The Role of Tree Plantations in Improving Soil Fertility and Carbon Sequestration on Coal Mine Spoils

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Abstract

Surface coal mining results in the degradation of habitat, altering soil properties, including its biological, physical and chemical features. This review explains the harmful effects of coal mining, such as increased soil erosion, nutrient leaching, increase in soil bulk density, accumulation of heavy metals in soils, and decline in soil pH, organic matter, plant available nutrients, cation exchange capacity (CEC), and microbial activity. Revegetation through tree plantations is one of the efficient methods of restoring fertility of soil by improving the organic matter content and its various properties, increasing plant available nutrients and CEC, and enhancing biological activities. Some promising tree species that could be used for revegetating coal mine spoils in India are, viz., *Acacia auriculiformis*, *Acacia holosericea*, *Acacia mangium*, *Albizia procera*, *Dalbergia sissoo*, *Leucaena leucocephala*, *Pithecellobium dulce* and *Prosopis cineraria*. These tree species are acid-tolerant, suitable for growing in infertile soil, and are able to add substantial quantity of organic matter to the soil. From this review, it may be concluded that the revegetation of coal mine spoil through tree plantations can improve fertility of soil and can support the establishment of vegetation; however, the process of restoration of the vegetation, close to the original level, may take longer time, depending on the extent of degradation.

Keywords

Coal mine spoil · Habitat degradation · Tree plantations · Restoration · Soil organic matter

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10.1 Introduction

Among the important processes linked with the economic development of a country, surface mining has been considered very significant. However, surface mining results in degradation of the habitat, altering soil properties, including its biological, physical, and chemical features (Sheoran et al. 2010; Macdonald et al. 2015). Due to unfavorable soil conditions for the growth of plants, the process of natural recovery of such altered systems generally becomes a time taking process, and could be considered very similar to the primary succession on the natural habitats (Ahirwal et al. 2016). The process of mining removes plant covers, alters soil structure by excavation, disturbs the microbial communities, transforms landforms, and damages the surface and subsurface hydrological cycle (Sheoran et al. 2010; Shrestha and Lal 2011). When favorable soil nutrients are removed, the original soil properties are disrupted in the process. In the open cast mining of coal, large amount of nutrient poor overburden soil material is piled on the surface of the nearby land, which creates a serious problem for the rehabilitation of such kind of highly disturbed ecosystem (Ahirwal and Maiti 2018). In the overburden dumps, the bioavailability of metals increases, proportion of sand in soil becomes higher, moisture declines, bulk density increases, and the soil organic matter relatively decreases (Sheoran et al. 2010), leading to the formation of adverse conditions for revegetation (Chaturvedi and Singh 2017).

In naturally colonized sites, the overall plant biomass may increase with age of reclamation; however, the variations could also be due to species composition and density of trees present at a specific site (Fig. 10.1). Coal mine spoils are deficient in

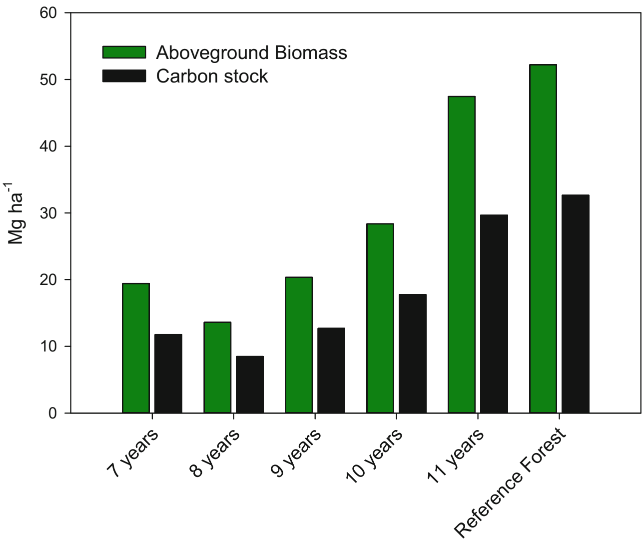

Fig. 10.1 Tree aboveground biomass and total tree carbon stock of the reclaimed chronosequence sites (naturally colonized) and the native forest site. Adapted from Ahirwal et al. (2017)

major physical, chemical, and biological properties of normal soils, however upon revegetation, the changes in soil characteristics and accumulation of nutrients during the regrowth of ecosystem could be detected in the form of changes in the level of biomass and diversity of plant species (Bradshaw 1983). There could be various ways for the evaluation of successful reclamation; however, changes in soil properties are the most important signals for restoring the ecosystems.

Although the natural restoration of coal mine spoil is a slow process, it can be enhanced by plantations of important trees and herbaceous species. This mechanism of two-tiered vegetation establishment increases the biodiversity and soil fertility of coal mine spoil (Dutta and Agarwal 2002). Often, for mitigating the problem of deficiency in soil nutrients, various kinds of fertilizers have also been suggested. Several studies have highlighted the increment in biomass and productivity of important herbaceous species as a result of fertilization (e.g., Piha et al. 1995 and Singh et al. 1996). However, few studies have also indicated that fertilization has variable impact on the development of woody species which are planted on mined landscape (Vogel 1981).

According to Singh et al. (2002), plantations can play a significant role in the revegetation of coal mine spoils. On the sites which are severely degraded, plantations of suitable species have shown remarkable catalytic effects on the successional growth of native forest than on the unplanted sites (Parrotta and Knowles 2001; Chaturvedi and Singh 2017). Since all plants exhibit different rates of growth, they also differ in their capacity of stabilization and nutrient enrichment. Generally, the trees and shrubs are considered to provide a permanent cover of vegetation on coal mine sites with very little aftercare. Several trees have been reported to exhibit a capacity to maintain or increase the organic matter content of soil, enhance the nitrogen-fixing capacity, minimize the rate of erosion, and improve the physicochemical and biological properties of soil (Jha and Singh 1991; Frouz et al. 2009). However, it has been suggested that the impact of trees on nutrient content of soil will depend mainly on their nutrient cycling features, for example, the chemical composition of litter and decomposition rate (Byard et al. 1996). Since all tree species do not possess equal capacity of growing in a harsh environment of coal mines, selection of suitable tree species that can resist a wide fluctuation in climatic conditions, for example, severe drought, high temperature, and poor soil nutrient conditions, has been considered significant for restoration effort (Ahirwal et al. 2017). Moreover, the tree species that possess the capacity to grow under low-nutrient conditions and exhibit high biomass accumulation capacity are considered more suitable for revegetation of coal mine spoil (Singh et al. 2006; Mukhopadhyay et al. 2013, 2014).

10.2 Characteristics of Tree Plantations

Trees have been considered to be very efficient, as compared to other plants in supplementing large amount of organic matter to aboveground and belowground vegetation and to the soil layer (Chaturvedi et al. 2011; Chaturvedi et al. 2012;

Chaturvedi and Raghubanshi 2015; Chaturvedi et al. 2017a, b; Singh and Chaturvedi 2018). The deep roots of trees could cover a greater soil depth in the revegetating coal mine compared to the grasses, and can easily penetrate to the comparatively soft spoil layers, which are beneath the "cap" of hard trapped clays (Mensah 2015). Generally, the rooting depth for herbaceous species is around 50 cm, while for trees, it is around 3 m; although, there are certain *phreatophytes* growing in coal mines which may tap into groundwater and have been found to reach the soil depths up to 15 m, particularly in arid climates (Mensah 2015).

Trees perform various ecosystem functions and can sufficiently improve soil properties through different processes, such as maintenance or improvement of soil organic matter content, nitrogen fixation through biological processes, nutrient uptake from aboveground to belowground soil layers and transfer to roots of understory herbaceous flora, maximizing water infiltration and accumulation, reducing the loss of nutrients due to erosion and leaching, improvement of soil physical characteristics and of biological activities of soil, and reduction in soil acidity. Trees have also been found to create new self-sustaining top soils, while the plant litter and exudates from roots enhance the nutrient cycling in soil (Padmavathiamma and Li 2007; Mertens et al. 2007; Mensah 2015; Singh and Chaturvedi 2018).

Moreover, revegetating coal mine spoils with suitable trees could reduce the tendency of soil for compaction (Chaturvedi and Singh 2017). Trees could increase the drainage of rainwater in the vegetated mine spoil, compared to the new soil; therefore, less amount of water remains at the upper soil surface, which minimizes the possibility of soil erosion (Mensah 2015). Also, the efficiency of trees in absorbing nutrients released by weathering of rocks is more compared to the herbaceous species (Young 1989).

The investigation of spatial patterns of distribution of plants on the afforested land of restored mine spoils could provide important information which may be utilized to test the restoration measures applied for the revegetation (Moreno-de las Heras et al. 2008). Zhao et al. (2012) described the processes and patterns of spatial distribution of afforested plants and suggested that these investigations are important for checking whether or not the applied reclamation measures are sufficiently able to produce sustainable communities of plants and to what extent they are providing theoretical evidence for the improvement of ecological recovery techniques. Further, Zhao et al. (2015) studied the changes in structure of population and size class, and the patterns of spatial distribution of the two dominant species, *Robinia pseudoacacia* (ROPS) and *Pinus tabuliformis* (PITA), in the mixed forests after 17 consecutive years in the opencast coal mine spoil of Pingshuo located in Shuozhou City, northern Shanxi Province, northwestern China, and suggested relevant basic information important for ecological research and implementation of the projects for vegetation restoration in the opencast coal mines.

10.2.1 Monoculture Vs Mixed-Species Plantations

Single-species plantation in the initial stage of revegetation in coal mine spoil is generally not recommended, since in the marginal environment, single species will get very little or no maintenance; hence, the success of that species becomes unpredictable (Morgan 2005). Also, the monocultures are disadvantaged because of its vulnerability to being attacked by harmful pests and outbreak of diseases. Compared to mixed plantations, the single-species plantations cannot satisfactorily be utilized for multiple purposes and other conservation roles; such plantations are not able to provide a balanced ecosystem service and also are not able to produce a balanced and stable system in the context of changes in environmental conditions and other directional changes (Mensah 2015). Furthermore, the mixed plantations are more resistant to variations in climatic conditions; they could form a more stable ecosystem and can sequester carbon in a more sustainable way.

The mixed-species plantations commonly contain woody species, including bushes and trees, together with grasses and forbs. As reported by Young (1989), for controlling soil erosion, the tree canopy cover is less effective compared to those of ground-layer flora. In a study conducted for 10 years, Liao et al. (2000) observed that the total litter produced by the mixed plantation of *Cunninghamia lanceolata* and *Michelia macclurei* (both in the proportion of 1:1) was 43% greater compared to that of the monoculture of *C. lanceolata*. In another similar study, Parrotta (1999) reported that litter production was comparatively greater for mixed plantations compared to the monospecific *Eucalyptus* plantations located in Puerto Rico. In an earlier study, Zhang et al. (1993) observed that the annual litter production of a 55-year-old mixed plantations of *Pinus massoniana* and *M. macclurei* was 11.2% greater compared to that of an equal aged *P. massoniana* monoculture stand. Moreover, several studies have reported that the species composition is considerably important for the quantity of litter production at different regions within the same climate range (Yang et al. 2004; Mensah 2015).

For the maintenance and conservation of soil fertility in the forest ecosystems, nutrient released from the litter decomposition plays a significant role (Singh and Chaturvedi 2018). Wang et al. (1997) reported that the quantity of nutrient return via decomposition of leaf litter to forest floor recorded in the mixed plantation of *C. lanceolata* and *M. macclurei* was around two and three times greater compared to that in the pure culture of *C. lanceolata*. Besides, the study of Forrester et al. (2005) also reported that the mixed plantations of *Acacia mearnsii* and *Eucalyptus globulus* elevated the quantity as well as rates of nitrogen and phosphorus cycling through the aboveground litterfall as compared with the pure culture of *E. globulus*.

10.2.2 Exotic Vs Native Species Plantations

For the reclamation of coal mine spoil, tree species needs to be carefully selected because the newly introduced species could also become pests in some situations. The tree species selected for revegetation should be checked carefully so that it could not become a problematic weed for the local or regional habitat. If any exotic tree is introduced for plantation, priority should be given to those species which exhibit better adaptation to the local environment. For plantation in a new developing habitat, native or indigenous species are generally preferred to exotics also because they are mostly expected to adjust into the fully functional ecosystem and also they are climatically adapted to the habitat (Singh et al. 2004a; Chaney et al. 2007; Li et al. 2015).

The revegetation plan for coal mine spoils should be focused toward the natural succession of the plant communities. In most of the cases, the objective of reclamation is to establish pioneer species so that the mine spoil could be covered and soil be improved in short time period, allowing native species to establish and become abundant as the colonizing pioneer plants decline (Morgan 2005). Singh et al. (2004a) suggested that for revegetating coal mine spoil, native species should be given preference. If we measure the plant diversity of the neighboring sites, we could get better information about the species which are most suitable for surviving in that habitat (Morgan 2005). Chaturvedi and Singh (2017) reported that the soil fertility of the revegetating coal mine spoil improve much faster when planted with native leguminous species compared to the native nonleguminous species. Moreover, the native leguminous species are more efficient in modifying soil properties compared to exotic leguminous species in the short time period (Sheoran et al. 2010). However, if the site condition is very severe, the use of foreign or exotic plant species could not be ruled out, particularly when the local environment has degraded drastically or where very few local species are found (Mensah 2015).

On the coal mine spoils, nitrogen has been observed to be a major limiting soil nutrient, and regular application of nitrogen in the form of fertilizers may be required for maintaining healthy growth and development of the vegetation (Song et al. 2004). A more convenient and alternative approach could be the introduction of leguminous trees and other nitrogen-fixing species. Studies in coal mine spoils have reported that the nitrogen-fixing leguminous species have a remarkable effect on the fertility of soil because legumes produce readily decomposable and nutrient-rich litter and they have high turnover of fine roots as well as nodules (Singh et al. 2002, 2004b; Tripathi et al. 2014). Also, the mineralization of nitrogen-rich litter from leguminous species substantially transfers nutrients to companion species, subsequently increasing the nitrogen cycling, leading to the development of a self-sustaining healthy ecosystem (Zhang et al. 2001).

10.3 Effect of Tree Plantations on Soil Properties

10.3.1 Physical Properties

The comparative evaluations of the physicochemical properties of the soils by Chaturvedi and Singh (2017) for natural forest, deforested land, and mine spoils at different stages of natural recovery are given in Table 10.1. Among the important soil properties, soil organic carbon contents for the natural forest and deforested land

Table 10.1 Soil properties of the mine spoils and the native forest and deforested land

Soil properties	Forest soil	Deforested soil	5-year-old spoil	10-year-old spoil	12-year-old spoil	16-year-old spoil	20-year-old spoil
Root biomass ($g\ m^{-2}$)	–	–	284	342	537	485	553
pH	6.4	7.3	7.7	7.9	8.1	8.1	7.9
Water holding capacity (%)	52	46	52	45	46	48	50
Gravimetric soil water (%)	8.6	2.9	4.6	2.9	4.2	2.6	5.4
Mineral nitrogen (N) ($\mu g\ g^{-1}$)	16.4	14.8	5.8	7.6	7.9	9.9	15.6
Total organic carbon (C) ($\mu g\ g^{-1}$)	867	422	209	276	356	360	496
Total N ($\mu g\ g^{-1}$)	75	40	20	23	28	32	36
Total phosphorus (P) ($\mu g\ g^{-1}$)	29	15	7	10	12	13	16
C/N	11.6	10.6	10.5	12	12.7	11.3	13.8
Microbial biomass N (%)	4.3	4.7	4.8	4.2	3.9	4.4	3.6
Microbial biomass P (%)	1.7	1.8	1.7	1.8	1.7	1.8	1.6

Adapted from Chaturvedi and Singh (2017)

area were 3.01 and 1.98%, respectively. The total nitrogen in the 5-year-old spoil was only 23% of that in the native forest soil. Microbial carbon (C), nitrogen (N), and phosphorus (P) in the soil varied from 209 to 867 μg C g^{-1}, from 20 to 75 μg N g^{-1}, and from 7 to 29 μg P g^{-1} soil, respectively. The recorded values were maximum in the natural forest soil and minimum in the 5-year-old spoil (Table 10.1). Microbial biomass carbon, nitrogen, and phosphorus were around four times higher in the natural forest soil compared to the 5-year-old spoil.

Under natural forest cover, the soil structure is of superior quality, porosity and moisture conditions are favorable for plant growth, and the soil is resistant to erosion, while these soil properties remarkably decline after forest clearance (Singh and Chaturvedi 2018). Porosity is the most important physical property of the soil; pores with diameter ranging from 5 to 50 μm determine the water holding capacity of soil, while the pore size over 250 μm diameter are required for the penetration of roots (Young 1989).

Tree plantations favor the development of ground vegetation such as herbs and shrubs by improving soil conditions. Consequently, the established ground vegetation protects the soil from erosion by the impact of raindrops and runoff, and they also trap sediments moving with rainwater. Trees and shrubs also increase the strength of the top-layer soil through their large root network. Due to the influence of vegetation cover, infiltration of rainwater into the soil has been observed to increase (Morgan 2005). According to Young (1997), the decline in runoff to some degree occurs by canopy interception as well as direct transpiration; however, the major part of decline in runoff is caused by greater soil infiltration capacity under the tree cover. Hamilton and Pearce (1987) also highlighted that the large network of surface root system under tree plantations serves to increase infiltration as well as hold the soil, thus reducing erosion.

The distribution of soil particle size is a critical soil physical factor in determining a successful revegetation on overburden dumps in coal mines as it affects water holding capacity, bulk density, and the availability of soil moisture as well as nutrients (Sheoran et al. 2010). Jha and Singh (1991) reported that the soil textures of coal mine spoils are heavily disturbed as a result of irregular pilling of materials on overburden dumps. An investigation by Dutta and Agarwal (2002) shows that tree plantations in a coal mine spoil exhibit significant variations in silt and clay contents, which indicates that plantations are able to change the soil texture in due course, after their growth and establishment.

The vegetation cover also acts as buffer and controls the rapid change in soil temperature. The bare soil of coal mine spoil absorbs heat from the sun and in a very short time becomes very hot during summer season and very cold during winter; however, when the soil is covered by vegetation, it is insulated from the direct heat of the sun, and therefore, it becomes neither very hot nor very cold (Kolay 2000).

10.3.2 Chemical Properties

Tree plantations tend to decrease the acidity of soil through addition of alkaline substances to the soil surface after litter decomposition (Singh et al. 2002). However, whether the litter from the selected tree plantation could significantly increase the pH of acidic soils is not very certain, since it depends on the selected tree species and the quantity of litterfall (Singh et al. 2004b; Mukhopadhyay et al. 2013). The soil pH increment due to tree plantations indicates that the organic matter input from the planted trees modifies the pH of the soil of coal mine spoil. Since majority of the plant species selected for revegetation are generally dicotyledonous, they release more base cations such as Ca^{2+} into the soil, leading to increase in the pH of the soil of revegetated coal mine spoil, compared to the fresh mine spoil (Dutta and Agrawal 2003).

The atmospheric nitrogen is absorbed by the nitrogen-fixing organisms and stored in the soil. This nitrogen is then taken up by plants in the form of nitrates. Fixation of nitrogen in soil is commonly done by leguminous species which contain root nodules to achieve this function. In coal mine spoil, leguminous trees such as *Acacia auriculiformis*, *Acacia holosericea*, *Acacia mangium*, *Albizia procera*, *Dalbergia sissoo*, *Leucaena leucocephala*, *Pithecellobium dulce* and *Prosopis cineraria* are more effective. The atmospheric nitrogen absorbed by the leguminous trees in turn contributes to improving the fertility of soil. Moreover, the litterfall elevates the organic matter content of the soil which ultimately provides a suitable soil environment for the fixation of atmospheric nitrogen (Banning et al. 2011; Chaturvedi and Singh 2017). The protein concentration in this organic matter, together with the protein contents of soil microorganisms which decompose into amino acids and later oxidize to nitrates, is absorbed by plants (Singh and Chaturvedi 2018). According to Franco and de Faria (1997), the legume tree species used for plantation could contribute about 12 tons of dry litter biomass and 190 kg of N/ha/yr. for renovation of the degraded soils.

The soils fertilized with organic matter also contain higher mineralized phosphorus. Mbagwu et al. (1994) observed that the soils treated with higher rates of organic matter exhibited remarkable increase in phosphorus content. It has also been reported that the surface litter contributes only small percentage of the total phosphorus accumulated in the forest (Ren and Yu 2008). Moreover, Ren and Yu (2008) reported that the deficiency of phosphorus is the inhibitive factor leading to slow growth of *Acacia mangium* plantation.

10.3.3 Biological Properties

Organic matter content of soil is the portion of soil that includes animal as well as plant remains occurring at various stages of decay (Singh and Chaturvedi 2018). The soil organic matter, according to Plaster (2009), is commonly composed of three components: (1) living biota (plant roots, microbial organisms, and various other organisms which occupy the soil), (2) fragments of plants as well as animal remains present at various stages of decay (fallen leaves, dead and decomposed organisms, animal excreta, and crop residues), and (3) residues of active decay and several organic compounds present in the soil which is commonly called humus.

On coal mine spoils the increased litter supply from aboveground and belowground plant residue during establishment of vegetation is generally responsible for the elevation of organic matter content in soil and improvement of the soil productivity (Singh et al. 2002). In a study by Kumar et al. (2018), the soil organic carbon pools (particulate organic carbon, non-particulate organic carbon, and total organic carbon) were observed to increase with the age of reclaimed mine spoil (Fig. 10.2); however, the carbon/nitrogen ratio was reported higher in young dumps, compared to the intermediate and old dumps (Fig. 10.2). The study by Kumar et al. (2018) also exhibited that even after 26 years of reclamation, the carbon pools of the coal mine spoil do not reach to the level of natural forests, although the quantity of total nitrogen and microbial biomass carbon was very similar in both habitats (Fig. 10.3).

Although tree plantations improve soil fertility in various ways, the maintenance of soil organic matter levels by supplementing litter and root residues has been considered as the major factor for soil fertility improvements. It has been reported that the approximate chemical composition of organic matter in soil is 50% carbon, 5% nitrogen, 0.5% phosphorus, 39% oxygen, and 3% hydrogen (Barber 1995). However, these values may vary from soil to soil in different habitats. In a typical well-drained mineral soil, the organic matter content is low and varies from 1 to 6%

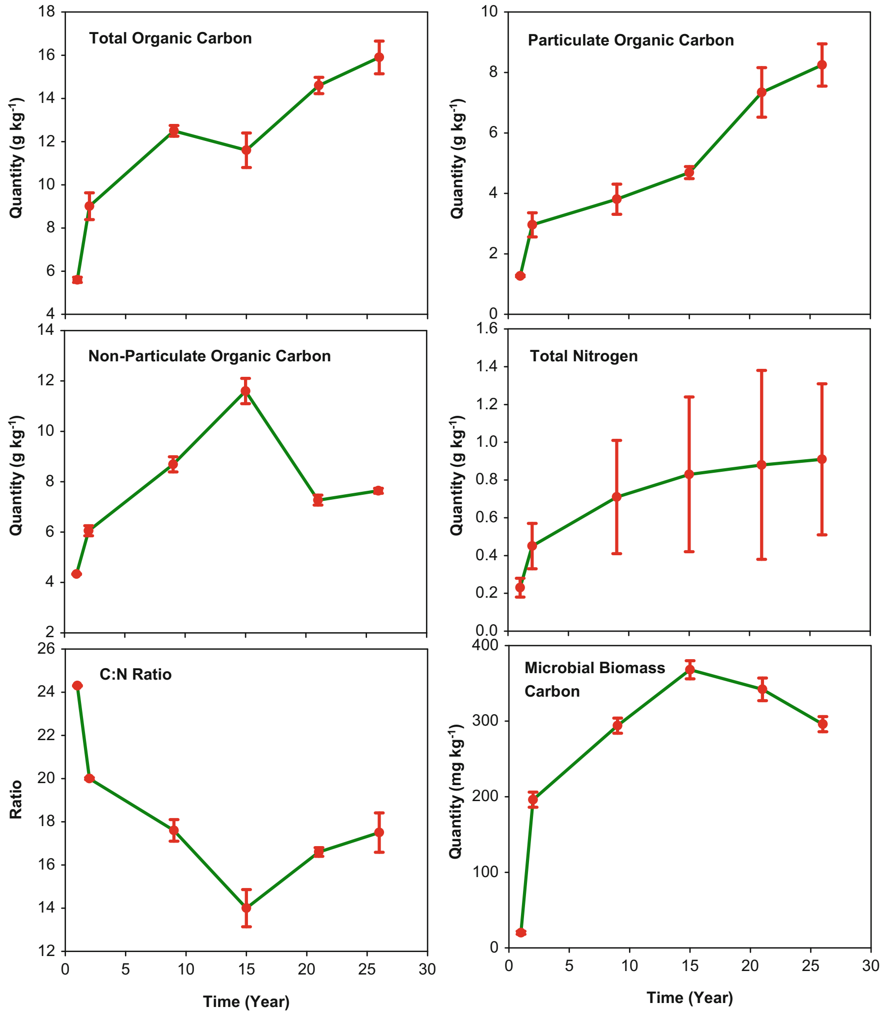

Fig. 10.2 Soil organic carbon pools of the reclaimed chronosequence coal mine sites. Mean ± standard deviation (SD) ($n = 6$). Adapted from Kumar et al. (2018)

by dry weight in the top-layer soil, and the value is even less in the down layer, subsoil (Barber 1995).

The organic matter in soil improves conditions of all types of mineral soils for several reasons. In sandy soils, organic matter helps in increasing the capacity of soils for holding water and nutrients. For clay soils, organic matter makes loosen up the clay particles and improves their tilth (Plaster 2009). The important function of organic matter has been noticed during the supply of nutrients where the organic matter blocks the phosphorus fixation sites, which increases the phosphorus availability to plants. It has been reported that a good organic matter level in soil provides

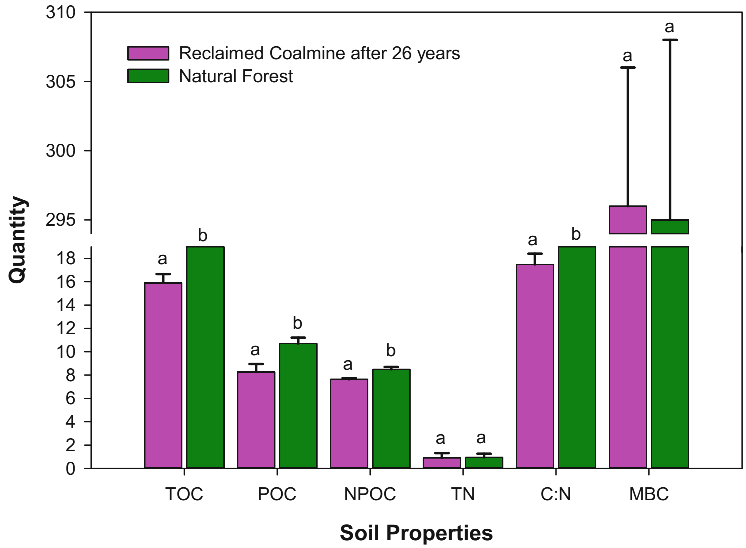

Fig. 10.3 Soil organic carbon pools (total organic carbon, TOC; particulate organic carbon, POC; non-particulate organic carbon, NPOC), total nitrogen (TN), carbon/nitrogen ratio (C/N), and microbial biomass carbon (MBC) of the coal mine sites after 26 years of reclamation and reference forest site. Mean ± standard deviation (SD) ($n = 6$). Letters indicate significant differences for each parameter separately using Duncan multiple range tests (DMRTs) at significant $p < 0.05$ level (ANOVA analysis, $n = 6$). Adapted from Kumar et al. (2018)

suitable environment for fixation of nitrogen (Singh and Chaturvedi 2018). Another chemical effect of organic matter is the remarkable increment of cation exchange capacity (CEC) by the formation of clay-humus complex, which is particularly significant where CEC of a clay mineral is considerably low (Singh and Chaturvedi 2018). Raising CEC improves the retention of nutrients both in naturally recycled vegetation as well as those supplemented with fertilizer (Mukhopadhyay et al. 2016a; Chaturvedi and Singh 2017).

10.4 Controlling Soil Erosion

Vegetation plays a significant role in controlling erosion on gullied areas, land near construction sites, road embankments, landslides, sandstone mines, coal mine spoils, and pipeline corridors (Morgan 2005). The major erosion-prone areas on the coal mine spoil are the overburden banks where erosion occurs very rapidly, and because the habitat is infertile and toxic, the growth of vegetation is very slow (Morgan 2005). Chaturvedi and Singh (2017) emphasized that the only effective method for controlling erosion and the logical path of bringing coal mine spoils back into usefulness is to plant trees and revegetate them. The most important purpose of controlling soil erosion on the infertile and degraded coal mine spoil is to create a stable habitat for the establishment and growth of vegetation. An important objective of the revegetation of coal mine spoils is controlling erosion by increasing plant cover and growth of a self-sustaining plant community through the process of recolonization of particularly native plant species (Huang et al. 2016). Also, for improving the quality of soil in coal mine areas, reclamation has been suggested to be an effective mechanism (Tripathi et al. 2016).

When the coal mine spoils are revegetated with tree plantations, the aboveground components, for example, leaves and stems, absorb significant energy of falling raindrops, flooding water, as well as wind storms, so that their direct impact on soil becomes very less, whereas the belowground components, mainly comprising of root systems, provide mechanical strength to the soil (Morgan 2005). Therefore, after revegetation, the soil of coal mine spoil becomes mechanically stronger which helps to minimize runoff and preserve the soil moisture, which ultimately leads to increase in water availability for the growing plants.

Grass species, such as *Pennisetum pedicellatum* and *Cymbopogon citratus*, and legume plants, such as *Stylosanthes humilis*, *S. hamata*, *Sesbania sesban*, and *Crotalaria juncea*, have been reported to be effective in controlling soil erosion in initial stages of the restoration of coal mine spoil (Maiti and Maiti 2015; Chaturvedi and Singh 2017).

10.5 Improvement of Soil Fertility

The coal mine spoil without plant cover is exposed to harmful effects of torrential rains causing high level of soil erosion; therefore, trees and litter layer are necessary to prevent the soil surface from direct impact of raindrops (Morgan 2005). The biomass of trees after decomposition yield organic matter resulting in improvement of the structure, fertility, as well as other hydro-physical properties of soil (Mukhopadhyay et al. 2016a; Chaturvedi and Singh 2017). Moreover, trees support the growth of other herbs and shrubs which further increase the supply of organic materials to the mine spoil soil through the decomposition of litter, and therefore increase the rate of returning of natural fertility to the degraded fallow land.

Dutta and Agarwal (2002) reported that litterfall from tree plantations act as an important regulating component for the enrichment of microbial biomass on coal mine spoil. The belowground root biomass and aboveground biomass of plants have been observed to be the major source of soil organic matter, and this organic matter is highly associated with microbial biomass in soil (Singh et al. 2006; Chaturvedi and Singh 2017; Singh and Chaturvedi 2018). Kimaro et al. (2007) investigated nutrient use efficiency as well as biomass production of the planted tree species, where after 5 years of rotation, they found that the top soils under *Gliricidia sepium* (Jaqua), *Acacia polycantha*, and *Acacia mangium* were highly enriched with soil organic carbon as well as exchangeable cation. Moreover, the fertility of soil under plantations in their study was very similar to those in the adjoining natural forests.

Tree plantations have been considered to enhance the structural, chemical, and biological properties of soils in various ways. The improvement in soil structure includes stabilization and better aggregation of soil particles, reduction in bulk density, increased water holding capacity, and improvement in infiltration (Mukhopadhyay et al. 2016a). These processes are closely associated with increasing levels of organic matter, enhancement in underground root biomass, and increment in macrofaunal activities (Tripathi et al. 2016). However, these are evenly affected by texture and clay content in soil. Moreover, organic resins as well as fungal and bacterial communities contribute to aggregation of soil particles, leading to structural stability as well as better distribution of pore size, which further provides better water holding capacity, suitable permeability, and aeration, together with good rooting depth, as well as protection from surface erosion (Singh and Chaturvedi 2018). Tree plantations have been reported to accelerate activity of various soil organisms, for example, fungi, earthworms, arthropods, and termites, by providing a cool and moist microclimate under the canopy. Besides, the rhizosphere provides substrate to soil microbial communities that may contribute to their nutrient needs as well as support the production of various growth-promoting substances and other useful biochemicals (Singh and Chaturvedi 2018). Tree plantations increase the nutrient status of coal mine spoil by stabilizing the nutrient cycle by capturing nutrients, which otherwise are leached into deep soil layers (Singh et al. 2002). Due to tree plantations, the cation exchange capacity (CEC) of soil improves, leading to enhancement in nutrient retention and the efficiency of nutrient utilization (Singh et al. 2006; Chaturvedi and Singh 2017). Tree plantations are also known to reduce metal toxicity and elevate pH in soil through enhanced cycling of bases, and by producing various metabolic substances which buffer soil against rapid shift in acidity, alkalinity, and salinity (Sheoran et al. 2010).

Chaturvedi and Singh (2017) reviewed the change in soil properties after tree plantations on the coal mine spoils (Table 10.2). According to their report, soil under 5-year-old plantation accounted 98% higher organic carbon and 67% higher total nitrogen compared to that under 3-year-old plantation. The reported variation of soil C/N ratio (from 8 to 10) could be due to the effect of plantations. However, as observed for soil organic carbon and total nitrogen, the difference was not significant with the age of plantation in mineral N or PO_4-P. Singh and Singh (1999) found that significant amounts of carbon, nitrogen, and phosphorus were immobilized in the biomass of microbial communities and the amount of nutrient immobilization increased with age, which is very similar to the increasing trend of soil organic carbon and total nitrogen (Table 10.2). Singh and Singh (1999) further reported that the associations between microbial carbon and total soil organic carbon, and between microbial nitrogen and total soil nitrogen are significantly positive. As shown in Table 10.2, while the microbial carbon in 5-year-old plantation was 152% greater, microbial nitrogen and phosphorus were observed only 96 and 78% greater compared to the 3-year-old plantation. It is evident that with increase in the age of plantation, proportions of organic carbon, total nitrogen, and total soil phosphorus became greater, leading to immobilization of nutrients in the biomass of soil microbial communities, which highlights the process of redevelopment of the degraded soil.

Table 10.2 Nutrient contents and soil microbial biomass in plantations at different ages in coal mine spoil

Parameters	Plantation age		
	3 years	4 years	5 years
Total organic carbon (C) (%)	0.34[a]	0.50[b]	0.67[c]
Total nitrogen (N) (%)	0.04[a]	0.05[b]	0.07[c]
Total phosphorus (P) (%)	0.01[a]	0.01[a]	0.01[a]
C/N	8.48[a]	9.22[a, b]	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 (%)	3.77[a]	4.38[a, b]	4.74[b]
Microbial biomass N (%)	4.82[a]	5.38[a]	5.61[a]
Microbial biomass P (%)	7.46[a]	9.45[a, b]	12.13[b]

Adapted from Chaturvedi and Singh (2017)
[a,b,c]Values in a row superscripted with different letters are significantly different from each other at $P < 0.05$

For the long-term restoration of coal mine spoil, it is necessary to establish the stable nutrient cycles supported by the growth of plants and the processes involving microorganisms (Sheoran et al. 2010; de Quadros et al. 2016). Litterfall and the process of decomposition are considered as the starting point for the development of organic carbon and nutrient contents in soil; therefore, the upper soil surface of the coal mine can be treated as a proxy to indicate the status and progress of restoration (Akala and Lal 2000). Ahirwal and Maiti (2018) have clearly described the process of nutrient accumulation in the revegetating coal mine spoil, which is an important mechanism of ecosystem development. Their study suggested that soil is the basic factor of vegetation restoration in coal mine spoils and the condition of soil indicates the direction of vegetation development after reclamation. Therefore, proper understanding of soil dynamics during the process of reclamation and recovery is very significant for planning the future ecological restoration of coal mine spoil. A number of other studies have also highlighted the significance of nutrient dynamics in the revegetation of coal mine soil and its importance in global climate change (e.g., Shrestha and Lal 2011; Mukhopadhyay and Maiti 2014; Mukhopadhyay et al. 2016b; Tripathi et al. 2016).

Vegetation plays a major role in accumulation of organic matter as well as plant nutrients in soil. Similarly, the tree species growing on the reclaimed site have been observed to significantly influence the soil nutrients in the rhizosphere (Table 10.3). Moreover, the microorganisms growing in soil significantly contribute to the reestablishment and functioning of biogeochemical processes and help in the redevelopment and maintenance of the soil fertility. The study by Mukhopadhyay et al. (2016b) indicated that an integrated carbon accumulation index constructed on the basis of the rhizosphere effect of total carbon, labile carbon, and microbial biomass carbon and rhizosphere nitrogen could substantially predict carbon sequestration in

Table 10.3 Tree biomass carbon stock and soil carbon, nitrogen, and phosphorus in the rhizosphere of different tree species growing in the reclaimed coal mine overburden dumps of Chandan opencast project, Jharia Coalfields, Dhanbad, Jharkhand, India (mean ± standard deviation, different letters in the same column indicate significant differences at $p < 0.05$ according to Duncan's multiple range test)

Plant species	Total carbon density $tree^{-1}$ (kg)	Total carbon (%)	Microbial biomass carbon ($mg\ kg^{-1}$)	Available nitrogen ($mg\ kg^{-1}$)	Available phosphorus ($mg\ kg^{-1}$)
Acacia auriculiformis	$39.6^{a} \pm 11.5$	$2.27^{c} \pm 0.53$	$162^{c} \pm 38.1$	$89.4^{b} \pm 13.2$	$5.41^{d} \pm 0.65$
Albizia lebbeck	$20.7^{c} \pm 3.89$	$2.47^{b,c} \pm 0.62$	$176^{c} \pm 16.9$	$89.5^{b} \pm 11.7$	$5.63^{d} \pm 0.36$
Cassia siamea	$34.8^{a,b} \pm 9.61$	$4.38^{a} \pm 0.55$	$280^{a} \pm 56.4$	$105^{d} \pm 17.8$	$6.33^{c} \pm 0.23$
Delonix regia	$36.3^{a,b} \pm 11.3$	$3.04^{b} \pm 0.32$	$220^{b} \pm 54.8$	$90.2^{b} \pm 14.4$	$9.43^{a} \pm 0.47$
Dalbergia sissoo	$43.7^{a} \pm 16.1$	$3.99^{a} \pm 0.54$	$228^{b} \pm 28.3$	$84.3^{b} \pm 13.3$	$8.49^{b} \pm 0.37$
Non-rhizosphere mine soil		$4.08^{a} \pm 0.82$	$127^{d} \pm 24.1$	$36.8^{c} \pm 3.08$	$3.40^{e} \pm 0.16$

Adapted from Mukhopadhyay et al. (2016b) reclaimed mine spoils. In several studies, the importance of microorganisms involved in soil formation and plant regeneration through their activities such as decomposition and nutrient cycling, N_2 fixing, and mycorrhizal symbiosis have been broadly recognized. According to Jenkinson and Ladd (1981), the soil microbial biomass (i.e., living part of the organic matter in soil) is an important agent for the conversion of added and native organic matter and serves as an active reservoir for nitrogen, phosphorus, and sulfur in soil. Generally, plants act as an important source of carbon for the development of microbial community, and in return, microbial population provides nutrients for the growth of plants through mineralization (Singh and Chaturvedi 2018). Recognition of the role of soil microorganisms in ecosystem functioning by acting as a source of plant nutrition has now attracted considerable interest toward the measurement of nutrients held in the microbial biomass (Singh and Chaturvedi 2018).

10.6 Carbon Sequestration

Various studies have reported the high potential of restored coal mine sites for atmospheric carbon sequestration; however, the capacity to accumulate carbon may differ according to climatic conditions and plant species used for the restoration of coal mine (Lal 2005; Akala and Lal 2000; Pietrzykowski and Daniels 2014). Table 10.4 summarizes carbon stocks and rate of carbon sequestration in the revegetated mine land or reclaimed forest lands for the studies carried out in different countries. The soil organic carbon sequestration rate has been reported to range from 0.1 to 1.2 Mg C ha^{-1} $year^{-1}$ for the reclaimed forest in Czech Republic (Frouz et al. 2009) and from 0.7 to 5.2 Mg C ha^{-1} $year^{-1}$ for the reclaimed forest in Poland (Pietrzykowski and Daniels 2014). The growth of vegetation cover and modification of soil properties on revegetated sites can lead to a higher carbon sequestration with increment in the age of revegetation (Amichev et al. 2008). According to Kutsch et al. (2009), the respiration by plant roots and microbial communities in soil also results in emission of carbon into the atmosphere.

In a recent study, Ahirwal et al. (2017) have analyzed the effect of revegetation on soil characteristics, in the form of gradual accumulation of soil carbon and nitrogen stock, and variations in ecosystem carbon pool, and soil CO_2 flux at the open strip coal mining project situated in Burmu block of Ranchi District, Central Coalfields Limited (CCL), Jharkhand. According to their results, the nutrient content of the revegetated coal mine soil elevated with the age of revegetation: after 7–11 years of revegetation, soil carbon and nitrogen stocks elevated two times and the carbon sequestration rate registered 1.71 Mg C ha^{-1} $yr.^{-1}$, while the total ecosystem carbon pool increased at the rate of 3.72 Mg C ha^{-1} $yr.^{-1}$. When the revegetated coal mine was resampled after 11 years, the soil CO_2 flux (2.36 ± 0.95 μmol m^{-2} s^{-1}), registered the value four times higher compared to that of the soil of adjoining natural forest. These studies suggest that after plantation, the coal mine soil could act both as a carbon sink and as a source of CO_2 in the terrestrial landscape.

Table 10.4 Comparative analysis of soil carbon stock and rate of carbon sequestration in afforested/reclaimed coal mine areas in different countries

Land use (study area)	Age of reclamation (years)	Soil depth (cm)	SOC stock (Mg C ha^{-1})	SOC sequestration rate (Mg C ha^{-1} $year^{-1}$)	References
Reclaimed forest (Ohio, USA)	25	0–15	37.10	0.2–2.6	Akala and Lal (2000)
Reclaimed forest (Ohio, USA)	20	0–15	14–48.6	1.64	Akala and Lal (2001)
Reclaimed forest (Ohio, USA)	25	0–50	79.9	2.40	Ussiri et al. (2006)
Reclaimed forest (Singrauli, India)	05	0–20	3.8–11.1	0.1–3.2	Singh et al. (2006)
Reclaimed forest (Czech Republic)	22–32	0.10	4.5–38.0	0.1–1.2	Frouz et al. (2009)
Reclaimed forest (Poland)	24	0–110	16.8–65.0	0.7–5.2	Pietrzykowski and Daniels (2014)
Revegetated mine land (Singrauli, India)	19	0–30	22.9	1.3	Tripathi et al. (2014)
Reclaimed forest (Jharkhand, India)	7–11	0–30	11.4–24.4	1.2–2.2	Ahirwal et al. (2017)

Source: Ahirwal et al. (2017)

10.7 Conclusion

This communication describes the role of tree plantations in recovery of the degraded coal mine spoil which has toxic and unfavorable environment for the growth of vegetation. This review explains the harmful effects of coal mining which results in the degradation of soil by destructing its physical, chemical, and biological structure, accelerating soil erosion, enhancing nutrient leaching, making soil compact by overburden dump, reducing soil pH, accumulating heavy metals in soils, depleting soil organic matter, decreasing plant available nutrients, reducing CEC, and decreasing microbial activity. This study suggests that revegetation through tree plantations is one of the efficient methods for restoring the fertility of soil by improving the organic matter content and its various properties, by increasing plant available nutrients and CEC, and incrementing biological activities. From this review, it may be concluded that the revegetation of coal mine spoil through tree plantations can improve fertility of soil and can support the establishment of vegetation; however, the process of restoration of the vegetation, close to the original level, may take longer time, depending on the extent of degradation. Based on literature survey, this study suggests some promising tree species that could be used for revegetating coal mine spoils, viz., *Acacia auriculiformis*, *Acacia holosericea*, *Acacia mangium*, *Albizia procera*, *Dalbergia sissoo*, *Leucaena leucocephala*, *Pithecellobium dulce* and *Prosopis cineraria*. These tree species are acid-tolerant, suitable for growing in infertile soil, and are able to add substantial quantity of organic matter to the soil.

For achieving long-term sustainability in the mining area, restoration process should be aimed to construct an ecosystem that is abundant with native species (Singh et al. 2004a; Chaturvedi and Singh 2017). In the process of ecological restoration, priority should be given toward the persistence of species through natural establishment and survival, factors influencing functioning of food webs, as well as system-wide nutrient conservation through interactions among the community of animals, plants, and organisms involved in decomposition (Jackson et al. 1995). In the process of mining, the top soil is removed, soil seed bank and root stocks are excavated, and the overall soil profile is disturbed, leading to slowing down of the natural succession process on coal mine spoils. However, it has been reported that the revegetation process may be enhanced by plantations of suitable native species together with addition of herbaceous species via ground seeding (Singh et al. 1996).

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