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Ecological study of revegetated coal mine spoil of an Indian dry tropical ecosystem along an age gradient

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Abstract Mineral nitrogen (MN), belowground (root) biomass (BGB), soil nitrogen (N) mineralization (NM), microbial biomass N (MBN) and mine dump stability of a revegetated mine spoil were studied after 2, 6, 10 and 12 years of re-vegetation on coal mine spoil site. MN in revegetated mine spoil ranged from 7.4 to 11.6 kg ha^{-1}, NM from 38.4 to 252 kg ha^{-1} year^{-1}, MBN from 86 to 426 kg ha^{-1}, and BGB from 380 to 3,750 kg ha^{-1}. Mining caused decline of physico-chemical characteristics of soil like MN by 46 %, N-mineralization by 92 %, MBN values by 91 %, respectively compared to forest ecosystems and reduction of total plant biomass (above ground and below ground). Revegetation of mine spoil caused increase in MN values by 12, 36 and 76 %, BGB values by 380, 1770 and 3750 times, NM values by 0.6, 3.58 and 9.5 times and MBN values by 0.43, 2.77, and 6.07 times in 2, 6 and 12 years, respectively. BGB was highly correlated with MN and MBN. Clay content was positively correlated to MN, NM, and the age of revegetation ($P < 0.01$). Numerical modelling indicated that revegetation increased the dump slope stability with a factor of safety from 1.2 to 1.4, 1.7, 1.9 and 2.1 after 2, 6, 10 and 12 years, respectively. Thus, long-term revegetation was found to enhance the dump stability and the soil fertility status in mine spoil, where plant biomass and microbial biomass provide major contributions in ecological redevelopment of the mine spoil.

Keywords Mine spoil · Revegetation · Belowground biomass · N-mineralization · Dump stability · Factor of safety

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Introduction

Our society and civilization rely heavily on the mining industry to operate and maintain comfort (Li 2006), for which there is a need of huge amount of coal for massive energy generation. In India, the estimated resource of coal reserve is about 64,786 MT out of which, approximately 52,546 MT is considered geologically proved reserve, whereas 30,356 MT of coal reserve is possible to extract with present knowledge and technology. The total coal production from coal India limited is to about 431 MT for the year 10–11 and estimated dump will be more than 2–3 times of coal (Singh 2011). In India, open pit coal mining constitutes 81 % of the total coal extraction resulting substantial removal of undesirable waste materials in the form of mine spoil dumps.

Generation of huge quantity of mine spoil dumps causes extensive landscape destruction. The dump material needs proper place for safe disposal. It is also intricate to get land around the mine due to restriction either by environmental act, forest land or agricultural land. The steeper dump slope is always preferred because it occupies less surface area but it is often vulnerable to failure, which leads to hamper the regular coal production, loss of life, equipment and surrounding eco-system. Failure of dump is also associated with environmental degradation like land, water, air and ecological changes (Singh et al. 2007). In spite of the claims of competent practices by many mining companies in India, dump failures are being reported from some coal mines. However, flatter dump requires more land which is also not an economical situation for the mine management. Land availability is limited and complicated to manage the dump in the demarcated land. The best solution is to optimize the slope for better dump material adjustment (Vishal et al. 2010). Mine dump represent the highest proportion of waste produced by industrial activity, with billions of tons being produced annually (Bell 1998). A major negative legacy of the mining industry is land dereliction, caused by surface extraction of minerals and the waste products disposal from mineral workings in the form of waste rock piles or mine dumps and tailing ponds (Bell 1996). Mine spoils possess very rigorous conditions for both plant and microbial growth because of low organic matter contents, and other unfavorable physico-chemical characteristics (Singh et al. 2002). It is devoid of soil microbes, organic matter, and soil moisture and plant available nutrients, hence treated as contaminated. To restore such degraded lands is a challenging ecological task.

Natural recovery of disturbed habitats takes much longer time through colonization of plant and animal species (Sharma and Sunderraj 2005). Restoration programmes help to restore the soil fertility and enhance the biological diversity (Singh and Singh 2001, 2006). Revegetation is supposed to be the best tool for reclamation of mine spoils (Fisher 1990; Torbert and Burger 1993; Singh et al. 2002) and a common and efficient approach used to accelerate forest formation on degraded areas (Wang et al. 2007). Reforestation can facilitate forest succession by providing an understory environment favorable for native plant recruitment (Chapman and Chapman 1996; Oberhauser 1997). Plant species may be used as indicators of mine spoil/overburden chemistry. According to Filcheva et al. (2000), trees, being efficient biomass generators, add more organic material (both above- and below-ground) to the soil and are associated with a relatively large array of soil organisms, including earthworms (Banov et al. 1995). Their deep roots involve a greater depth of raw mine stones in the soil organic system. The anchorage of roots and the improvement of slope stability mainly depend on the properties of root systems such as the root distribution and tensile strength (Normaniza and Barakbah 2006; Li et al. 2007), as well as soil conditions.

Revegetation through trees and grasses is one of the widely used techniques for controlling soil erosion and stabilization of dump slope (Singh et al. 1996a; Chaulya et al. 2000; Singh 2011), and consequently maintaining ecological stability of the area (Jorgensen 1994). Vegetation growth and succession on dump slopes can be described as hydrogeological and mechanical actions (Cherubini and Giasi 1997), where the roots play a crucial role in enhancing dump stability by regulating rain water interception and evapo-transpiration and the resulting pore pressure reduction (Hussain 1995), and ultimately regulating hydrogeological cycle. Further, plant roots, by mechanical action, reinforce the mine dump material and enhance the shear strength of the dump material. This function is closely related to root density, depth and strength (Hall et al. 1994). Nonetheless, quantitative evaluation of biological stabilization and soil fertility is still poorly understood and the subject requires further study.

We hypothesized that revegetation will have positive impact on soil fertility along with dump stability along an age gradient. Therefore, the objective of the present study was to evince the long-term changes in soil properties on revegetated mine spoil areas with respect to the status of inorganic nutrients, belowground biomass (BGB), nitrogen transformation, microbial biomass and bio-stabilization of dump slope in a dry tropical environment of India.

Materials and methods

Study sites

The study was performed on coalmine overburden dumpsites of Naya Dara colliery, Kapasara area of

Eastern Coalfield Limited and adjacent forest site of Topchachi Sanctuary of Dhanbad district. The study site is located between 30 and 120 km from Central Institute of Mining and Fuel Research, Dhanbad (23°47″N latitude and 86°43″E longitude). Prior to mining, the study site was gently sloping to moderately sloping land, where the huge quantity of overburden was dumped through a shovel-dumper combination. The mine waste was freshly dumped from open cast mining in 1997 and plantation of sapling was carried out by the Dhanbad Forest Department in the area of 50 ha in June–July 1998, in which three uniform plots of 1 ha areas were demarcated for the study. The details about the plantation procedure were followed as described in Singh et al. (1996a) and the plant monitoring and soil sampling were carried out in the month of October–November 1998, and subsequently in the same months in the years 2000, 2006, 2008 and 2010. Twenty native and fast growing exotic plant species including legumes were planted on flat portions at the distance of 2 × 2 m and three grass species (*Dendrocalamus strictus*, *Vetiveria zizonoides*, *Cymbopogon flexuous*) were used on slopes at a distance of 0.5 × 0.5 m. The average heights of the dump were 28–32 m and the average slope angles were 35°.

The climate is dry tropical with a year divisible into three seasons, namely a cold winter (December to February), a very hot summer (April–June) and a rainy season (July–September). The annual rainfall averages 1, 376 mm, 80 % of which occurs between late June and September. The mean daily temperature within the annual cycle ranges from 10 to 28 °C, while mean daily maximum ranges from 26 to 45 °C (Singh et al. 1996b). The soil surface layer is 100–110 mm thick consisting of grey brown to very pale brown sandy loam, and clay loam with a sub-angular blocky structure. The bedrock is formed of medium to coarse-grained sandstone, clay with ferruginous bands and carbonaceous shales. The overburden dumps consist of alluvium, loose sand, gravel, shale and sandstone (Singh et al. 1996b).

The native typical mixed dry deciduous forest is dominated by tree species *Shorea robusta* (Sal), *Terminalia tomentosa* (Asan), *Butea monosperma* (Palash) and *Dalbergia sisoo* (Shishum). On mine spoil, *Dalbergia sisoo*, *Azadirachta indica* (Neem) and *Leucena leucocephala* (Subabool) among the tree species and *Dendrocalamus strictus* (Bas), *Cynodon dactylon* (Doob), *Saccharum spontaneum* (Kashi) and *Ergrostris tenella* among the herbaceous species has been found to be the most frequently occurring plant species.

Sample collection and soil analyses

The site monitoring for soil nutrients and dump stability was done at the time of revegetation and further at the intervals of 2, 6, 10 and 12 years. The soil samples were collected randomly from each of the five replicate plots from upper 0–10 cm layer in each plot. Each sample was divided into two parts. One part in its field-moist condition was used for determining nitrification, nitrogen mineralization by buried bag technique (Eno 1960; Melillo 1981; Pastor et al. 1984) and microbial biomass N (MBN) by fumigation extraction method (Brookes et al. 1985), and the other part was air-dried for the analysis of physico-chemical properties. BGB (live + dead root) was determined by sampling five replicates of randomly selected monoliths of 25 × 25 × 50 cm size in each plot as our preliminary study shown 60 % of the biomass was confined to this depth due to heavy compaction of the dump material inside. The monoliths were washed with a fine jet of water and collected on a 0.5 mm mesh screen. The roots were oven-dried at 80 °C to constant weight.

Soil pH was determined by using glass electrode (1:2, soil water ratio) while water holding capacity (WHC) was measured as described by Jenkinson and Powlson (1976). Gravitational soil water (GSW) content of soil, at the time of sampling, was determined after drying a pre-weighted 100 g soil sample until constant weight at 105 °C. PAN (NH_4–N + NO_3–N) on the field-moist soil was estimated following steam distillation with MgO method using Devarda's alloy to reduce NO_3–N to NH_4–N. Nitrate–N and ammonium-N were determined by the phenol-di-sulphonic acid (Jackson 1958), and phenate methods (Wetzel and Likens 1979), respectively. Organic C of the air dried sample was determined by Walkley and Black's rapid titration method (Jackson 1958) total N by Kjeldahl digestion (Brookes et al. 1985), total P by the perchloric acid digestion (Mehta et al. 1954). Statistical analysis (analysis of variance and least significant difference) was performed through the statistical software package (SPSS 1997).

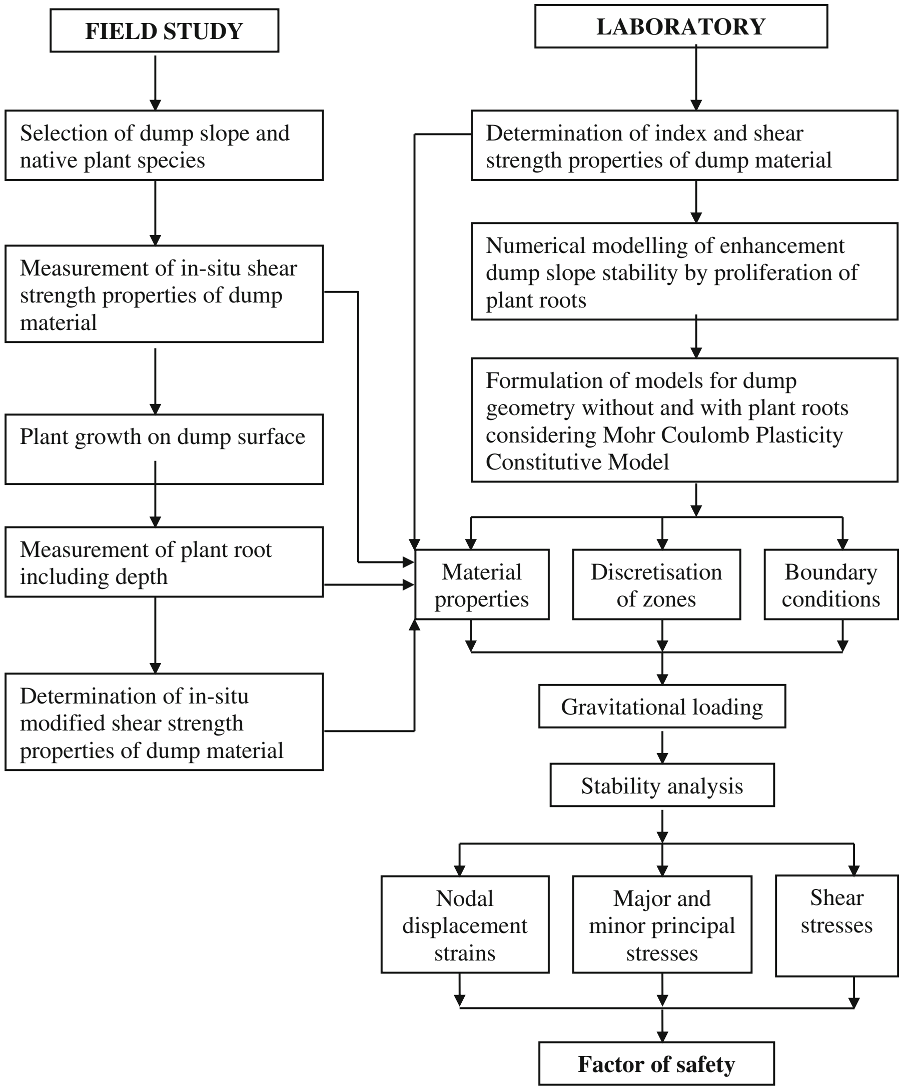


Fig. 1 Flow chart of the methodologies adopted for bio-stability analysis

Bio-stability analysis

The procedures adopted for the field and laboratory studies to analyze the bio-stability of dump slope are systematically presented in Fig. 1. The dump geometry was measured by surveying with electronic distance meter (EDM), before revegetation. The Digital Terrain Model (3-D view) of the dumpsite is depicted in Fig. 2. Two models have been formulated to simulate the field conditions (with and without plants) and analyzed by Finite Difference Method (FDM). Numerical modeling was analyzed by assigning the dumps geometry, material properties and boundary conditions to the simulated models. It is assumed that the dump formation is gravity loaded and no external load is applied on the model. Initial nodal displacement (i.e., movement of element due to gravitational loading) of each zone is calculated and the strains were quantified; then from strains maximum shear stresses were calculated. Lambe and Whitman (1979) have reported that dump failure occurs due to shear stress. The visco-elastic behaviour due to the presence of water poses serious threat during the rainy season. The shear strength reduction due to rise in pore pressure leads to the failure (Singh 2011). Therefore, utilizing Mohr–Coulomb constitutive

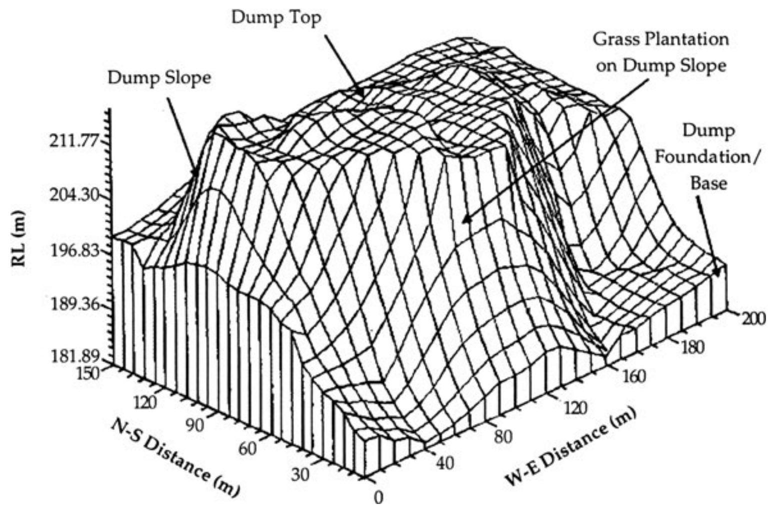


Fig. 2 3D view of a typical Indian mine spoil dump

relation, factor of safety (FOS) was calculated for each zone. Contours of FOS safety have been drawn by Kriging method for the whole domain.

Numerical modelling

FDM was used for simulation of numerical modelling for the problem. In this method, the whole domain has been discredited into small two-dimensional zones (elements), which are interconnected with their grid points (nodes). Over each zone the differential equation of equilibrium has been approximated. This has resulted into a system of simultaneous equations, which are generally solved by iteration methods. A two-dimensional FDM package FLAC version 2.27 (developed by Itasca Consulting Group Inc., USA) has been utilized for the analysis.

Shear strength properties

Shear strength properties of dump material play a vital role in the dump stability (Tesarick and Mckibbin 1999). Determination of reliable shear strength values is a critical part of any dump slope design and small variation in it can result in significant change in the dump slope stability. For most of the evaluations regarding the stability on dump slope, it is necessary to use failure relationship, which is a straight line and is also known as Mohr–Coulomb failure law (Lambe and Whitman 1979; Chaulya et al. 1999).

Factor of safety

The FOS is generally defined as the ratio of available shear strength of the dump material to the shear resistance required maintaining equilibrium. FOS is the critical and reliable approach for evaluating the stability of slopes.

In situ jack shear test

In situ shear strength properties of the dump material (before revegetation and after 6 and 12 years growth of plant species) have been carried out by in situ jack sear test as described by Anand and Rao (1967) and Hribar et al. (1986), and subsequently studied by Singh (1992) and Chaulya (1997). These tests have been repeated five times for both barren dump and reclaimed dump (separately for dump material with plant roots).

Formulation of models

The field observation has indicated that the average depth of plant roots is 0.5 m after 6 years of vegetation. Mohr–Coulomb Plasticity Constitutive model has been used to represent the dump materials behavior as discussed earlier. To study the revegetation effect on dump slopes following two models have been formulated and run separately:

(i) The whole domain has been assigned with same properties as measured in the respective field to simulate the natural dump material i.e. without plants; and

Table 1 Physico-chemical characteristics of forest, mine spoil and revegetated mine spoil under different ages of revegetation (±1 SE)

Parameters	Forest	Mine spoils	2 years	6 years	10 years	12 years
pH	5.38 ± 0.014	7.28 ± 0.023	7.25 ± 0.021	7.05 ± 0.020	6.40 ± 0.016	6.44 ± 0.016
Porosity (%)	36 ± 0.82	12 ± 0.92	12 ± 0.92	16 ± 1.2	20 ± 1.6	21 ± 1.6
Permeability cm/h	0.22 ± 0.01	0.0307 ± 0.002	0.0307 ± 0.002	0.086 ± 0.002	0.106 ± 0.01	0.131 ± 0.01
Sand (%)	61 ± 0.2	73 ± 0.4	73 ± 0.4	73 ± 0.4	70 ± 0.4	69 ± 1.4
Silt (%)	26 ± 0.4	22 ± 0.45	22 ± 0.45	22 ± 0.45	22 ± 0.45	23 ± 1.0
Clay (%)	13 ± 0.3	5 ± 0.40	5 ± 0.38	5 ± 0.38	8 ± 0.42	8 ± 0.42
WHC (%)	42 ± 0.82	18 ± 1.66	18 ± 1.5	20 ± 1.0	25 ± 1.0	28 ± 1.0
GSW (%)	11 ± 0.4	3.5 ± 0.26	3.8 ± 0.6	5.6 ± 0.64	6.8 ± 0.7	7.0 ± 0.6
BD g/cm^3	1.06 ± 0.1	1.80 ± 0.22	1.80 ± 0.22	1.78 ± 0.22	1.72 ± 0.20	1.70 ± 0.20
Mineral N (kg ha^{-1})	12.4 ± 1.2	6.6 ± 0.75	7.4 ± 0.84	9.0 ± 0.67	10.6 ± 0.48	11.6 ± 0.4
PO_4–P (kg ha^{-1})	5.10 ± 0.3	2.10 ± 0.08	2.9 ± 0.3	3.8 ± 0.26	5.45 ± 0.3	5.66 ± 0.28
Organic C (kg ha^{-1})	15,052 ± 245	5,040 ± 175	6,480 ± 195	12,282 ± 239	13,244 ± 258	14,960 ± 264
Total N (kg ha^{-1})	1,696 ± 52	810 ± 35	954 ± 35	1,513 ± 46	1,686 ± 52	1,870 ± 48
Total P (kg ha^{-1})	604 ± 12	162 ± 7	414 ± 9	694 ± 12	740 ± 12	816 ± 14
BGB (kg ha^{-1})	5,750 ± 42	0	380 ± 15	1,770 ± 26	3,140 ± 58	3,750 ± 69
N-mineralization (kg ha^{-1} year^{-1})	308	24	38.4	110.4	204.4	252.2
MBN (kg ha^{-1})	712.6	60.4	86.07	226.4	408.8	426.8

(ii) A modified layer with c and ϕ values as measured in the field of 0.5 m thick along the dump slope has been assigned to represent dump with plants roots.

Slope angle and dump height are observed to be 35° and 30 m, respectively. Base length of 70 m is selected considering the dump geometry and stress influence. Whole domain has been discredited into two different sizes of two-dimensional elements. Near the slope (area of interest) fine elements of 0.5 × 0.5 m size and for rest area 0.5 × 2 m size elements have been selected. The boundary conditions applied include roller boundary (i.e. displacement in vertical direction is allowed and horizontal direction is fixed) along the rear side of the dump and fixed boundary (i.e. no displacement by horizontal and vertical directions) along the base.

Results and discussion

The physico-chemical properties of the forest soil and mine spoil are given in Table 1. Coal mining changed the soil properties by reducing soil permeability, WHC, GSW; and increase in pH and bulk density (Table 1). It is commonly recognized that at pH 6.5 nutrient availability to plants is maximum and toxicity at minimum (Harris et al. 1996). Revegetation increased the WHC, GSW, soil permeability and reduced the bulk density along an age gradient (Table 1). Srivastava et al. (1989) reported increasing trend in WHC and pH and no trend in GSW over an age gradient of coal mine spoils. Macyk (2002) reported that reconstructed mine spoil soil had a coarser texture, higher pH, and lower levels of infiltration rates. Bauer and Black (1981); Voroney et al. (1981); Tripathi and Singh (2009) have also reported an increase in bulk density due to alternate land use. This may be due to loosening of soil by the plant roots and accumulation of organic matter. There exists an inverse relation between soil bulk density and soil organic matter content (Singh et al. 2007). Textural properties were also changed due to mining (Table 1). There was a decline in clay particles proportion in mine spoil by 5 % compared to forest and revegetation resulted increase by 8 % after 12 years. The increase in clay content may be due to fragmentation, redistribution and aggregation of soil particles with the passage of time along with plant root development contributing in soil processes. Soil clay content further affects mineral nutrient and its transformation in mine spoils. Clay content showed significant correlation with OC, TN and TP, nitrification, NM and MBN (Table 1).

Mining caused decline in OC, TN and TP contents of soil by 67, 52 and 73 %, respectively. Revegetation increased the OC by 1.3, 2.5 and 2.96 times; TN by 1.2, 1.9 and 2.3 times, and TP by 2.6, 4.3 and 5.0 times after 2, 6 and 12 years of revegetation, respectively.

Elevated levels of soil OC, TN and TP were observed along an age gradient. Sanchez et al. (1985) and Miller (1984) have also shown that tree plantations improve soil conditions by increasing the organic matter and available nutrients concentrations. Jacinthe et al. (2004) observed higher SOC concentration in mine reclaimed hardwood plantation than reclaimed grassland. Srivastava (1992) found increasing trend of TN and TP and indicate significant relation with microbial biomass along mine spoil age. According to NRC (1981) report, high levels of organic matter could improve aggregation and infiltration capacities and increase the availability of nutrients in soil. Singh et al. (2004) proposed that underlying physico-chemical processes render very long time to soil development in minespoil. They also suggested that the differences found between the soil properties could be attributable primarily to vegetation development.

Below ground biomass

The below ground (root) biomass (BGB) in forest, mine spoils and revegetated sites were 5,750, 0 and 380–3,750 kg ha^{-1}, respectively (Table 1). Mining caused decline in BGB by 100 % as compared to forest, while revegetation caused increase in BGB by 380, 1770 and 3750 times after 2, 6, and 12 years, respectively.

Revegetation showed a gradual increase in BGB along an age gradient. The increase may be due to gradual enhancement of organic matter accumulation by leaf litter fall and root decay. Fixation of soil nitrogen by the leguminous plants further enhances the N limiting mine spoil for root growth. Additional, contributions by soil microbial activity, soil microfauna and bird droppings may also not be ignored (Tripathi and Singh 2008). According to Singh and Singh (2006), 5 years old revegetated mine spoil provides 2.7–24.7 t ha^{-1} year^{-1} of plant productivity and shows significant relationship between foliage biomass and net primary productivity, which is comparable to natural and normal soil plantation of the dry tropical forest. Jha and Singh (1991) reported 7 t ha^{-1} of plant productivity in naturally revegetated tropical mine spoil in dry tropical environment. Srivastava et al. (1989) observed 2.84–5.53 t ha^{-1} BGB in 5–20 years old mine spoil sites. The measurement of biomass helps to evaluate the nutrient cycling, organic matter and energy transfer and to predict the stability of plantation stands (Dutta and Agrawal 2003). Consequently, substantial amount of below ground biomass is added in 12 years, which also contributes in formation of organic matter and improvement of soil fertility. Revegetation with native species grasses on slopes fulfills the dual purpose of stabilizing the site and modifying soil properties suitable for the colonization of other plants, and at the same time producing animal browse. It is essential to investigate if there were higher metal concentrations taken up by the grass, and the subsequent effects on the quantity and quality of produce.

Perennial native trees (*D. sisoo*, *L. leucocephala*, *A. procera*) are the legumes which possess the quality of fast growth as well as root nodules can be used to modify properties of mine spoils, by supplying the much needed N and organic matter. Fisher (1990) defined five mechanisms by which tree can ameliorate mine degraded soil nitrogen fixation, efficient nutrient cycling, organic matter additions, microclimate moderation and rhizosphere interactions. The plant is able to compete with the exotic plant species by providing good timber value. Apart from having a very high growth rate, it is also tolerant to toxic metals and low nutrient status, and therefore will be an ideal pioneer species to accelerate ecological succession of the manmade habitats.

BGB is directly related to above ground plant production and microbial biomass, as it provides a direct input of carbon and nutrients to the soil microbial population through organic secretions and also upon mortality (Srivastava et al. 1989). In the present study, microbial N was positively related to the root biomass. Singh (2011) reported that to improve the shear strength, we actually need compound roots spreading more on horizontal direction than vertical one for stabilization of dump materials.

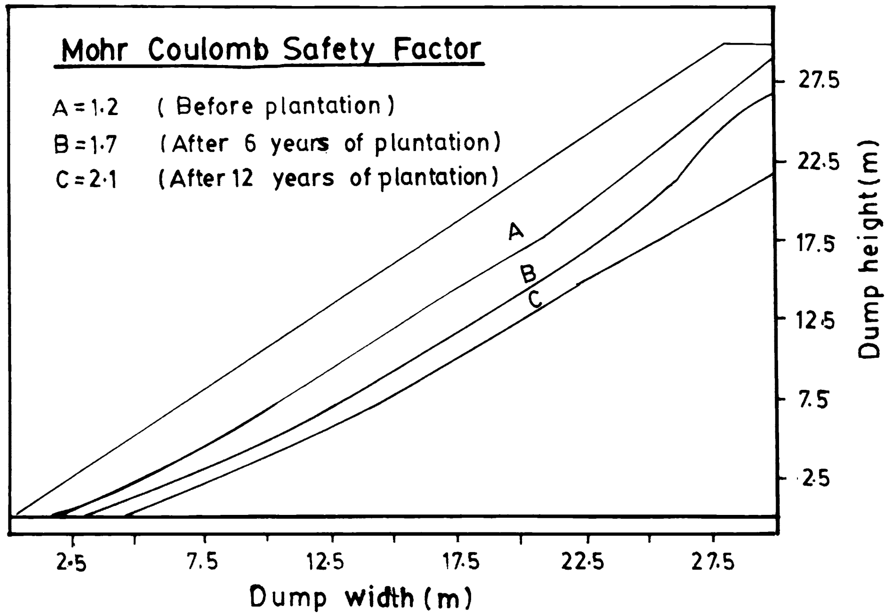
Shear strength properties

The shear (jack) test results, showing the increased strength properties of the revegetated dump over an age series are given in Table 2. The results show that both the grass and tree roots played crucial role to significantly enhance the shear strength properties of dump material. It was observed that the stress concentration was reduced by grass and tree roots near the surface of dump slope as compared to the barren slope. Contours of Mohr–Colomb FOS for the dump slope without and with revegetation age of 2, 6, 10 and 12 years (Fig. 3) have shown that FOS was enhanced from 1.2 to 1.4, 1.7, 1.9 and 2.1, respectively due to plantation on the dump slope and trees on the flat portions, and thereby enhancement of shear strength of dump material by the root matrix. The path of critical failure of dump surface was also changed. This is because of the mechanical action of the tree and grass roots, which reinforces the dump material by roots and enhances the shear strength of the dump material (Hall et al. 1994; Cherubini and Giasi 1997; Chaulya et al. 2000). Sun et al. (2008) observed that the root anchorage resistance was closely related to slope gradient and root distribution, while upslope-grown roots were positively related to anchorage resistance. Root biomass was highest after 12 years of study, which may be attributed to the enhanced proliferated root biomass on the topsoil of the dump. Therefore, binding of the dump slope surface together with vegetation roots and increase in shear strength has lead to an enhanced FOS. The depth of critical failure surface (i.e., the surface along which dump failure occurs) increases for the dump slope with grasses and trees compared to the barren slope. This is also an important factor for maintaining long-term stability of a coal mine overburden dump. Vegetation improved the dump slope stability as there was no failure plane observed in the simulated slope. This is due to the reinforcement of dump material vegetation. The maximum displacement is less as compared to vegetation free dump slope (Singh 2011). Mafian et al. (2009) observed approximately 85.5 % reduction in maximum displacement with vegetation cover keeping the same slope angle. According to Kalilnejad et al. (2012) plant roots plays a silent role in soil improvement and mechanical role to increase the shear and pulling out stress on the soil. The mechanical reinforcement of roots has increased the shear

Table 2 Results of in situ (jack) shear test (±1 SE) of revegetated minespoils

Parameters	Unit	Barren dump material	2 years		6 years		10 years		12 years	
			Grasses	Trees	Grasses	Trees	Grasses	Trees	Grasses	Trees
Cohesion	kN m^{-2}	64 ± 4	78 ± 2	117 ± 3	112 ± 5	141 ± 6	121 ± 3	147 ± 6	125 ± 9	151 ± 11
Friction angle	Degree	32 ± 1.5	32.5 ± 0.7	32.9 ± 0.8	33.8 ± 2.5	34.7 ± 2.9	34 ± 1.3	35.1 ± 1.9	34.3 ± 2.2	35.4 ± 2.8

Fig. 3 FOS of dump slope



strength and cohesion of dump materials against the tensile stress.

Inorganic nutrients and net N-mineralization

Mining caused decline of MN by 46.8 % and the values in revegetated sites ranged from 7.4 to 11.6 kg ha^{-1} (Table 1). Singh et al. (2007) also reported lower levels of plant available nutrients in mine spoil. Revegetation caused increase in MN by 12 % after 2 years, 36.4 % after 6 years and 75.8 % after 12 years, respectively. Srivastava (1992), Singh et al. (2004), Singh and Singh (2006) found increasing trend of mineral N in 4–6 years old revegetated mine spoil. It is commonly recognized that at pH 6.5 nutrient availability to plants is at a maximum and toxicity at a minimum (Harris et al. 1996). Consequently, the nutrient availability enhanced along an age gradient. Bradshaw (1997) and Sanchez et al. (1985) suggested that the plants bring mineral nutrients to the surface of the soil and accumulate them in available form; consequently mineral N increases with age of mine spoil.

The values of net N-mineralization in forest ecosystem, mine spoil and revegetated sites were 308, 24 and 38.4–252.2 kg ha^{-1} year^{-1}, respectively (Table 1). Mining caused decline of N-mineralization by 92 % in comparison to forest. Revegetation caused increase in net N-mineralization rate by 1.6, 4.6 and 10.51 times after 2, 6 and 12 years, respectively compared to the mine spoil. The values increased gradually from 2 to 12 years after revegetation.

The decline in N-mineralization in the mine spoils after mining may be due to reduced total nitrogen content. The original soil of mine degraded lands is usually lost or damaged, with only skeletal materials. There is commonly a lack of organic matter and its associated nutrients such as nitrogen (N) in most degraded land materials (Singh et al. 2007). Organic matter provides a continuous source of nutrients, e.g., it provides most of the N reserve in soils and comprises typically 5 % N which is mineralized at about 2 % per year (Harris et al. 1996). Due to the low organic C content of mine spoils, N appeared to be the primary limiting nutrient for plant growth (Mays and Bengston 1978). Lack of plant available N may be a major problem in the revegetation of lands disturbed by surface mining (Voos and Sabey 1987; Singh et al. 2004). In mine spoils, nitrogen-fixing species exert very important effect on soil property by producing the readily decomposable, nutrient-rich litter and turn over of fine root and nodule (Bernhard-Reversat 1988). The litter is very rich in nitrogen contents, which is mineralized by the nitrogen-fixing species, thereby allowing substantial transfer of nitrogen to other species (Singh et al. 2002). Wild (1987) suggested that the leguminous tree *Leucena leucocephala* is of great importance as far as bioreclamation is concerned. Under ordinary field conditions, it fixes about 100 kg ha^{-1} $year^{-1}$ nitrogen. Besides, *Acacia* spp. and *Albizzia lebbek* are also found to be the promising leguminous planted species. Sharma and Sunderraj (2005) have also suggested the use of these two species for degraded areas, because of very high nitrogenous activity in their root nodules.

Brady and Weil (2002) suggested that soil biological, physical and chemical processes cause many changes in N. Harris (2003) and Singh and Singh (2006) reported that restoration could enhance the rate of N-mineralization. Kaye and Hart (1997) also observed in their study that restoration produced 2–3 times greater annual net N-mineralization and 3–5 times greater annual net nitrification than the non-revegetated sites.

Microbial biomass N

The values of MBN ranged from 60.4 to 712.6 kg ha^{-1}, with highest values in forest and lowest in mine spoil. The values in revegetated sites were 86.07–426.8 kg ha^{-1} (Table 1). Mining caused decline of MBN by 92 % over forested soil. Revegetation caused increase in MBN by 1.42, 3.75 and 7.07 times after 2, 6 and 12 years, respectively.

Srivastava et al. (1989) and Singh et al. (2007) have reported a decline in microbial nutrients in mine spoils as compared to a virgin forest. Stroo and Jencks (1982) and Insam and Domsch (1988) also indicated that microbial growth and activity decreased as a result of mining. Corbett et al. (1996) postulated that for developing a stable plant community on mine spoils, there must be a functional soil microbe community; because microorganisms are used as an index of progress of soil genesis in mine spoils (Segal and Mancinelli 1987; Singh et al. 2004). Tate (1985) and Singh and Singh (2006) studied the role and importance of microorganisms in mine soils and ecosystem restoration and concluded that soil structure development, nutrient cycling, and soil chemical and physical limitations to plant growth are mediated and mitigated by microorganisms. Microbial biomass, thus, may regulate the nitrogen mineralization in the mine spoil. In the present study, the status of microbial N was positively related to the net N-mineralization rate.

Visser et al. (1983) suggested that the reduced microbial nutrients in the mine spoils may be due to the lack of (i) a topsoil layer with its associated plant components, (ii) favorable nutrient levels, and (iii) active microbial system. Vegetation and associated microbiological activity also influence the composition of the mine spoil environment. A well vegetated and biologically active mine spoil increase carbon dioxide levels in the mine spoil and reduce oxygen flux into the mine spoil. The oxygen content of mine spoil is frequently inversely related to the carbon dioxide content (i.e. oxygen levels decline as carbon dioxide increases).

In our study, trends in MBN in mine spoils were related to age gradient. There was an increase of 52–72.5 % in MBN after 6 and 12 years of revegetation, respectively. This may be due to gradual accumulation of leaf litter and dead roots on the mine spoil and its decomposition. Several biological factors, such as 'ecosystem engineers' (mainly invertebrates such as pelecycopda, oristacca, ants, termites, earthworms and the microbes that break down organic matter and aerate soil) and pollinators, may have essential roles to play in the reconstruction of terrestrial ecosystems on mining materials. The microbial biomass can provide one of the most satisfactory estimates of the restoration of soil microbial population (Ross et al. 1990).

Ruzek et al. (2001) and Singh et al. (2004) demonstrated a clear relationship between time since restoration and increases in soil microbial biomass. This was related both to organic matter content as a starting point in new reclamations and textural characteristics of the soils reclaimed (Harris 2003). Ross et al. (1990) and Singh et al. (2004) also found in their study a constant increase in MBN with age, which they attributed as an indicator of continuous soil redevelopment on mine spoils. They reported faster recovery of microbial biomass than the recovery of total soil nutrient pools. Bentham et al. (1992) observed that during recovery of soil 5 years after lignite mining, microbial biomass increased more rapidly than soil organic matter.

Wang et al. (2007) have reported that after 12 years of reforestation, the vegetation cover of the artificial forests reached 90 % and an understory vegetation community consisting of local species had naturally developed. Hart et al. (1989) showed that after 10–25 years, microbial and earthworm populations and the easily mineralized pools of N had almost recovered in mine soil. Restoration via plant succession holds promise for vegetation recovery and desertification control within protected, fenced enclosures (Zhang et al. 2005). In our study, the extrapolation of root biomass and MBN has indicated that the mine spoil would take 25 and 30 years to reach the level of forest ecosystem. Likewise, organic C, total N and total P of the mine spoil after revegetation will reach up to the level of forest in 18, 15 and 14 years, respectively.

Conclusion

It may be concluded that in revegetated coal mine spoil, plant root proliferations play a very crucial role in the stabilization of dump slopes by creating mechanical reinforcement of dump material and enhancing shear strength of dump material (Singh 2011), which in turn increases the long-term stability of dump slopes. The FOS is enhanced from 1.2 for barren dump slope to 1.4, 1.7, 1.9 and 2.1 for the same dump slope covered with plant roots after 2, 6, 10 and 12 years of revegetation. Often mine dump failure occurs after significant deformation with prior warning signals. Results of numerical behavior analysis of slope stability have indicated that the maximum deformation occurs near the crest region. Therefore, a deformation-monitoring programme should be monitored near the crest of dumps. In case of steep and high faces of dumps, continuous assessment of deformation is recommended by wire line extensometer fitted with constant recording arrangement so that dump failure and risk hazards can be minimized for the safety of mine and local workers. The plant root systems greatly improved the dump stability by providing strong plant anchorage and enhanced FOS. Many of these management options that may increase SOC tend to also increase overall farm productivity, profitability and sustainability, and as such are not being rapidly adopted in various mining regions of India. However, numerous other management shifts (for example, converting from annual crops to pastures) which may have the greatest positive impact on SOC stocks will likely need incentives, either in the form of direct government subsidies or credits from an emissions trading market, before wide-scale adoption is seen.

Nevertheless, revegetation also increases the soil organic and inorganic nutrients along with root biomass and microbial biomass along an age gradient. These positive attributes are important for improvement in soil fertility and carbon stabilization in an impoverished coal mine spoil of dry tropical forest ecosystem. Thereby, selection of suitable plant species having well-developed root systems may help to restore the vegetation for ecological engineering and also making the slopes more stable. Therefore, revegetation can be considered as a management tool for the sustainable development of the mining industries. Further, revegetation processes must be facilitated by creation of conducive environment for the regeneration of vegetation so that it may also provide conservation of desired biodiversity, economic benefits, and carbon sequestration in addition to a cleaner environment.

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