becomes high, it is expected to increase aggregation and infiltration capacities leading to increase in the availability of nutrients (NRC, 1981). Omodt *et al.* (1975) indicated that organic matter is particularly influential for augmenting and improving plant growth. Soil organic C is a parameter which points out the quantity of dry matter deposition in the form of litter fall. Giardina *et al.* (2001) reported that high quality litter results in the development of high quality organic C and N in the soil. In the study by Singh *et al.* (2004b), soil C and N enhanced with the age of plantation for both species (Fig. 11). They observed considerably greater soil organic C values in *A. lebbeck* compared to *A. procera* plantation however; the amount of litter fall did not show substantial difference between the two plantations. Evidently higher amount of C was transported in the soil under *A. lebbeck* due to greater rate of litter breakdown.

Nitrogen is considered as the most important nutrient for plants. It is the principal element in soil processes, and it is not found in a mineral form, and therefore it is absent from the primary minerals (Bradshaw, 1997). Thus, N is a major key element in soil restoration (Bradshaw *et al.*, 1982; Kendle and Bradshaw, 1992). In the study of Singh *et al.* (2004b), total soil N was higher for *A. lebbeck* plantation (Fig. 11), as a result of higher N deposition through litter fall. Like N, P is also an essential element for the growth of plants (Dragovich and Patterson, 1995) and in coal mine spoil sites, it is basically a limiting nutrient (Bloomfield *et al.*, 1982). Singh *et al.* (2004b) found that soil total P exhibited an age-dependent behaviour but not PO_4-P. They observed age wise increase in the soil C:N ratio in the plantations of *A. lebbeck* and *A. procera* (Fig. 11). It has been suggested that the widening of C:N ratio reflects the effect of vegetation (Crocker and Dickson, 1957). Many studies have reported increase in C:N ratio with time in re-vegetating ecosystems (Chichester and Hauser, 1991;

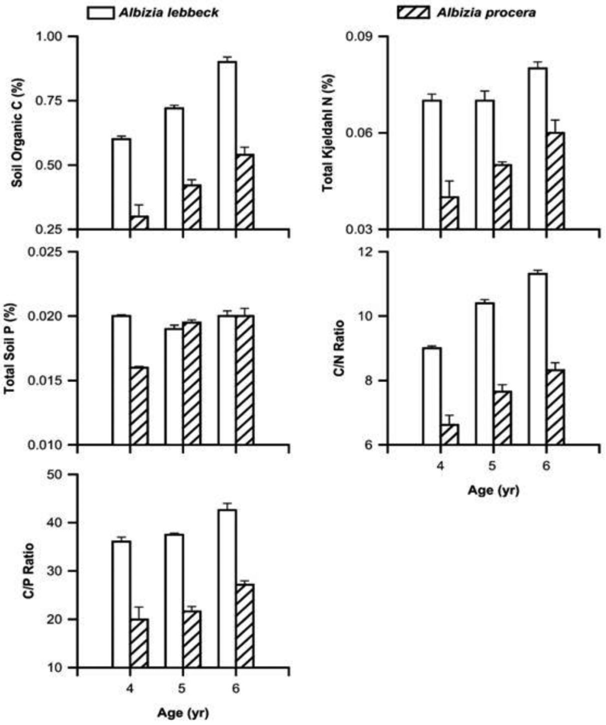

Fig. 11: Soil organic carbon (SOC), Kjeldahl N (TKN), total phosphorus (TP), and their ratios (C/N, C/P) in re-developing soil under plantations on mine spoil. Bars are in ±1S.E. (Source: Singh *et al.*, 2004b)

Lanning and Williams, 1979; Singh and Singh, 1999).

Through the process of mineralization the level of available N increases in the soil (Lindemann *et al.*, 1989). Singh *et al.* (2004b) reported that the level of available N and N-mineralization rates were greater in *A. lebbeck* compared to *A. procera* plantation (Figs. 12 and 13). However, these mineralization rates are lower compared to those reported in the natural deciduous forests (upto 18 μg g^{-1}month^{-1}, Singh *et al.*, 1989). Observations by Parrotta (1992) indicate that average nitrogen mineralization during a 22-day *in situ* incubation to 30 cm depth, was approximately 39% higher in *Albizia* plantation (8.1μg g^{-1} soil) compared to control (without plantations) (5.8 μg g^{-1}). The rate of N-mineralization exhibited significant increase with age in plantations of both the species (Fig. 13). The rate of N-mineralization at 6-yr old mine spoil was one and half-times higher than that at 4-yr old, but the variations in the concentration of mineral-N in soil with age were not significant. According to Richter *et al.* (1999), the forest ecosystem which is aggrading is a strong C sink and

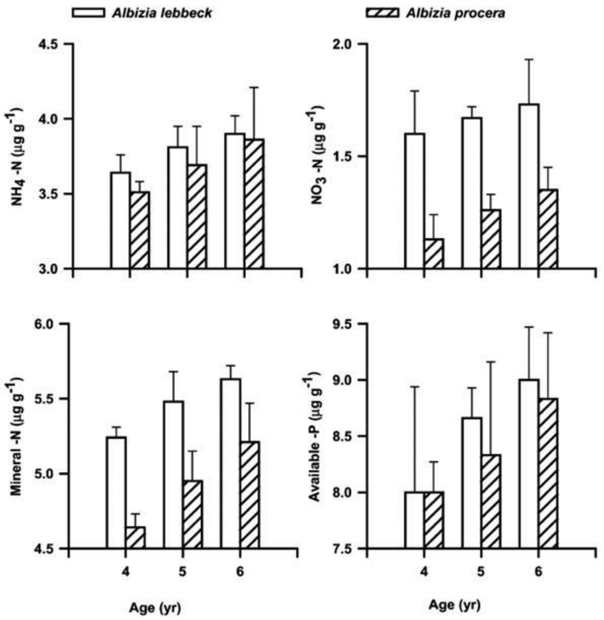

Fig. 12: Mineral N (NH$_4$–N + NO$_3$–N) and available phosphorus (PO$_4$-Pi) in re-developing soil under plantations of *A. lebbeck* and *A. procera* on mine spoil. Bars are ±1S.E. (Source: Singh *et al.*, 2004b)

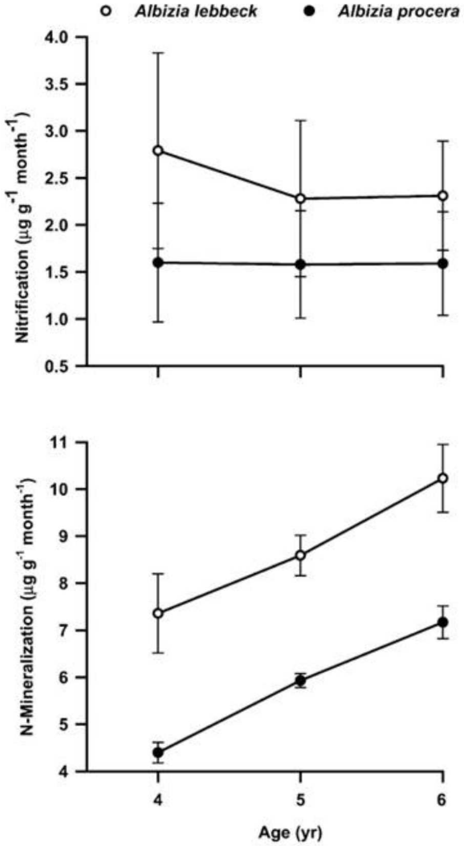

Fig. 13: Nitrogen mineralization and nitrification rates in redeveloping soil under plantations of *A. lebbeck* and *A. procera* on mine spoil. Data points in ±1S.E. (Source: Singh *et al.*, 2004b)

as the demand by the aggrading plant biomass increases, the accumulation of available N and P in the soil declines. Greater rate of mineralization in *A. lebbeck* but similar NH_4–N levels, pointed out higher soil N uptake by the more productive *A. lebbeck* compared to *A. procera*. In majority of forest ecosystems maximum available N produced is nitrate-N (Bernhard-Reversat, 1988; Pereira, 1982). However, contrary to this, in the study of Singh *et al.* (2004b), maximum N mineralized was NH_4–N. Other studies in adjoining forest and bamboo plantations have also reported that the dominant form of available N was NH_4–N (Jha *et al.*, 1996; Singh and Singh, 1999). In the study of Singh *et al.* (2004b), the absolute rate of nitrification decreased with the availability of NH_4–N (N-mineralization), suggesting a tightening of N-cycling as also observed for bamboo plantation on mine spoil (Singh and Singh, 1999).

Re-establishment of soil organisms is an important part of successful restoration effort (Scullion, 1992), as disruption of the biological activity of soil occurs during the process of mining and rehabilitation (Dragovich and Patterson, 1995). For a successful reclamation programme, development of an active microbial community is being considered as an important component (Tate and Klein, 1985). Singh *et al.* (2004b) observed aggradation of the soil microbial biomass with age of mine spoil, and it was greater for *A. lebbeck* than for the *A. procera* plantation (Fig. 14). The microbial biomass levels at 6-yr old spoil were lower than those observed in the native forest ecosystems, but are almost similar to the values documented for 20-year-old naturally regenerating mine spoil (Srivastava *et al.*, 1989).

Soil microbial biomass is considered as a function of soil organic C and N. The study of Singh *et al.* (2004b) reported a positive exponential relationship between soil organic C and microbial biomass C, and soil N and microbial biomass N. When data were pooled across age and replicates, microbial biomass C (Y) was related to soil organic C (X) according to $Y = 23.128\ e^{3.3401X}$ ($R^2 = 0.87$, $P < 0.0001$) in *A. lebbeck*, and $Y = 56.766\ e^{3.2525X}$ ($R^2 = 0.7272$, $P < 0.001$) in *A. procera*. Similarly, microbial biomass N (Y1) was related to soil N (X1) according to $Y1 = 0.727\ e^{53.613X1}$ ($R^2 = 0.653$, $P < 0.001$) in *A. lebbeck* and $Y1 = 5.5133\ e^{30.762X1}$ ($R^2 = 0.716$, $P < 0.001$) in *A. procera*. Several studies have also reported a positive relationship between microbial C and total soil C, and between microbial N and total soil N (Ruess and Seagle, 1994; Singh and Singh, 1995). Further in the study of Singh *et al.* (2004b), the proportional increment with time in microbial biomass was considerably higher compared to the proportional increment in soil C or N. For example, microbial C in *A. lebbeck* plantation at 6-yr old spoil was 3.2 times of that at 4-yr old spoil but soil organic C at 6-yr old spoil was only 1.5 times of that at 4-yr old spoil. This result is similar to the reporting of Powlson *et al.* (1987), Saffigna *et al.* (1989), and Singh and Singh (1999). Therefore, the soil microbial biomass level could give an early sign of changes in soil organic matter.

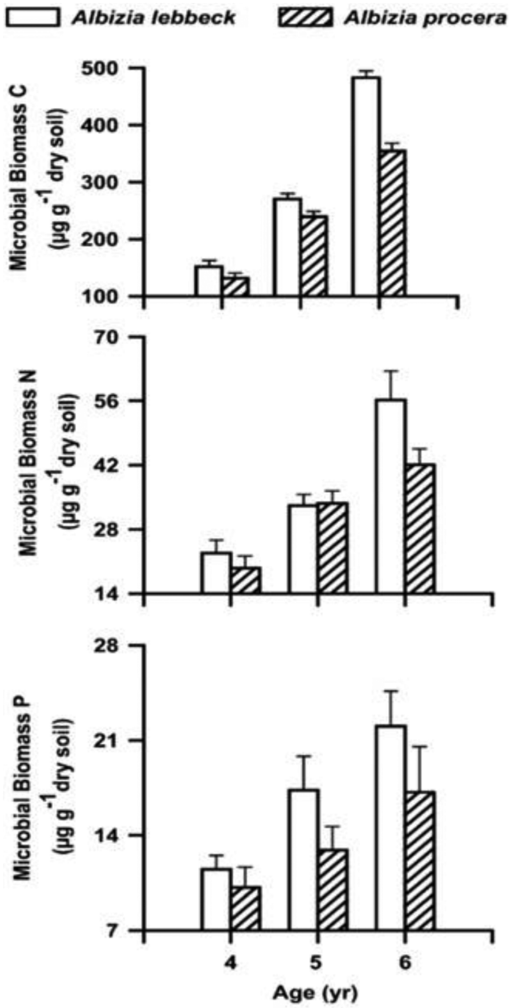

Fig. 14: Soil microbial biomass C (MBC), microbial biomass N (MBN), and microbial biomass P (MBP) in re-developing soil under plantations of *A. lebbeck* and *A. procera* plantations on mine spoil. Bars are in ±1S.E. (Source: Singh *et al.*, 2004b)

Tree Canopy Development in Young Plantations

A mosaic of monocultures composed of many different species may produce an acceptable level of landscape diversity. Besides the establishment of tree species mixture or mosaic of monocultures, development of ground flora is suggested to further improve the stabilization of the community (Singh *et al.*, 1995). The multi-stratal vegetation is necessary for creation of diverse ecological niches as well as for the conservation of soil and water (Jha and Singh, 1994). Jha *et al.* (1999) investigated the growth of seeded grasses, *Heteropogon contortus* and *Pennisetum pedicellatum* in the plantation plots of different tree species after three years of plantation. This study was performed at Jayant coal mine located in Singrauli coalfield region (23°47'–24°12' N lat. and 81°48'–82°52' E long.). In this study, tree monocultures were developed in about 2 ha area in July 1993. Nursery raised seedlings of following tree species were planted: *Acacia catechu*, *Albizia lebbek*, *Azadirachta indica*, *Dalbergia sissoo*, *Dendrocalamus strictus*, *Phyllanthus emblica*, *Gmelina arborea*, *Leucaena leucocephala*, *Pongamia pinnata*, *Tectona grandis*, and *Terminalia bellirica*. Plot size for each species was 20 x 20 m with three to six random replicate plots. The spacing between/within rows was 2 x 2 m. Ground seeding was done in July 1993, and repeated in June 1994 and June 1995 with grasses, *Pennisetum pedicellatum* and *Heteropogon contortus* in between rows of plantations. At peak growth period, i.e., in October of the year 1996, above-ground biomass of grasses was measured under tree canopy and in open area.

After three years of the development of vegetation, Jha *et al.* (1999) found that the seeded grass *Pennisetum pedicellatum* was completely removed by the dense canopy of *Gmelina arborea*. However, under the dense canopy of *G. arborea*, the growth of *Heteropogon contortus* was satisfactory. The above-ground biomass of *H. contortus* under the dense canopy of *G. arborea* was 742 g m^{-2}, whereas in open area it was 2564 g m^{-2}. In open area the above-ground biomass of *P. pedicellatum* was 1734 g m^{-2}, whereas it was nil under the dense canopy of *G. arborea*. It was also observed that the dense canopies of *D. strictus*, *P. pinnata* and *L. leucocephala* completely removed the seeded grass *H. contortus* and *P. pedicellatum*.

Jha *et al.* (1999) observed that after three years of revegetation, *G. arborea*, *P. pinnata* and *L. leucocephala* attained 3.05 m and 6.28 cm, 2.67 m and 4.11 cm, and 2.54 m and 3.02 cm height and diameter, respectively. In the case of *D. strictus*, the number of culms/clump ranged from 2 to 7 having height 2 to 5 m and diameter 1.91 to 3.82 cm (Singh *et al.*, 1996).

Jha *et al.* (1999) reported that to increase the diversity of herbaceous layer, thinning is needed in young plantations on mine spoils after three-four years. Otherwise, the ground flora will be removed after the establishment of dense tree canopies. *H. contortus* is more hardy than *P. pedicellatum*. Therefore, for ground seeding, *H. contortus* should be given preference compared to *P. pedicellatum*. Biomass accumulation observed by Jha *et al.* (1999) was more for *H. contortus* compared to *P. pedicellatum*.

Influence of a Developing Tree Canopy on The Yield of *Pennisetum Pedicellatum* Sown on A Mine Spoil

The establishment of herbaceous layer is necessary for the restoration of extremely degraded habitats such as coal-mine spoils. Here the primary objective for re-vegetation is the soil erosion control through plant cover in the short-term and the establishment of a self-sustaining community by colonization of native plants in the long-term (Jha and Singh, 1993). Plantations of selected suitable tree species of variable potential heights and ground layer seeding with grasses and leguminous forbs is suggested as a low-input technique for the development of a multi-stratal vegetation canopy on the mine spoils (Jha and Singh, 1994). The grass cover adds organic C to the spoil, as well as serves as a trap for wind blown seeds and other material and as mulch. Therefore, it is important to know how and to what level the developing canopies of planted trees affect the growth of seeded grass.

Tree canopies substantially improve the micro-environment and modify below-canopy structure and fertility of soil conditions (Weltzin and Coughenour, 1990). Trees can either support or harm the grass production by altering the availability of resources to under-storey grasses (Vetaas, 1992). In tropical forests, where light falls perpendicular to the ground, light declines gradually from gap centre to edge, and from above canopy to below-canopy locations (Chazdon, 1986; Denslow, 1987). Influence of gaps on the development of woody plants in tropical forests has been reported (Denslow, 1980; Denslow, 1987), however little research has been done to observe the effect of canopy openness on ground layer herb communities in tree plantations. Singh *et al.* (1997) estimated shoot and root biomass yield of the grass, *Pennisetum pedicellatum*, sown below-canopy, canopy edge and in open locations in young monoculture stands of eight tree species planted on a coalmine spoil. Study of Singh *et al.* (1997) was performed at Jayant coal mine located in Singrauli coal-field region (23°47'–24°12' N lat. and 81°48'–82°52' E long.). Several tree monocultures were planted with 2 × 2 m spacing in 1990-1991. Mine spoils were fresh at the time of planting, and natural vegetation was absent. Irrigation and fertilization of trees was not done. Singh *et al.* (1997) selected eight tree species for the study. Measurement was done in the year 1994 for height, stem circumference at breast height and crown shape. In these plantations, *Pennisetum* seeds (6 kg ha^{-1}) were sown in June 1994 after light ploughing, and data on grass biomass were recorded at peak growth in November 1994. At each tree plantation, Singh *et al.* (1997) established three permanent plots, each 15m×15m, and three locations were identified in each plot: (1) below-canopy: directly under the densest part of the tree canopy near the bole, (2) canopy edge: under the most sparse part of the canopy, and (3) in the open. These locations represented an increasing gradient of canopy openness.

Singh *et al.* (1997) reported that biomass of the grass *Pennisetum pedicellatum* differed significantly in harvest plots present below the canopies of different tree species (Table 22). This variation may occur because of several factors which exhibit variations among tree species. Tree species may change the below-canopy structure and fertility of soil (Weltzin and Coughenour, 1990), intercept and re-distribute rainwater on the basis of canopy and bark characteristics (Pathak *et al.*, 1985) and withdraw nutrients in varying amounts from the senescing leaves, leading to variable litter quality (Vitousek and Sanford, 1986) and consequently exhibiting variations in the release pattern of nutrients (Upadhyay and Singh, 1989). These factors show different effect for different species, leading to change in the sub-canopy environment to varying degrees (Vetaas, 1992).

One major process by which trees modify the environment of sub-canopy, however, is the direct solar radiation interception, which may also reduce the soil temperatures and evapotranspiration affecting the below-canopy soil moisture regime (Vetaas, 1992). Light interception show considerable variation among species depending upon the canopy architecture and the width, as well as, inclination of leaves. Canham *et al.* (1994) reported that different canopy tree species may show variation in interception of light, therefore tree species may affect the growth of saplings. The

Table 22: Shoot and root biomass of *Pennisetum pedicellatum* at three locations in different tree plantations. (g m^{-2}). (Source: Singh *et al.*, 1997)

Tree species	Shoot			Root		
	Below-canopy	Canopy edge	Open	Below-canopy	Canopy edge	Open
Albizia lebbeck	$^{a}43_{x}$	$^{a}91_{x}$	$^{a}294_{y}$	$^{a}7_{x}$	$^{bc}17_{y}$	$^{a}43_{z}$
Albizia procera	$^{abc}140_{x}$	$^{abc}265_{x}$	-	$^{ab}14_{x}$	$^{abc}45_{x}$	-
Azadirachta indica	$^{ab}104_{x}$	$^{abc}391_{x}$	-	$^{b}16_{x}$	$^{bc}40_{x}$	-
Cassia siamea	$^{a}37_{x}$	$^{a}73_{xy}$	$^{b}144_{y}$	$^{a}7_{x}$	$^{b}15_{x}$	$^{a}38_{y}$
Dalbergia sissoo	$^{c}215_{x}$	$^{c}221_{x}$	-	$^{d}32_{x}$	$^{c}50_{x}$	-
Eucalyptus hybrid	$^{bc}316_{x}$	-	$^{d}582_{x}$	$^{bcd}59_{x}$	-	$^{ab}96_{x}$
Grevillea pteridifolia	$^{bc}316_{x}$	-	$^{abcd}485_{x}$	$^{cd}46_{x}$	-	$^{ab}90_{x}$
Pongamia pinnata	$^{bc}172_{x}$	$^{b}483_{y}$	$^{c}779^{z}$	$^{abcd}20_{x}$	$^{a}85_{y}$	$^{b}118_{y}$

Values in a column with different superscripts are significantly different ($P < 0.05$) from each other.

Values in a row within a component (shoot or root) with different subscripts are significantly different ($P < 0.05$) from each other.

measurements of incident percentage sunlight by Singh *et al.* (1997) showed a significant difference due to tree species (Table 23). When Singh *et al.* (1997) treated percentage light values as co-variates in the ANOVA for analysing the effect of tree species on grass biomass in below-canopy locations, the differences in grass biomass due to tree species (df 7; 16) became non-significant (for shoot weight, F = 1.543, P = 0.227; for root weight, F =1.384, P = 0.281; and for total plant weight, F =1.708, P = 0.182). Thus, light regime variability in the study of Singh *et al.* (1997) was the only important factor causing variation in grass biomass in below-canopy locations of different tree species.

The study of Singh *et al.* (1997) emphasised that irrespective of the tree species, the biomass of grass declined from open to below-canopy through canopy edge location (Table 22). Several savanna ecosystems have also reported lower grass production under tree canopies (Mordelet and Menaut, 1995). Competition between tree and grass roots for uptake of nutrients and moisture might be one possible reason for reduction in grass biomass from open to below-canopy location. Ellison and Houston (1958) reported reduction in herbaceous production under the canopy of western aspen tree than observed in the canopy openings, and assigned this effect to root competition from aspen.

In the study by Singh *et al.* (1997), an increasing light availability gradient from below-canopy to canopy edge to open location was observed in all tree species plots (Table 23). These differences in light environment were significantly correlated with the biomass accumulation in *P. pedicellatum*; the percentage of full sunlight accounted for 77.7 % and 82.6% of the variation in shoot and root biomass of the grass, respectively (Fig. 15). Therefore, the incident light gradient, instead of root competition, could be the major factor influencing the variation in grass biomass from below-canopy to open locations. Tree canopy light interception has been suggested as the major important factor responsible for the decline of the grass layer biomass and productivity under tree canopy, despite soil nutrient enrichment by the tree layer (Strong *et al.*, 1991; Mordelet and Menaut, 1995). The assimilation rate in the leaves which remain continuously shaded under canopies can be five to six times lower compared to that in leaves present in open conditions in full sunshine (Mordelet and Menaut, 1995).

Table 23 : Percentage of full sunlight at three locations in different tree plantations (%). (Source: Singh *et al.*, 1997)

Tree species	Below canopy	Canopy edge	Open
Albizia lebbeck	$^{a}1.77_{x}$	$^{a}5.90_{y}$	$^{a}13.58_{z}$
Albizia procera	$^{c}6.00_{x}$	$^{b}9.42_{y}$	-
Azadirachta indica	$^{b}3.71_{x}$	$^{c}8.21_{y}$	-
Cassia siamea	$^{ab}1.61_{x}$	$^{a}4.75_{y}$	$^{a}13.42_{z}$
Dalbergia sissoo	$^{c}7.65_{x}$	$^{abc}8.34_{x}$	-
Eucalyptus hybrid	$^{d}17.70_{x}$	-	$^{b}41.92_{y}$
Grevillea pteridifolia	$^{d}23.00_{x}$	-	$^{b}38.90_{y}$
Pongamia pinnata	$^{bc}5.50_{x}$	$^{abc}8.57_{x}$	$^{b}31.28_{y}$

Values in a column with different superscripts are significantly different (P < 0.05) from each other. Values in a row with different subscripts are significantly different (P < 0.05) from each other

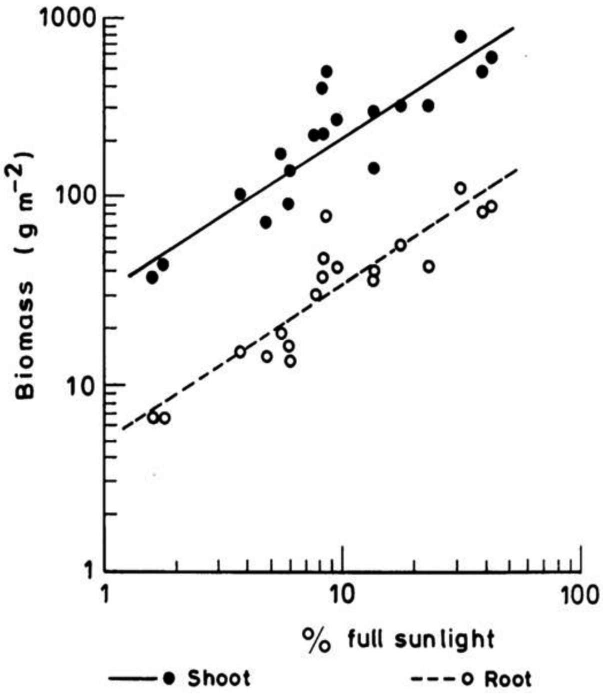

Fig. 15 : Relationships of shoot and root biomass (Y, g m^{-2}) of *P. pedicellatum* with percentage incident full sunlight (X). The regression equations are: for shoot biomass, log Y = 1.515 + 0.822 log X, R^{2} = 0.777, P = 0.000; and for root biomass, log Y = 0.712 + 0.838 log X, R^{2} = 0.826, P = 0.000. (Source: Singh *et al.*, 1997)

Singh *et al.* (1997) expected a significant difference on shoot: root ratio due to the effect of light conditions, according to which the shoot: root ratio is commonly observed to increase along a gradient of decreasing light (Hunt, 1975). However, in the study of Singh *et al.* (1997) the variations in shoot: root ratio exhibited non significant effect both across tree species as well as locations. Evidently, in the grass species selected by Singh *et al.* (1997) the shoot and root growth were equally affected by the level of light intensity, and remained strongly related with each other across the light conditions.

Biomass, Net Primary Production and Impact of Bamboo Plantation on Soil Re-Development

The effect of plant species on the soil of mine spoil, which is undergoing re-development under plantations, may vary from species to species. For example, Alexander (1989a) and Alexander (1989b) studied the development of *Acacia albida* and *Eucalyptus camaldulensis* on the tin-mine spoil in Jos Plateau, Nigeria, and compared their effects. They observed that due to *A. albida* plantation physical, as well as nutritional levels of soil improved in the top 20 cm of the soil beneath its canopy, however *E. camaldulensis* plantation exhibited a gradual increase in the acidity of soil and reduction in base content of the soil. We believe that for planting a desirable species on mine spoils, the species should possess the ability to (i) develop on poor and dry soils, (ii) improve the vegetation cover in a short time and increase biomass rapidly, and (iii) increase the quantity of soil organic matter and microbial biomass, thereby increasing the plant available nutrients in soil. Besides, the species should possess properties for multi-purpose economic use. Singh and Singh (1999) investigated the impact of *D. strictus* on soil properties during the initial stage of mine spoil revegetation. Through the research findings of Singh and Singh (1999) we could understand the processes involved in soil re-development following extensive ecosystem degradation. Experimental plots used by Singh and Singh (1999) were located at Jayant coal mine in Singrauli coalfield region (23°47'–24°12' N lat. and 81°48'–82°52' E long.). *Dendrocalamus strictus* was planted in July-August 1991 on fresh mine spoil by 8-month old nursery-raised seedlings in previously dug pits (40 x 40 x 40 cm) at a spacing of 2 x 2 m. In the bamboo plantation, three plots, each of 15 x 15 m area, were marked in 1994. Number of bamboo clumps in each plot ranged from 45-47. In each plot, five clumps were randomly marked and the culm numbers in each clump was recorded annually from 1994 (3-yr old) to 1996 (5-yr old). Categorization of the bamboo shoots was done into current year, old, and standing dead shoots. All culms were measured 10 cm above the ground for stem circumference and tallied into five size classes between 5 and 15 cm at 2 cm intervals. Harvesting of fifteen culms of different size classes was done for biomass estimation. The oven-dry weights of different components, viz., stem, foliage, rhizome, and root were determined. Important findings of the study are discussed below.

Culm Recruitment and Mortality

In *D. strictus* culms emerge from the nodes located on the rhizomes of the previous year culms during the rainy season and grow to full height before branching in about 3-4 months. The production of new culms shows linear relationship with the number of old culms in a clump, and many of new culms are produced by the rhizomes of 1-2 yr old culms (Tomar, 1963). Taylor and Zisheng (1987) observed mean annual culm recruitment between 8.2% (*Fargesia spathacea*) and 13.7% (*Fargesia scabrida*) in bamboos which are the dominant under-storey species under montane and subalpine forests of Sichuan, China, and Tripathi and Singh (1996) found 10.6-12.3% culm recruitment in the plantation of mature *D. strictus* in the Indian dry tropics. In the mine spoil plantation studied by Singh and Singh (1999), the annual recruitment varied from 18% (between the 3rd and 4th year) to 36% (between 4th and 5th year). Among the three species of *Fargesia*, the annual mortality varied from 8.5% to 10.6% (Taylor and Zisheng, 1987), and in the mature *D. strictus* plantation it varied from 6.6% to 10.6% (Tripathi and Singh, 1996). These reports are comparable to the mortality rates observed by Singh and Singh (1999) for the *D. strictus* plantation on mine spoil (6-7%). Thus, this study proves that the mine spoil habitat is suitable for the growth and survival of *D. strictus*.

Biomass and Net Primary Production

The biomass per unit area is considered as the primary inventory data for understanding the cycling of nutrient and water in the ecosystem. Singh and Singh (1999) reported that the bamboo plantation established on the mine spoil accumulated a considerable amount of

Table 24: Oven-dry stand biomass of bamboo plantation at different ages on mine spoil. (Source: Singh and Singh, 1999)

Components	Biomass (t ha^{-1})		
	3-year old^a	4-year old^a	5-year old^a
Foliage	6.1^a	7.9^a	10.7^b
Current shoot stem	4.5^a	3.7^a	5.4^a
Old shoot stem	15.3^a	19.6^a	26.4^b
Dead shoot stem	4.5^a	5.3^a	6.7^a
Rhizome	11.9^a	14.0^a	18.8^b
Root	3.6^a	4.1^a	5.3^b
Total	46.9^a	55.8^a	74.7^b

^{a}Values in a row superscripted with different letters are significantly different from each other at $P < 0.05$

biomass (Table 24). Compared to 30-49 t ha^{-1} biomass accumulation in the study of Singh and Singh (1999), several bamboo forests and plantations have documented 0.8 to 24 t ha^{-1} above-ground biomass (Veblen *et al.*, 1980; Taylor and Zisheng, 1987; Rao and Ramakrishnan, 1989; Tripathi and Singh, 1996). The above-ground biomass observed for other bamboo species across the globe are *Sasa kurilensis* in Japan (90 t ha^{-1}, Oshima, 1961), *Chusquea culeou* in San Pablo, Andes (158.8 t ha^{-1}, Veblen *et al.*, 1980) and *Arundinaria alpina* in Kenya (100 t ha^{-1}, Wimbush, 1945). In the adjoining native dry tropical deciduous forest, above-ground biomass varied between 32-363 t ha^{-1} (Singh and Singh, 1991a; Chaturvedi *et al.*, 2011; Chaturvedi and Raghubanshi, 2015). In the native dry tropical forest, 86% of the tree biomass was contributed by above-ground component and 14% by the below-ground component, while in the study of Singh and Singh (1999), the contribution was 65% for above-ground and 35% for below-ground component in the bamboo plantation. In the study of Singh and Singh (1999), foliage biomass accounted for 14% of the total biomass compared to 7% reported for the native dry tropical forest (Singh and Singh, 1993), which is considered to contribute a high level of primary productivity.

When compared with data of biomass from tree plantations on mine spoils, the biomass of *D. strictus* indicated superiority. A plantation of 3-yr old black locust on mine spoils in Kentucky yielded 5.8 to 18.5 t ha^{-1} above-ground biomass (Creighton *et al.*, 1983). In Eastern-cotton wood, Virginia, the 10-yr old plantations of pine and black locust registered between 36 and 45.4 t ha^{-1} above-ground biomass (Vail and Wittwer, 1982).

The net primary production in *D. strictus* plantation was between 20.7 (3-yr old) and 32.0 t ha^{-1}yr^{-1}(5-yr old) compared to 11.3-19.2 t ha^{-1} yr^{-1} recorded for the native dry tropical forest (Singh and Singh, 1991a; Chaturvedi *et al.*, 2011). Several studies have reported above-ground net primary production in bamboo forests and bamboo plantations between 1.5-11.0 t ha^{-1}yr^{-1} (Veblen *et al.*, 1980; Taylor and Zisheng, 1987; Tripathi and Singh, 1996) which is lower than the range 17.0-24.7 t ha^{-1}yr^{-1} in the study of Singh and Singh (1999) (Fig. 16). In Japan, Isagi *et al.* (1993) have documented 24.6 t ha^{-1}yr^{-1} above-ground net primary productions for *Phyllostachys bambusoides*. In the study by Singh and Singh (1999), the total NPP of foliage was observed to be 33.7-38.9%, and the above-ground NPP, 43.3-46.5% (Fig.

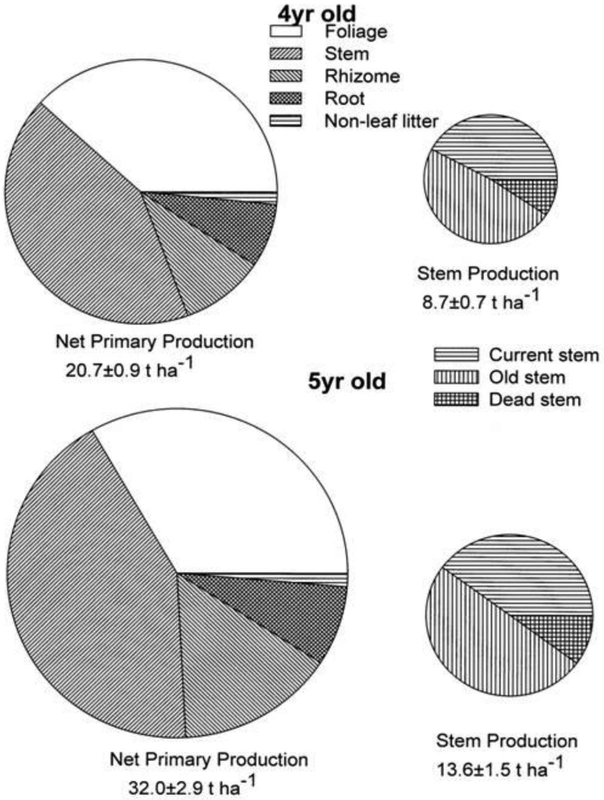

Fig. 16: Share of different plant components in total NPP of bamboo plantation. Values below the pies are total net production ±1 S.E. The pies on the right represent distribution of stem net production in current, old and dead categories. (Source: Singh and Singh, 1999)

16). In the adjoining native dry tropical forest, tree and shrub foliage accounted for 30% of NPP (Singh and Singh, 1993) and the above-ground tree NPP accounted for 38-57% of total NPP (Singh and Singh, 1991a). Production efficiency (i.e., NPP per unit weight of leaf) reported in the study by Singh and Singh (1999), varied between 2.6 to 3.0, whereas for a variety of deciduous species in south-eastern USA Hedman and Binkley (1988) reported production efficiency of 3.3.

The high NPP and relatively lower biomass reported in the study of Singh and Singh (1999) suggests short mean residence time (biomass accumulation ratio, biomass: net production) of different plant components. The mean biomass accumulation ratio for foliage was 1 year, for culm, 5 years, for rhizome, 5 years and for roots, 2.3 years (Fig. 16). Isagi (1994) reported biomass accumulation ratio of 6 years for culms of *Phyllostachys bambusoides*, while this ratio for the dry tropical forest trees has been reported at13.7 (Singh and Singh, 1991a). The biomass accumulation ratio of bamboo culms reported by Singh and Singh (1999) supports 3-5 years felling cycle for bamboos. However, as majority of the products of bamboo stem last for a long time, the accumulated C could remain sequestered for a long time.

Litter Deposition, Decomposition and Nutrient Release

In the study of Singh and Singh (1999), fast turnover (1 year) of the foliage component and its high share of NPP results in substantial amount of nutrient deposition on the floor each year by the bamboo plantation. The nutrient deposition (45-79 kg N and 6-11 kg P $ha^{-1}yr^{-1}$) reported by Singh and Singh (1999) (Table 25) is similar to the range 51.6-69.6 kg N and 3.1-4.3 kg P $ha^{-1}yr^{-1}$ documented for native dry tropical forest (Singh and Singh, 1991b), and 40.8 kg N and 3.5 kg P $ha^{-1}yr^{-1}$ for a mature *D. strictus* plantation on unmined Ultisol (Tripathi and Singh, 1995).

Release of nutrients deposited on soil depends on the rate of decomposition. Roy and Singh (1994) observed a litter decay constant between 1.93 and 2.26 for the tropical dry deciduous forest, and Tripathi and Singh (1992) found a leaf litter decay constant of 1.51 for bamboo plantation in natural dry tropical habitat. Thus, on mine spoil, for 50% decomposition, *D. strictus* leaf litter takes 235 days and for 95% decomposition more than 1000 days. The corresponding values for natural habitats which are unmined are 168 and 725 days (Singh and Singh, 1999). On the other hand, the leaf litter of natural forest takes only 113-133 days for 50% decomposition, and 488-576 days for 95% decomposition (Singh and Singh, 1999). Therefore, a relatively lower rate of decomposition of bamboo leaf litter could lead to soil organic matter accumulation in the long-run and is supposed to provide benefits of mulching. Due to the leaf mulch accumulation, bamboo plantation contributes efficiently to the prevention of soil erosion and conservation of soil moisture (Yadav, 1963).

Impact of Plantation on Soil Redevelopment

The high litter deposition in the *D. strictus* plantation was exhibited by increase in soil organic C content and total N with the increasing age of the plantation (Singh and Singh, 1999) (Table 26). The soil under 5-yr old plantation registered 98% higher C, and 67% higher N compared to that under 3-yr old plantation. The observed variation of soil C:N ratio (from 8 to 10) is probably due to vegetation effect. As compared to the soil organic C and total N, significant difference was not detected with age in mineral N or PO_4-P. On the other side, the N-mineralization rate increased significantly with age. The N-mineralization rate observed by Singh and Singh (1999) under 5-yr old plantation was twice as found in the 3-yr old plantation (Table 27). Evidently, the increase in demand by the

Table 25 : Deposition of N and P through leaf-fall and release through decomposition. (Source: Singh and Singh, 1999)

Age (year)	Leaf fall ($kg\ ha^{-1}\ yr^{-1}$)	N deposition ($kg\ ha^{-1}\ yr^{-1}$)	P deposition ($kg\ ha^{-1}\ yr^{-1}$)	N release ($kg\ ha^{-1}\ yr^{-1}$)	P release ($kg\ ha^{-1}\ yr^{-1}$)
3	6150	45.51	6.33	37.89	5.27
4	7900	58.46	8.14	48.68	6.78
5	10680	79.03	11.00	65.81	9.16

Table 26 : Carbon and nutrient contents of soil and microbial biomass. (Source: Singh and Singh, 1999)

Parameters	Plantation age		
	3-year^{a}	4-year^{a}	5-year^{a}
Soil organic C (%)	0.34^{a}	0.50^{b}	0.67^{c}
Soil total N (%)	0.04^{a}	0.05^{b}	0.07^{c}
Soil total P (%)	0.01^{a}	0.01^{a}	0.01^{a}
SOC : TN	8.48^{a}	9.22^{ab}	10.05^{b}
NH_4-N (µg g^{-1})	3.2^{a}	3.4^{a}	3.7^{a}
NO_3-N (µg g^{-1})	0.9^{a}	1.1^{a}	1.2^{a}
Mineral N (µg g^{-1})	4.1^{a}	4.5^{a}	4.9^{a}
PO_4-P (µg g^{-1})	8.0^{a}	8.0^{a}	8.8^{a}
Microbial biomass C (µg g^{-1})	126.8^{a}	217.6^{b}	319.1^{c}
Microbial biomass N (µg g^{-1})	19.2^{a}	29.3^{b}	37.5^{c}
Microbial biomass P (µg g^{-1})	9.1^{a}	12.7^{b}	16.2^{c}
SOC in biomass C (%)	3.77^{a}	4.38^{ab}	4.74^{b}
TN in biomass N (%)	4.82^{a}	5.38^{a}	5.61^{a}
Total P in biomass P (%)	7.46^{a}	9.45^{ab}	12.13^{b}
MB-C/MB-N	6.72^{a}	7.47^{a}	8.56^{b}
MB-C/MB-P	13.93^{a}	17.10^{b}	19.73^{c}
N concentration in microbial biomass (%)	7.48^{a}	6.71^{b}	5.86^{c}
P concentration in microbial biomass (%)	3.65^{a}	2.93^{a}	2.53^{b}

^{a}Values in a row superscripted with different letters are significantly different from each other at $P < 0.05$. SOC = soil organic carbon, TN = total nitrogen, MB-C = microbial carbon, MB-N = microbial nitrogen, MB-P = microbial phosphorus

aggrading biomass of plant does not allow the accumulation of mineral N and P in the soil. Several studies on the native forest ecosystems reported a rainy season range of 2.1-6.8 µg mineral N and 1.2-3.1 µg PO_4-P per gram dry soil, and N-mineralization rates of 18-48 µg N g^{-1}month^{-1} (Roy and Singh, 1994; Roy and Singh, 1995; Jha *et al.*, 1996). Therefore, while the value of mineral N pool in bamboo plantation exhibited similarity, even in the 5-yr old plantation, the value of N-mineralization rate was only 14-40% of that reported for the native forest. This suggests a high nutrient use efficiency of the bamboo species. The dominant form of available N observed by Singh and Singh (1999) in both the native forest and the bamboo plantation was ammonium, which suggests a preferential uptake of nitrate by plants (Jha *et al.*, 1996). Nevertheless, in the bamboo plantation, where the absolute net rate of nitrification enhanced with NH_4 availability (N-mineralization), only 35% (3-yr old plantation) to 27% (5-yr old plantation) of mineralized N was transformed into NO_3-N by nitrifying bacteria. The higher accumulation of ammonium might be at least partly because of lower efficiency of nitrification process, or because of substantial microbial assimilation of NO_3 as suggested by Stark and Hart (1997). The accumulation of less mobile form of plant-available N is an evidence of progressively tighter nutrient cycle.

Singh and Singh (1999) observed that considerable amounts of C, N and P were immobilized in microbial biomass, and the quantity of immobilization elevated with age in accordance with increasing soil organic C and total N (Table 26). The microbial biomass levels recorded in the study of Singh and Singh (1999) are substantially lower than reported for native forest ecosystems, but are similar to those found in naturally vegetating mine spoils (Srivastava *et al.*, 1989). Studies have suggested positive associations between microbial C and total soil organic C, and between microbial N and total soil N (Wardle, 1992; Ruess and Seagle, 1994; Singh and Singh, 1995). After addition of C and N through litter fall, the microbial biomass could substantially increase the levels of both C and N in the nutrient deficient mine spoils. In the study by Singh and Singh (1999), while the microbial C in the 5-yr old plantation was 152% higher, microbial N and P were recorded only 96 and 78% higher than in the 3-yr old plantation (Table 26). As the age of plantation increased, proportions of organic C, total N and total soil P became higher resulting into immobilization of nutrients in the microbial biomass, which indicates the process of soil re-development. The microbial C to total soil C ratio is suggested to be an accurate soil microbiological index which could evaluate the status of a restored ecosystem (Insam

Table 27 : Nitrogen mineralization in soils under bamboo plantation. (Source: Singh and Singh, 1999)

Age (year)	Nitrification (µg g^{-1} month^{-1})	N-mineralization (µg g^{-1} month^{-1})
3	1.2^{a}	3.3^{a}
4	1.7^{b}	5.2^{b}
5	1.9^{c}	6.9^{c}

Values in a column superscripted with different letters are significantly different from each other at $P < 0.05$

and Domsch, 1988). Stark and Hart (1997) have suggested that, in the habitats where C and N in soil are accumulating, the microbial biomass could become a net sink for inorganic N, including NO_3.

According to Singh and Singh (1999), the ratio of microbial biomass C:N and C:P elevated in the mine spoil with time and the concentrations of N and P in microbial biomass registered decline (Table 26). These findings suggest a possible change in the microbial biomass composition. As the litter layer accumulates, food web in the soil might progressively become dominated by fungal communities (Hendrix *et al.*, 1986). An increasing fungal composition in the microbial biomass during restoration of grasslands has been reported by Bentham *et al.* (1992). Fungi and bacteria have substantially different C:nutrient ratios. For example, the C:N ratio of fungal hyphae is greater (10-12) than that observed in bacteria (usually between 3-5) (Jenkinson and Ladd, 1981). Compared with the higher turnover and C losses in the habitats dominated with bacterial population, the domination by fungal population could lead to greater retention of microbial-C (Coleman and Hendrix, 1988; Singh and Singh, 1995). This is comparable with the increasing availability of NH_4 (i.e. N-mineralization) reported by Singh and Singh (1999), which is common N-source for microbial population (Recous *et al.*, 1990). Increasing N availability has been suggested to increase immobilization of C in microbial biomass (Elliott *et al.*, 1983).

In the study by Singh and Singh (1999) the proportional rise in microbial biomass was considerably higher than the proportional rise in soil C or N, which is in conformity with Powlson *et al.* (1987) and Saffigna *et al.* (1989). Positive relationships have been observed between microbial biomass and soil structure, and nutrient content (Drury *et al.*, 1991; Singh and Singh, 1995). Therefore, a rapid increment of microbial biomass in the mine spoil is a sign of efficient restoration potential of the *D. strictus* plantation.

Conclusions

Nature is capable of achieving restoration unaided, and can develop fully functional soil, as demonstrated by the process of natural succession. When a plant becomes established on the degraded mine spoil, organic matter in the soil increases, bulk density decreases, mineral nutrients are brought back to the surface and accumulated in the available form. Nitrogen fixing species increase the level of nitrogen in soil and provide a nitrogen capital, which becomes adequate for the normal functioning of the ecosystem. Our review suggests that soil microbial biomass is a critical factor in recovery of the mine spoils as it aids in re-establishment of nutrient cycling. The levels of biomass C, N and P may be treated as functional indexes of soil re-development. Spoil characteristics and species composition changes with increase in spoil age. Therefore, microsite conditions should be given much importance in any revegetation programme and on the basis of post-mining land objectives, to enhance natural revegetation process; proper selection of desired natural colonizing species of higher successional order should be done.

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