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Estimation of carbon sequestration in reclaimed coalmine degraded land dominated by *Albizia lebbeck, Dalbergia sissoo* and *Bambusa arundinacea* plantation: a case study from Jharia Coalfields, India

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Abstract Reclaimed mined lands provide an excellent opportunity to sequester carbon and combat global warming. Carbon sequestration on reclaimed sites depend on age of reclamation, composition of species, geomining conditions (soil characteristics) and prevailing climate. The aims of the present study were to calculate carbon (C)—stock of biomass of 4 years old plantation (dominated by *Albizia lebbeck*, *Dalbergia sissoo* and *Bambusa arundinacea*), understorey vegetation and litter, soil organic carbon in reclaimed minesoil (RMS) and compare with reference forest site. Allometric equation was used for the estimation of biomass C stock and found 13.0 Mg C ha^{-1} (*A lebbeck* 7.8 Mg C ha^{-1}, *D sissoo* 3.5 Mg C ha^{-1} and *B. arundincea* 1.2 Mg C ha^{-1}), while stock of understorey vegetation was 0.98 Mg C ha^{-1}. In RMS, C stock was 16.3 Mg C ha^{-1}, out of which inorganic C contributed 1.7 g kg^{-1} (8 % of total soil C), Coal C 8.7 g kg^{-1} (43 % of total soil C) and biogenic C 9.8 g kg^{-1} (49 % of total soil C). Total C stock in reclaimed site was calculated as 30.3 Mg C ha^{-1} (equivalent to 111 Mg CO_2 ha^{-1}). The study concluded that (i) coal C is responsible for overestimation of C stock in RMS (ii) Maximun C stock stored in aboveground biomass component and (iii) reclaimed mined lands will take approximately 17 years to reach the level of C stock of reference forest site in dry tropical climate.

Keywords Coal · Opencast mining · Reclaimed mine soils · Biomass carbon · Carbon sequestration · Carbon stock

1 Introduction

Carbon (C) sequestration is defined as "the process of increasing the C content of a C pool other than the atmosphere" (IPCC 2000). Terrestrial C sequestration is the process of (i) transforming or transferring atmospheric CO_2 through photosynthesis into biomass components such as trees, shrubs, vegetation, and soil organic matter (SOM), and (ii) incorporation of biomass into the soil as humus. This leads to the effective storage of atmospheric CO_2 in these biomass components until decomposition of biomass into the soil. Soil contains approximately 75 % of the terrestrial C pool, which is three times more than the amount stored in living plants and hence it plays a vital role in the global C cycling (Schlesinger and Bernhardt 2013).

In India, massive expansion of opencast mines is envisaged by adoption of latest technologies to meet the target and about 90 % of the coal is extracted by the opencast mining. During the process of surface coal mining, vegetation cover is completely stripped, and soils and overburden (OB) rocks are removed to reach the coal-deposit, which generates huge volume of heterogeneous mass, stored as OB dumps (external dumps) or used as backfill materials to fill open cast voids (internal dumping). These OB dumps, initially devoid of soil organic carbon (SOC) and generally reclaimed into a forest land through forestry reclamation approach (FRA) (Zipper et al. 2011; Skousen and Zipper 2014). Establishment of vegetation cover with high biomass production in reclaimed minesoils (RMS) reduces soil degradation and improves SOC with time. During technical reclamation, after dressing the

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surface, topsoil is applied and slope is blanketing with coir mat, and seeded with grass-legume mixture as an initial colonizer to the site (Maiti and Maiti 2015; Xiao et al. 2014). In the top flat surface of the dump, fast growing tree species saplings are planted with addition of topsoil in plantation pits (Maiti and Ghose 2005; Maiti et al. 2007).

Studies across the globe on C sequestration through reclaimed coal mine soils have received considerable attention in recent past (IPCC 2000; Akala and Lal 2000, 2001; Ussiri and Lal 2005; Sperow 2006; Amichev et al. 2008; Shrestha and Lal 2010; Tripathi et al. 2014, 2016; Das and Maiti 2016). The CO_2 sequestration in reclaimed mine sites is calculated by estimating C-stock of biomass (aboveground and belowground), litter and reclaimed minesoils (Fig. 1). The aboveground biomass (AGB) C-stock consists of all living vegetation above the soil, inclusive of stems, stumps, branches, bark, seeds and foliage, while the belowground biomass (BGB) C-stock consists of the biomass contained within live roots. The greatest fraction of total biomass of forests is represented by trees, whereas the other carbon pools (understory, dead wood, litter and BGB) represent only a fraction of the total tree biomass. The understorey was estimated 3 % of AGB, dead wood 5 %–40 %, and fine litters only 5 % of that in the AGB (Brown 1997). Destructive sampling is the most accurate method to estimate C-stock of biomass, whereby vegetation is harvested, dried to a constant mass and the dry-to-wet biomass ratio established and correlated with biomass vis. DBH (Diameter at Breast Height). Two other approaches for estimating the tree biomass are: (a) regression equations or allometric equations which provide estimates of biomass per tree based on three main climatic zones, regardless of species; and (b) the conversion of wood volume to biomass density using biomass expansion factors (Brown et al. 1989; Brown 1997). Allometric equations play important role in accurate estimation of above and belowground biomass stock of tree species based on measured independent variables (like, DBH) (Brown et al. 1989). Allometric equations can be represented in many ways, but the most commonly represented by a linear equation (Dudley and Fownes 1992). However, they may also vary according to diameter classes (in particular for higher diameter classes and for smaller diameter class <10 cm). Hence the biomass estimation also varies according to various factors such as DBH of tree species, stand age of the species and topography. Cairns et al. (1997) formulated regression equations to estimate root biomass based on above-ground biomass carbon in tropical, temperate and boreal forests and found a mean root-to-shoot (RS) ratio of 0.26, ranging between 0.18 and 0.30 and stated that the most of the root biomass (heavy roots >2 mm diameter) is close to 20 percent of the total AGB. According to MacDicken (1997), the ratio of belowground to aboveground biomass in forests is about 0.2, depending on species.

In India, several authors have published biomass estimations through destructive sampling methods and developed allometric equations for a few tree species >10 cm DBH in reclaimed minesoils and forests (Singh and Singh 1995; Lodhiyal et al. 2002). Amichev et al. (2008) also derived allometric equations for the estimation of biomass in reclaimed minesoil of Midwestern and Appalachian coalfields of USA.

Litter accumulation is also an important parameter for consideration in the C sequestration study. Litterfall consists of dead plant material, such as leaves, bark, seeds, logs, or reproductive organs, and twigs that has fallen to the ground. Litterfall depends upon type of tree species, plant debris, the type of ecosystem (forest or grassland) and various factors. For example forest ecosystem accounts for 70 % of litterfall (leaf), but woody litter increase with forest age, however in grassland ecosystem, the annual litterfall is very low due to very little aboveground perennial tissue (Lonsdale 1988).

Mining and associated disturbances disrupt the SOC equilibrium relationship, causing severe losses of SOC due to unfavorable physico-chemical characteristics, leading to a C deficit and poor conditions for both plant and microbial growth and SOC. Revegetation and proper management practices help to regain the lost C; improve the soil quality and restore the SOC by reabsorbing it from the atmosphere (Lal and Bruce 1999). Several researchers in USA studied C accumulation in minesoils which were reclaimed to cropland, pasture or forest (Akala and Lal 2000, 2001; Amichev et al. 2008; Sperow 2006). Total soil C (TSC) content in reclaimed or biologically restored minesoils consist of three types of pools namely (i) soil inorganic C (SIC), (ii) geogenic C (coal-C or fossil C) and (iii) biogenic C (plant derived recent SOC) (Ussiri and Lal 2008). Sources of SIC are parent rock of overburden materials which consists of carbonates or calcite and dolomite in significant concentrations. "Geogenic C" in minesoils originates from the incorporation of coal particles or coal dust during overburden removal, coal mining and reclamation operations, while "biogenic C" originates from recent biological inputs. Microbial decomposition of biogenic C sources (litter) along with different pedogenic process leads to their mixing with coal C and also the humus fraction. The stable fractions of"biogenic C" such as the humus and mineralizable fractions are responsible for maintaining long term CO_2 sequestration as it controls the SOC pool. However, standard procedures for quantifying SOC concentrations in RMS cannot distinguish coal C from biogenic C due to presence of large amount of coal carbon. This leads to overestimation of C pools and

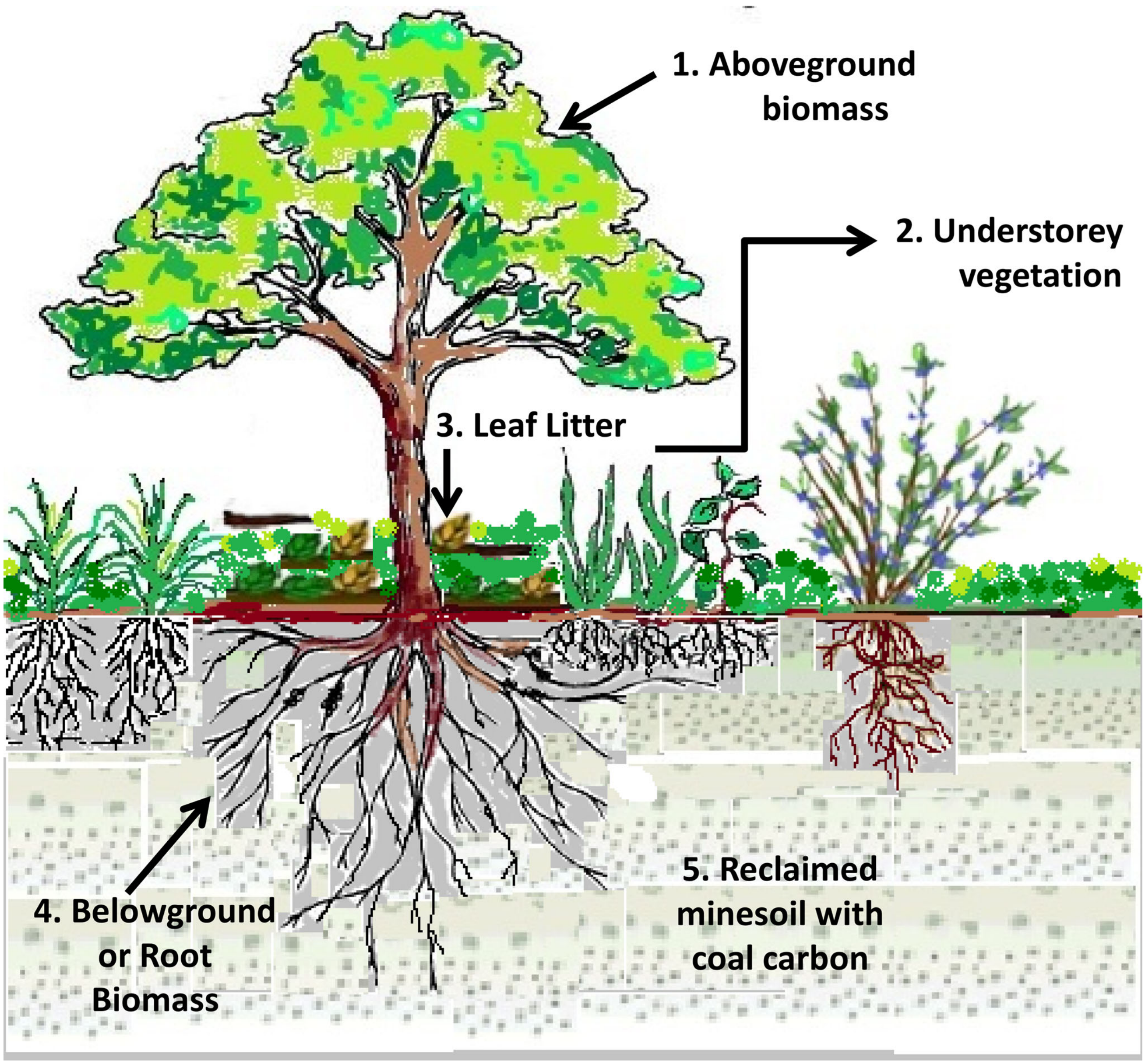

Fig. 1 Schematic diagram showing distrribution of carbon-stock stored in reclaimed coalmine site (*1* to *5*) and summation of all components gives CO seqquestration values (Million gram carbon per hectar, Mg C ha^{-1}). *1* Aboveground biomass, *2* and *3* Litterfall and understorey vegetation which includes shrubs, herbs, *4* Root biomass and *5* Soil organic carbon in reclaimed minesoils intermixed with coal carbon

sequestration rates, which must be corrected (Ussiri et al. 2014),

Scanty literature is available on C sequestration potential in RMS of India inspite of plentiful reports available worldwide. Direct tree harvest data is difficult to obtain and very less numbers of studies are available in the literature. In the present study, non harvest technique and allometric equations were used to estimate biomass and total carbon sequestered by different plant species in the reclaimed site. The aims of the present study are: (i) to estimate biomass C stock by using allometric equation; (ii) to estimate C stock of understorey vegetation, (iii) to study accumulation of C stock in mine soil and (iv) to study the distribution of sequestered C in different components of RMS (SOC or biogenic carbon; after removal of coal and inorganic carbon) and, (iv) to estimate rate of C sequestration and predict recovery of C stock in reclaimed mine soil to reference forest site.

2 Materials and methods

2.1 Location of study area

Carbon sequestration potential study was carried in a ecologically restored coalmine overburden dumps located in the Damoda colliery, Barora area, Jharia Coalfields (Bharat Coking Coal Limited, BCCL), Jharkhand, India. The Jharia coalfields falls between latitudes 23°39′–23°48′N and longitudes 86°11′–86°27′ E covering an area of 450 km^2. The site was located in the western part of Jharia coalfield which is characterized for the long history of land degradation, hostile climatic conditions, different tree species composition and slow succession process. The climate of the study area is dry tropical and characterized by hot and dry summer (March to June), rainy (July to October) and winter season (November to February). The average annual relative humidity is about 63 %. In summer months, the relative humidity (RH) varies between 32 % and 72 %. The temperature rises up to 42 to 46 °C on some summer days. In winter, the maximum and minimum temperature is 22 and 8 °C respectively, and sometimes drops down to 5–7 °C, in December and January, are the coldest months. Dust storms are common in dry season (May and June) before the onset of monsoon with increase in temperature and wind speed in the afternoon coupled with low humidity. The area receives annual rainfall of about 1140–1700 mm (average: 1306 mm), out of which 75 %–80 % of the annual rainfall occurs during the three months of June to September with smaller amounts during winter months. Number of rainy days in a year is about 100 days and the maximum rainfall occurring in the month of August. The wind speed of the area varies from 1.5 to 2.8 ms^{-1}.

The mining has been carried out by shovel–dumper combination and carbon sequestration study was carried out in a backfilled, lavelled OB dumps with presence of large rocks at surface. The rock types consist of sandstone (45 %), carbonaceous shale (20 %), intermixed shale and sandstone (16 %), Jhama (heat affected coal) with mica peridotite (3 %), subsoil (4 %) and coal (12 %) (Chandra 1992). The chemical composition of the rocks is very important because significant quantities of various plant nutrients are usually made available during the weathering process (Coppin and Bradshaw 1982).

The total study area was approximately 4 ha (40000 m^2) and the age of the entire restored site is 4 years. Location of study area is shown in Fig. 2. A 3-tier plantation consisting of grasses, shrubs and several tree species (native to the nearby forest) were raised before the onset on monsoon in the year 2011 by the BCCL in association with Forest Department to re-establish forest vegetation in the overburden dump. For raising tree species, saplings were planted in the plantation pits (30 cm × 30 cm × 30 cm) with the addition topsoil with weathered OB materials (soil: spoil; 1:4). Tree saplings used in the restoration purposes, are characterized by low in stature, water and nutrient demands, deciduous, and has economic and ecological values with high survival rate (Fig. 3). Figure 4 shows the arising of tender shoots from the node of bamboo culms after the propagation at initial stage of reclamation at the site. Figure 5 shows growing tree species (*Albizia lebbeck*), a shrub species (*Z. oenoplia*) and bamboo clumps at initial stage of plantation. The vegetation was protected from cattle by a boundary wall made of stones and boulders. A cemented signboard showing the type and no. of species planted is placed near the boundary wall (Fig. 6). During summer, trees were watered and additional soil was applied in the plantation pits of new growing trees or saplings to ameliorate the rhizospheric temperature and prevent them from dying. Bamboo, Kala siris (*Abizzia lebbeck*), Safed Siris (*A. procera*) and Shisham (*Dalbergia sissoo*) were the dominating species in the site along with Amla (*Phyllanthus emblica*) and grasses Dennanath *(Pennisetum pedicellatum)*, Kash (*Saccharam munja, S. spontaneum*). The dense growth of all these tree species and undergrowth of grasses and shrubs established complete 3-tier vegetation (Fig. 7)

2.2 Vegetation characteristics of the study area

The study area consists of 3-tier plantation of grasses, shrubs and several fast growing deciduous tree species (Table 1). Three random quadrats of size 10 m × 10 m (each quadrat of 100 m^2 area) (Fig. 8) were laid down and no. of trees of a particular species in each quadrat was recorded. Total 13 species were present in the quadrate including different grasses, bamboo and saplings of trees, out of which some of the saplings constituted *Phyllanthus emblica, Albizia lebbeck, D. sissoo, Terminalia arjuna, Lannea coromandelica*, and others. Bamboo clumps were recorded separately since the bamboo plantation dominated in the study site for calculation of density ha^{-1}. The girth of each tree species was measured at the height of 1.37 m above the ground level (i.e., DBH). The relative density of tree species with height >1.5 m and DBH >3 cm was calculated separately and the saplings height <1.5 m and DBH <3 cm were not considered for carbon sequestration study.

Two dominant tree species, *Albizia lebbeck* (58 %) and *Dalbergia sissoo* (33 %) together constitute 90 % of total plants population followed by *Phyllanthus emblica* (4 %), *Mitragyna parviflora* (2 %), *Syzizium cumini* (1 %) and *Ziziphus oenoplia* (1 %). Relative distribution of tree species in reclaimed site is shown in Fig. 9. Sixty one nos of bamboo clumps were observed in the three quadrats. Therefore the density of bamboo clumps was calculated as 2033 clumps ha^{-1}; whereas the tree density was 2500 trees ha^{-1}.

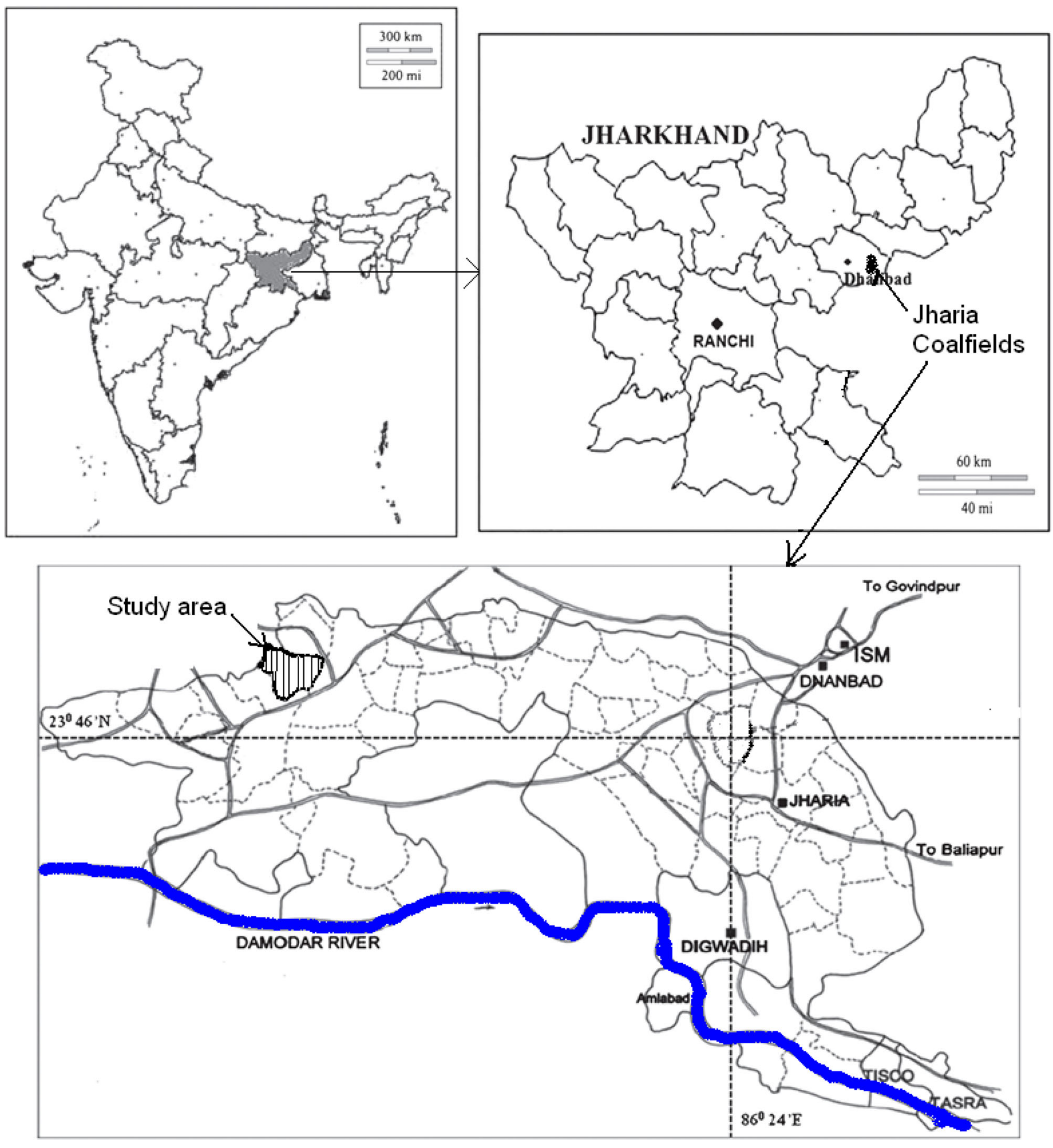

Fig. 2 Location map of study area

2.3 Reclaimed minesoil sampling and analysis

Sampling sites were selected underneath the canopy of different tree species *A. lebbeck, B. monosperma* and bamboo plantation. Total 5 replicates of minesoil samples were randomly collected by laying metal quadrat of 50 cm × 50 cm using the soil corer at 0–15 cm depth after the removal of litter layer (if any). Samples were properly packed in air tight sampling bags and brought carefully to laboratory for physical and chemical analysis.

Separate soil core were also collected with corer (15 cm height) for the measurement of bulk density at these sites. The soil samples were air dried for a week, crushed lightly by using mortar and pestle to remove the soil particles

Fig. 3 Initial stage of establishment of tree saplings of Safed Siris (*A. procera*) by pit plantation. Natural colonisation of Palash (*Butea monosperma*) on the site

sticking to the non soil particles, followed by sieving through a 2-mm sieve to separate the soil and non soil parts, reweighted to record the proportion of soil fraction (<2 mm size), labeled and kept in air tight sampling bags for further analysis.

The field moisture content of fresh soil was determined by gravimetric method and bulk density was determined by core method (dividing the oven dried mass of soil by the volume of the sample) (Maiti 2013) and corrected for gravel content. The paste pH and electrical conductivity (EC) was determined in soil: water ratio (1:1; w/v) suspension with a pH meter and Conductivity meter respectively (McLean 1982). Soil organic carbon was estimated by rapid dichromate oxidation technique (Nelson and Sommers 1996), available nitrogen by the alkaline potassium permanganate method (Subbiah and Asija 1956), available phosphorus by Bray's method (Bray and Kurtz 1966).

2.4 Estimation of inorganic, biogenic and coal carbon in reclaimed mine soil (RMS)

In reclaimed mine soil, the fraction of inorganic C, biogenic C (labile and stable) and coal C was determined by the methods suggested by Ussiri and Lal (2008), Chaudhuri et al. (2013) and Das and Maiti (2016). Total soil carbon (TSC) was determined in the CHNS elemental analyser (model: Euro EA) using CRM soil # 3 as a standard reference material after the sieving through the RMS samples <250 μ sieve size. The soil was pretreated with 1 M HCl, and loss of weight gives amount of inorganic C(IC).

$$\text{Inorganic C } (\%) = \text{TSC } (\%) - \text{TSC } (\%) \text{ after 1 N HCl treatment}$$

$$\text{Biogenic C } (\%) = \text{TSC } (\%) - (\text{Coal C } \% + \text{ IC } \%)$$

2.4.1 Estimation of C stock in reclaimed minesoil

The estimation of carbon sequestration is based on soil organic carbon (SOC) (%), corrected bulk density (g cc^{-1}) and depth (m) of soil. The SOC sequestration potential for RMS in mine soil samples is estimated using the following equation (Lal et al. 1998):

$$\text{Mg C ha}^{-1} = [\%\text{C} \times \text{Corrected B}_d \times \text{d (m)} \times 10^4 \text{m}^2 \text{ha}^{-1}]/100$$

where Mg C ha^{-1} is the mega grams C per hectare (1 Mg = 10^6), B_d (Mg m^{-3}) is the corrected soil bulk density (Mega gram per cubic meter), d soil depth (m), and % C is the biogenic carbon fraction in RMS as %.

Corrected soil bulk density was determined after removal of coarse fraction (>2 mm sieve size) from the sample.

2.5 Collection of understorey vegetation and litter and estimation of C stock

Understorey vegetation (grass, herbs, creepers, shrubs) and dry leaf litter accumulated underneath the canopy of different tree species (*D. sissoo, Albizzia spp.*) and bamboo (*B. arundinacea*) were collected within the metal quadrat 50 cm × 50 cm (Fig. 10a). In the RMS, understorey vegetation consists of dominant grass species *P. pedicellatum, C. ciliaris, C. setigerus,* etc. and shrubs (*Eupatorium, Lantata* etc.) (Figure 10b). Total 5 replicate of samples were collected from the study site. Samples were dried in an oven at 80 °C to constant weight to obtain the moisture free dry weight as followed by others (Karu et al. 2009; Singh et al. 2011) and expressed as Mg ha^{-1} C stock was calculated by multiplying a factor 0.4 assuming 40 % carbon present in the litter.

2.6 Estimation of biomass C stock

(a) *Calculation of above ground biomass* The DBH of individual tree species were divided according to their DBH classes (like, 3–5, 5–7, 7–9, 9–11, 11–13 cm). In the present study, non-destructive method of estimation of AGB was used. Mean DBH in each diameter class of individual tree species was used to calculate the AGB per tree (in kg) following regression equation, proposed for dry forest in India

Fig. 4 Tender shoots arising from the node of bamboo culms, which was planted during initial stage of reclamation

with rainfall >900 mm $year^{-1}$ (Brown et al. 1989; Brown 1997):

$$AGB = \exp\{-1.996 + 2.32 \times \ln(D)\}$$

where AGB is the aboveground biomass (kg) and D is the mean diameter at breast height (DBH) of each tree species in each diameter class (cm).

The average AGB multiplied to the tree density per hectare in the diameter classes to convert Mg ha^{-1}.

(b) *Calculation of below ground biomass* (BGB): In the present study 20 % of total above ground biomass was considered for the calculation of root biomass (MacDicken 1997). Several studies assumed 25 % of above ground biomass as the root biomass for hardwood species (IPCC 2006). Although there are limitations of using a constant factor for calculation of root biomass (Brown et al. 1989; Cairns et al. 1997), IPCC has proposed this method of estimating root biomass for reporting carbon stocks. Tree specific factors are available, but such factors vary with the age of the tree as well as with the soil characteristics (Brown et al. 1989). The use of constant factor may over/under estimate the total C stock (Cairns et al. 1997). Most of the research work revealed that AGB is strongly correlated with tree diameter (Brown et al. 1989). Also, it is accepted that simple model with only diameter as input is a good estimator of aboveground biomass.

Fig. 5 Growth of vegetation cover in the reclaimed site **a** *Albizia lebbeck* (Siris tree), **b** *Ziziphus oenoplia* (Wild jujube, a naturally colonizing shrub), **c** *Bambusa tudla* (Timber bamboo)

Fig. 6 Outside view of the reclaimed site showing different tree species; boundary wall and board indicating types and no. of species planted

$$\text{Below ground biomass}\left(\text{Mg ha}^{-1}\right) = \text{Average aboveground biomass}\left(\text{Mg ha}^{-1}\right) \times 0.2.$$

(c) *Estimation of total biomass* $(\text{Mg ha}^{-1}) = \text{AGB} + \text{BGB}$

Fig. 7 3-Tier vegetation established in the reclaimed site

(d) *Estimation of bamboo biomass*: In this study C stock of bamboo plantation was calculated by considering the work of Singh and Singh (1999).

(e) *Estimation of biomass C stock* The amount of carbon sequestered was calculated by reducing the biomass yield to its 50 % as per the guidelines of IPCC (2006). Hence biomass value was converted to

Table 1 Type of vegetation growing in Damoda reclaimed site

S no.	Scientific name (Family)	Common name	Remarks
1.	*Albizia lebbeck* Benth. (Fabaceae)	Silk flower (Siris)	Fast growing, medium-large tree, self-regenerated, common
2.	*Alstonia scholaris* (Linn.) R. Br. (Apocynaceae)	Devil tree (Chatim)	Small- medium size tree, poor growth
3.	*Azadirachta indica* A. Juss. (Meliaceae)	Margosa(Neem)	Large tree, native, poor growth
4.	*Bauhinia variegate* Linn. (Cesalpineae)	Bahunia	Medium size tree, not very common
5.	*Butea monosperma* L. (Fabaceae)	Flame of the forest (Palash)	Very common, grow naturally in reclaimed site
6.	*Dalbergia sissoo* Roxb. (Fabaceae)	Sissoo (Sisham)	Medium size tree, native, very common, luxuriant growth
7.	*Bambusa tulda* Roxb. (Poaceae)	Indian timber bamboo	Common in reclamation site
8.	*Bambusa arundinacea* (Retz.) Willd. (Poaceae)	Spiny bamboo	Common in reclamation site
9.	*Ficus infectoria* (Miq.) Domin. (Moraceae)	White Fig (Pakur)	Large tree, naturally colonise on reclaimed site
10.	*Lannea coromandelica* (Houtt.) Merr. (Anacardiaceae)	Indian ash tree (Doka)	Infrequent, naturally colonize
11.	*Matragyna perviflora* (Roxb.) Korth (Rubiaceae)	Kairn (Gulikadam)	Small- medium size tree, naturally colonize
12.	*Melia azedarach* L. (Meliaceae)	Persian lilac (Bakain)	Medium size tree, common in dump reclamation
13.	*Phyllanthus emblica* L. (Phyllanthaceae)	Indian gooseberry	Medium size tree, common, poor growth
14.	*Pongamia pinnata* Pierre. (Fabaceae)	Indian beech (Karanja)	Medium- large tree, common in dump reclamation
15.	*Syzygium cumini* (L.) Skeels (Myrtaceae)	Java plum	Medium size free tree, evergreen
16.	*Ziziphus oenoplia (L.)* Mill.	Wild jujube (Wild ber)	Evergreen shrub, spreading crown, self colonize

*Grass species Pennisetum pedicellatum (*Dennanath); *Saccharam munja, S. spontaneum* (Kans); *Cenchrus ciliaris (*Sui grass); *C. setigerus* (Dhaman grss); *Cynodon dactylon* (Doob)

Others Hemidesmus indicus (L.) R.Br. (common creeper, Asclepediaceae), *Tephrosia purpurea* (L.) Pers. (small shrubs, Fabaceae)

Fig. 8 Portion of quadrant sampling (shown by the rope) in the reclaimed site showing growth of *Albizzia lebbek* (kala siris), Bamboo and other tree species. Accumulation of litter at the floor consists of dry leaves and annual shrubs (*Eupatorium*)

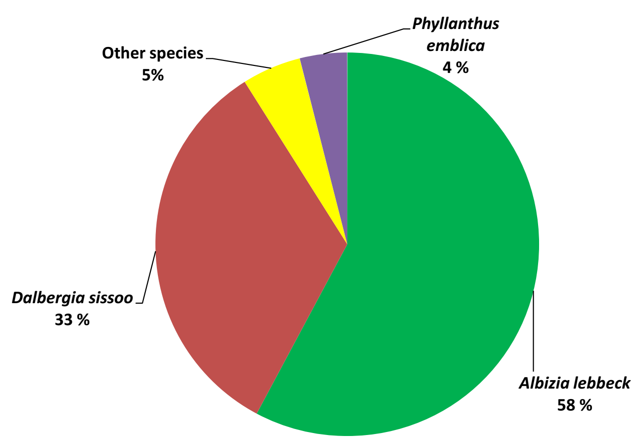

Fig. 9 Relative distribution of tree species in reclaimed site (others species - *Alstonia scholaris*, Mitragyna *parviflora, Syzygiumcumini* and *Ziziphus oenoplia*)

carbon stocks by multiplying a factor 0.5 and expressed as Mg C ha^{-1}.

2.7 Estimation of total C stock and CO_2 sequestration in reclaimed site

In RMS, there are three potential C sequestration pools, mainly: (i) above and below ground tree biomass, (ii) understorey vegetation and litter layer, and (iii) soil organic matter (SOM). Terrestrial plants can sequester carbon through photosynthesis which is stored in various above-ground (leaf, coarse woody material, branch, and logs) and belowground (live and dead roots, and SOM) biomass. This carbon is then transformed from live to dead organic matter

Fig. 10 **a** Close of view of quadrat sampling for litter collection (50 cm × 50 cm) taken within the sampling plot (10 m × 10 m). **b** Observed dried mulch of *Eupatorium* and other shrubs and grasses in the reclaimed site

by decomposition via microbes. Different tree species have different degree of influence on C pool in RMS due to variation in growth characteristics. Thus, the total C pool can be assessed by adding following components of an ecosystem (Shrestha and Lal 2010):

(a) Sum of Aboveground biomass (AGB) and below-ground biomass (BGB) C-pool (CPool $_{(AGB+BGB)}$)
(b) Understorey and litter C stock (C Pool $_{UL}$)
(c) SOC at 0 to 15 cm depth (C Pool $_{soil\ 0\text{-}15\ cm}$)

$$\text{Eco C Pool} = \text{C Pool}_{(AGB+BGB)} + \text{C Pool}_{UL} + \text{C Pool}_{soil(0-15cm)}$$

where Eco C Pool is the total ecosystem C stock (Mg C ha^{-1}).

Total C stock is converted to CO_2 equivalent by multiplying a factor of 3.67 (by 44/12 ratio). Carbon sequestration rate (Mg C ha^{-1} year^{-1}) is calculated by dividing total C stock in RMS (Mg C ha^{-1}) with the age of the dump.

3 Results and discussion

3.1 Physico-chemical characteristics of reclaimed mine soil

Physico-chemical characteristics of reclaimed mine soil (RMS) significantly influence vegetation growth and accumulation of C stock. Generally mine soil is characterized with high stone content, lesser soil forming materials, low water holding capacity, low soil organic matter and humus, lower plant available nitrogen and phosphorous (Maiti 2013). Physico-chemical characteristics of reclaimed mine sites and reference forest site are given in Table 2. Soil fraction in RMS found 62 %, which was significantly lower than reference forest site (81 %), while non-soil or coarse fraction (>2 mm size) were found double than reference site. Higher coarse fraction in RMS attributed due to nature of mining, characteristics of rocks, measures taken during technical reclamation and amount of top soil application. However, it was also reported as high as 80 %–85 % due to geo-mining conditions in most of the reclaimed coalmine overburden dumps (Maiti and Saxena 1998). Excessive amount of coarse fragments limit the fine earth volume required for root proliferation, water-holding capacity, and long-term nutrient availability of plants (Mukhopadhyay et al. 2013; Maiti 2013). It also reduces with time in surface horizons due to weathering processes (Haering et al. 1993; Johnson and Skousen 1995). Corrected bulk density was found 1.12 g cc^{-1} (corrected by subtracting courser fraction for soil), which is lower than reference site. Higher values of bulk densities (1.67 g cc^{-1}) in reclaimed dumps were reported, which is caused due to compaction and lack of organic matter (Barnshiel and Hower 1997; Maiti 2007; Kumar et al. 2015). New mine soils had a slightly higher bulk density than the native soils due to the differences in mining method rather than pedogenic processes. The bulk density decreased with increase in age of reclamation, which is due to root system development, addition of biomass, and improvement in soil structure (Mukhopadhyay et al. 2014). Bi and Zhang (2014) also reported that soil bulk density of surface soil decreased and soil porosity and field capacity increased after afforestation in coal mining subsidence land. Akala and Lal (2001) also reported that growth and development of roots over time incorporates soil organic carbon and loosens up the soil, thus decreasing soil bulk density. The field moisture content in the RMS was lower (4.7 %) compared to forest site (7.7 %). Lower moisture content in RMS depends on the time of sampling, height of dump, stone content, soil texture, amount of organic carbon, and litter layer on dump surface (Mukhopadhyay and Maiti 2011). pH of the mine soil mainly depends on the

Table 2 Physsico-chemical characteristics of reclaimed minesoils (n = 5)

Parameter	Reclaimed mine soil	Reference forest site
Soil fraction (<2 mm size) %	61.90 ± 11.89[a]	80.62 ± 5.42
	(46.78–74.75)	(75.3–87.4)
Non-Soil fraction (>2 mm size) %	38.10 ± 6.75	19.40 ± 2.98
	(24.25–53.22)	(15.6–28.2)
Corrected Bulk Density (g cc^{-1})	1.12 ± 0.05	1.34 ± 0.06
	(1.02–1.16)	(1.23–1.40)
pH (1:1; w:v)	7.27 ± 0.49	5.92 ± 0.19
	(6.78–7.85)	(5.52–6.32)
pH (1:2.5; w:v)	7.41 ± 0.54	6.25 ± 0.42
	(6.89–8.01)	(5.95–6.40)
EC(1:1; w:v) (dS m^{-1})	0.182 ± 0.06	0.107 ± 0.017
	(0.10–0.26)	(0.085–0.125)
Moisture content (%)	4.66 ± 1.04	7.29 ± 1.54
	(4.1-6.5)	(6.1–10.4)
SOC (%)[b]	4.27 ± 0.91	2.02 ± 0.20
	(3.23–5.41)	(1.75–2.15)
Av. N (mg kg^{-1})	94.50 ± 11.47	126.77 ± 11.02
	(84–110)	(108.2–144.2)
Av-P (mg kg^{-1})	2.45 ± 0.69	6.85 ± 1.41
	(1.82–3.32)	(4.5–8.84)

[a] Avg value ± SD (Min − Max)

[b] By Walkley–Black method (rapid dichromate digestion)

substrate and nature of the geological material of the overburden dump (the amount of acid-producing or acid-neutralizing material) (Mukhopadhyay and Maiti 2011). In the present study pH and electrical conductivity was found within the range and anticipate no detrimental effects on plant growth.

Variations in SOC may be mainly due to nature of mine soil, as well as decomposition of leaf litter of different tree species and humus to a large extent. The average SOC was found higher (4.27 %), due to accumulation of old, new and coal carbon fraction or mixing of recent carbon with coal carbon (Ussiri and Lal 2008). It has been reported that coalmine soil contains both recent (new) plant derived carbon fractions added through biological processes, detritus matter; and ancient (old) carbon fractions added by fossilized plant matter (humus), coal and inorganic carbonates (Maharaj et al. 2007). Plant available nitrogen was 94 mg kg^{-1}, which is lower than reference forest site, due to younger age of RMS. In the RMS, plant available P was 2.5 mg kg^{-1}, which also much lower than reference forest site. SOC, N and P have been reported as growth limiting factors on mined sites, but usually within the first 10-year after disturbance (Andrews et al. 2002). Increase in concentration of available N with increase in age of plantation has been observed by several researchers (Ahirwal and Maiti 2016; Mukhopadhyay and Maiti 2014; Maiti 2006, 2007). Low available N stock in the younger RMS suggests that N is limiting initially after reclamation when very little organic matter is present. Nitrogen accumulation is controlled by organic carbon input and N fixation, while phosphorus content is determined by the organic matter, pH of the soil substrate and weathering process (Andrews et al. 2002). Several chronosequence studies (Akala and Lal 2000; Maharaj et al. 2007; Shrestha and Lal 2010; Mukhopadhyay et al. 2013, 2014) have reported accumulation of C and N pools over time in RMS.

3.2 Tree biomass C stock and CO_2 sequestration

Tree species with DBH >3 cm found within the quadrat were classified according to DBH classes as applicable. *A. lebbeck,* the most dominant species was classified into 5 DBH classes ranging from 3 to 5 cm, 5 to 7 cm, 7 to 9 cm, 9 to 11 cm and 11 to 13 cm, with a total of 1433 nos of trees ha^{-1} and average DBH ranging from 4.08 to 12.42 cm (Table 3). Likewise, average DBH for other tree species were calculated. Out of 7 species, *A. lebbeck* contributed maximum AGB (13.04 Mg ha^{-1}) followed by *D. sissoo* (5.96 Mg ha^{-1}). The root biomass contributed by *A. lebbeck* was also highest (2.61 Mg ha^{-1}) than other tree

Table 3 Estimation of above ground biomass (AGB) and root biomass (RB) based on DBH (diameter at breast height) class for individual tree species in reclaimed site

Tree species name	DBH range (cm)	Avg DBH (cm)	No of trees ha^{-1}	AGB per tree (kg)	AGB of all trees ($Mg\ ha^{-1}$)	Root biomass (RB) ($Mg\ ha^{-1}$)[a]
Alzebia. lebbeck	3–5	4.08	600	3.54[b]	2.12[c]	0.42[d]
	5–7	5.88	533	8.27	4.41	0.88
	7–9	7.91	200	16.47	3.29	0.66
	9–11	9.43	67	24.76	1.65	0.33
	11–13	12.42	33	46.94	1.56	0.31
		Total	1433		13.04	2.61
Alstonia scholaris	3–5	3.18	33	2.00	0.07	0.01
		Total	33		0.07	0.013
Dalbergia sissoo	3–5	4.31	300	4.02	1.21	0.24
	5–7	5.80	467	8.02	3.74	0.75
	7–9	7.64	67	15.22	1.01	0.20
		Total	833		5.96	1.19
Mitragyna parviflora	3–5	3.82	33	3.05	0.10	0.02
		Total	33		0.10	0.02
Phyllanthus emblica	3–5	3.40	100	2.32	0.23	0.05
		Total	100		0.23	0.05
Syzygium cumini	3–5	4.78	33	5.11	0.17	0.03
		Total	33		0.17	0.03
Ziziphus oenoplia	3–5	3.82	33	3.05	0.10	0.02
		Total	33		0.10	0.02

[a] Root biomass (MacDicken 1997) = AGB ($Mg\ ha^{-1}$) $\times$ 0.2

[b] AGB (kg) = exp [−1.996 + 2.32 × ln DBH (cm)]; = exp [−1.996 +2.32 × ln (4.08)] = 3.54 kg

[c] 3.54 kg x 600 (no of trees ha^{-1}) $\times 10^{-3}$ = 2.12 ($Mg\ ha^{-1}$)

[d] 2.12 ($Mg\ ha^{-1}$) $\times$ 0.2 = 0.42 ($Mg\ ha^{-1}$)

species. It is noticed that AGB (kg $tree^{-1}$) increases exponentially at the higher DBH. Similar exponential relationship was noticed between biomass and DBH of tropical trees (Brown 1997).

Total tree biomass was estimated 23.6 $Mg\ ha^{-1}$ (AGB 19.67 $Mg\ ha^{-1}$ + RB 3.93 $Mg\ ha^{-1}$) (Table 4) and the biomass of bamboo clumps was estimated as 2.54 $Mg\ ha^{-1}$. Singh and Singh (1999) reported bamboo plantation developed on reclaimed mine spoil (Singrauli, India) accumulated substantial amount of biomass (46 $Mg\ ha^{-1}$ for 3 year plantation and 74.7 $Mg\ ha^{-1}$ for 5 year plantation). Several other studies in natural ecosystem of bamboo forests and plantations in India recorded 0.8 to 24 $Mg\ ha^{-1}$ aboveground biomass (Rao and Ramakrishnan 1989; Tripathi and Singh 1996). In the present study, total biomass (tree and bamboo) was estimated 25.97 $Mg\ ha^{-1}$. Studies by Singh and Singh (1991) reported higher aboveground biomass in the native dry tropical deciduous forest, in the range between 42 and 78 $Mg\ ha^{-1}$. Lodhiyal et al. (2002) estimated the AGB of Tarai Shisham forest, India (5–15 years age) in the range of 41–103 $Mg\ ha^{-1}$ and total biomass in the range of 59–136 $Mg\ ha^{-1}$.

Biomass C stock in reclaimed mine sites depends on tree species, climatic conditions and nature of substrate. A comparative C stock data under different climatic conditions, age of vegetation and forest type is presented in Table 5. In the present study, total biomass C stock was estimated as 13 $Mg\ C\ ha^{-1}$(equivalent to CO_2 sequestered of 47.96 $Mg\ CO_2\ ha^{-1}$), which is much lower than reference forest site. In Indian conditions (19 years old RMS of Singrauli, India), Tripathi et al. (2014) reported higher C stock (41.73 $Mg\ C\ ha^{-1}$) with an accumulation rate of 2.20 $Mg\ C\ ha^{-1}\ year^{-1}$. Average C accumulation rate in aboveground biomass for reclaimed pine and hardwood forests ranged from 1.4 $Mg\ C\ ha^{-1}\ year^{-1}$ in Indiana to 3.3 $Mg\ C\ ha^{-1}\ year^{-1}$ in West Virginia (Amichev et al. 2008). Terakunpisut et al. (2007) compared the C stock of the aboveground biomass in different forest ecosystems of Thong Pha Phum National Forest, Thailand based on DBH $\geq$ 4.5 cm using allometric equation and reported that tropical rain forest had higher C stock than dry evergreen

Table 4 Distribution of carbon stock in total above ground biomass (AGB), root biomass (RB) of trees and bamboo in reclaimed area

Tree species name	Nos ha^{-1}	AGB of tree species (Mg ha^{-1})	RB of tree species (Mg ha^{-1})	Biomass C-stock (Mg C ha^{-1})
Albizia spp	1433	13.04	2.61	7.82
Dalbergia sissoo	833	5.96	1.19	3.58
Other tree species[a]	234	0.67	0.13	0.40
B. arundinecea[b] (Clumps)	2033	2.36	0.18	1.27
Total		22.03	4.11	13.07

[a] *Alstonia scholaris, Mitragyna parviflora, Phyllanthus emblica, Syzygium cumini* and *Ziziphus oenoplia*

[b] Singh and Singh (1999) studied the biomass C of bamboo in the reclaimed mine sites of Singrauli, India, and reported that after 4 years, nos of clumps were 22475, which contributes above ground biomass of 26.1 Mg ha^{-1} (or 13.05 Mg C $ha^{-1)}$ and root biomass contributes 7.7 % of total biomass. So, in the present study, above ground bamboo biomass of 2033 nos clumps ha^{-1},is calculated as 2.36 Mg ha^{-1}. CO_2 sequestered = 13.07 t ha^{-1} × 3.67 (factor to convert C to CO_2) = 47.96 MgCO_2 ha^{-1}. Therefore, rate of CO_2 sequestration = [47.96 Mg ha^{-1}/4 years) = 12 Mg CO_2 ha^{-1} $year^{-1}$

and mixed deciduous forest in order of 137.7 ± 48, 70.3 ± 7.4 and 48 ± 16.7 Mg C ha^{-1}, respectively.

3.3 C stock in understorey vegetation and litter and CO_2 sequestration

Litter accumulation underneath of different trees and bamboo plantation were estimated in this study, which includes dry leaves, grasses, herbs and shrubs. In the present study average litter accumulation was 2.45 Mg ha^{-1}, and total C stock estimated as 0.98 Mg C ha^{-1} (0.3–1.86 Mg C $ha^{-1)}$, which is lower than reference forest site (Table 6). Dutta and Agarwal (2003) estimated overall litterfall rate in the range of 1.2–3.6 Mg ha^{-1} $year^{-1}$ in reclaimed coalmine site (Singraulli, India), whereas range 1-5.9 Mg ha^{-1} $year^{-1}$ was reported in established bamboo ecosystem of the same site (Tripathi and Singh 1996; Singh and Singh1999). Litterfall rate in Indian shisham forest (5–15 yrs age) was estimated in similar range of 2.2–5.1 Mg ha^{-1} $year^{-1}$ (Lodhiyal et al. 2002).

In the present study, carbon stored in the understorey vegetation and litter components was 0.98 Mg C ha^{-1}, which is lower than other reported values. (Karu et al. 2009; Pragasan and Parthasarathy 2005). C stock in litter component of reclaimed minesoil of Midwestern and Appalachian coalfields (USA) comprised of pine, hardwood and mixed stand was estimated 21.2, 14 and 6 Mg ha^{-1} respectively (Amichev et al. 2008). Other studies by Shrestha and Lal (2010) also estimated higher C stock than the present study in litter component of reclaimed minesoil of Ohio (USA) in forest ecosystem (3.96 Mg Cha^{-1}). In Indian mining conditions (revegetated minespoils of 19 years age, Singrauli, India) C accumulation by litter component was estimated 2.80 Mg C ha^{-1} @ 0.15 Mg C ha^{-1} $year^{-1}$ (Tripathi et al. 2014), which is higher than the present study. Studies reported that, with increase age of vegetation C stock in the understorey vegetation and litter fall also increases (Amichev et al. 2008; Singh et al. 2011).

3.4 C stock in reclaimed mine soil and CO_2 sequestration

C-stock in reclaimed mine soil (RMS) was estimated 16.33 MgC ha^{-1} and CO_2 sequestered was 59.93 Mg CO_2 ha^{-1}, which is lower than reference forest site (Table 7). In Indian reclaimed coal mine sites (Jayant project, Singrauli) accumulation of higher C-stock (22.9 Mg C ha^{-1}) was reported with an average accumulation rate of 1.20 Mg C ha^{-1} $year^{-1}$ (Tripathi et al. 2014). C stocks of reclaimed forest and grassland coal mine soils (0-30 cm) of Ohio, USA were reported in higher range of 37–45 Mg C ha^{-1} and 47–79 Mg C ha^{-1} over 21 and 25 year periods respectively (Akala and Lal 2000, 2001). Rate of accumulation of C stock was observed 0.1 to 3.1 Mg C ha^{-1} $year^{-1}$ and 0.7–4 Mg C ha^{-1} $year^{-1}$ in grass and forest RMS ecosystem respectively (Shrestha and Lal 2006; Akala and Lal 2001). Post and Kwon (2000) also reported a higher average C accumulation of 0.34 Mg C ha^{-1} $year^{-1}$ (at the top 30 cm soil in tropical to temperate forest) than permanent grasslands (0.74 Mg ha^{-1} $year^{-1}$ tropical dry lands to cool temperate ecoregion) which is lower than the RMS.

3.5 Total soil carbon fractionation of RMS

The total soil carbon content is considered as a key component of minesoil quality and its storage in reclaimed soil is recognized promising measure for mitigating global climate change through carbon sequestration (Lal 2004, 2005). Distribution of Total carbon (%), Inorganic

Table 5 C-stock in Total biomass, Above ground biomass (AGB) and accumulation rate under forest and reclaimed coal mine spoils in India and outside countries

Forest type/vegetation and location	Age (year)	Total biomass C (Mg C ha^{-1})	AGB C stock (Mg C ha^{-1})	Total biomass C accumulation rate (Mg C ha^{-1}yr^{-1})	Reference
Reclaimed minesoil, Northern Europe (*Pinus sylvestris*)	14	6.76	5.86	0.48	Karu et al. (2009)
	21	28.93	25.65	1.37	
	36	101.6	90.01	2.82	
Reforested post-mining sites, Poland (*Pinus sylvestris*)	17	24.41	22.13	1.43	Pietrzykowski and Daniels (2014)
	30	54.74	48.17	1.82	
	Con (30 yr)	71.10	64.50	2.37	
Reforested coal mine sites of Appalachian Coal Basin, USA	5	2.49	0.27	0.50	Avera et al. (2015)
	11	55.43	53.80	5.04	
	21	54.10	48.86	2.58	
	30	66.91	64.27	2.23	
	Unmined	136.09	125.71	–	
D. sissoo forests, Tarai forest, India	5	29.3	20.9	5.86	Lodhiyal et al. (2002)
	10	53	39.3	5.30	
	15	68	50.65	4.53	
D. sissoo forests, Bhabar forest, India	5	17.55	–	3.51	Lodhiyal and. Lodhiyal (2003)
	10	30.15	–	6.03	
	15	44.75	–	2.98	
Mixed plantation, Terai, India[a]	5	5.88	4.385	1.176	Singh et al. (2011)
D. sissoo,		0.325	0.285	0.065	
A. lebbeck		1.51	1.30	0.302	
A. catechu					
D. sissoo, Tarai, India	10	43.39	35.77	2.73	Kanime et al. (2013)
Tropical moist deciduous forests, *Techtona grandis* Tarai, India	5	15.8	13.9	3.16#	Jha (2015)
	11	35.4	31.2	3.21	
	18	39.0	34.2	2.17	
	24	61.5	54.3	2.65	
	30	73.2	63.8	2.44	
Reclaimed coal mine spoil, Singrauli, India *B. arundinacea*	3	23.45	21.65	7.81	Singh and Singh (1999)
	5	37.35	34.7	7.47	
Reclaimed coal mine spoil, Singrauli, India	2	1.74	1.52	0.87	Tripathi et al. (2016)
	4	5.45	4.75	1.36	
(Mixed plantation)	10	15.64	13.68	1.56	
	14	25.96	23.04	1.85	
	16	31.61	27.89	1.97	
	19	44.52	39.25	2.34	
Reclaimed coal mine spoil, Singrauli, India	3	10.95	7.8	3.65	Singh et al. (2011)
	6	33.9	25.55	5.65	
A. lebbek	3	6.55	3.2	2.18	
A. procera	6	20.1	13.65	3.35	
Reclaimed coalmine, *A. lebbeck, D. sissoo,*	4	13	11.01	3.25	*Present study*
B. arundinacea	Reference forest[b]	66.1	52.88	–	

[a] Total tree density—1332 trees ha^{-1}; (*D. sissoo*—770 ha^{-1}; *A. catechu*—376 ha^{-1} and *A. lebbeck*—176 ha^{-1}). [b] Natural forest, close proximity to the reclaimed site

Table 6 Carbon stock of understory vegetation and litter in 4 years old reclaimed dump

Forest type/vegetation, location	Components	Age of reclamation (years)	C- stock (Mg C ha^{-1})[a]	Reference
Reclaimed minesoil, Appalachian, USA	Pine stands	–	21.2	Amichev et al. (2008)
	Hardwood stands		13.9	
	Mixed stands		6.1	
Reclaimed minesoil, Northern Europe (*Pinus sylvestris*)	Herb + Shrub	14	6.76	Karu et al. (2009)
		21	0.62	
		36	7.8	
Reclaimed minesoil of Ohio, USA	Forest	25	3.96	Shrestha and Lal (2010)
Tropical dry evergreen forests, Coromandel coast, south India	Total fine litter		5.3–5.4	Pragasan and Parthasarathy (2005)
	Standing crop		1.64–1.94	
Terai Forest, India	Understorey	5	1.62	Singh et al. (2011)
	Floor litter		0.608	
Revegetated mine spoils, India		19	2.80 (0.15)[b]	Tripathi et al. (2014)
Temperate forests, Kashmir, India	Understorey	Natural forest-	0.08–1.18	Dar and Sundarapandian (2015)
	Detritus		2.01 -8.06	
Reclaimed coalmine, site, Jharia coalfields	Understory vegetation and litter	4	0.98 (0.288–1.856)	Present study
	Reference forest site	–	1.65 (0.842–2.103)	

Undestorey vegetation includes herbs, shrubs and grasses

[a] Total biomass is multiplied by 0.4 to calculate C-stock

[b] Values within brackets are C sequestration rate of understorey vegetation and litter

carbon (%), Coal carbon (%) and Biogenic carbon (%) of RMS samples collected under the canopy of different vegetation cover is shown in (Fig. 11). Total soil carbon (TSC) was found in the range of 1.72 %–2.31 % and the average value was 2.01 %. Carbon fractionation is important since intermixing of biogenic C with coal C leads to overestimation of C sequestration values (Ussiri and Lal 2005; Ussiri et al. 2014). In the present study, inorganic C was estimated as 0.17 %, which is 8 % of TSC. Stahl et al. (2009) reported IC concentration from 1.82 to 8.47 g C kg^{-1} in RMS (17 %–60 % of TSC) of Wyoming (USA). Ussiri and Lal (2008) reported coal C contributes 47.4 % of TSC (0–10 cm) in the RMS of Ohio. The quantity and quality of biogenic C have strong influences on other essential soil characteristics and is a major determinant of soil productivity and long-term stability of the reclaimed minesoil (Ussiri et al. 2014). Biogenic C was estimated in the present study in the range of 0.84 %–1.08 %, whereas coal C was estimated 0.63 %–1.03 %.

3.6 Coal C distribution in reclaimed minesoils

Depending on mining and reclamation techniques, the amount of coal C can be substantial (Table 8). In the present study, coal C contributed 43 % of total organic carbon (TOC) in RMS. In Indian conditions, average contribution of coal C to TOC in RMS ranged between 24 % and 68 % (Das and Maiti 2016). Coal contamination contributed to the irregular depth distribution of SOC in RMS (Thurman and Sencindiver 1986). In Lusatia mining district (Germany), lignite-C accounted for 25 % to 99 % of the total SOC in rehabilitated and reforested RMS (Rumpel et al. 1998, 2000). Coal C accounted for up to 80 % of the OC in the A- horizon of cultivated Mollisol contaminated by brown coal emissions from a briquette factory (Schmidt et al. 1996). Chabbi et al. (2006) reported lignite C contribution of 20 %–80 % of total SOC in RMS and sediment of Lusatia (Germany). Generally, the concentration of coal C increases with increase in soil depth, and nearly 100 % of OC in the C- horizon (mine spoil) can be of geogenic origin (Ussiri et al. 2014).

Age since reclamation had little effect on the relative abundance of Coal C in RMS probably due to its biochemical recalcitrance. For example, Rumpel et al. (2003) showed that lignite accounted for 80 %–93 % of the total C in the top 0–5 cm mineral horizon of the age-chronosequence series of minesoils ranging from 11 to 32 year old at Lusatian mining district in Germany. Rumpel et al. (1998) observed that after 36 year of restoration, more than half of the OC in 0–5 cm soil layer under red oak (*Querus*

Table 7 Soil carbon stock and rate of accumulation in afforested reclaimed coal mine soils and natural forest in India and abroad

Land use	Vegetation/land-use system	Age (year)	Soil depth (cm)	C stock (MgC ha^{-1})	Rate of C accumulation (MgC ha^{-1} year^{-1})	Reference
Reclaimed minesoil Ohio, USA	Pasture	25	0–30	36.7	1.468	Akala and Lal (2000)
	Forest	25	0–30	37.1	1.484	
Reclaimed minesoil, Ohio, USA	Pasture (with top soil)	0–25	0–15	9.2–55.4	3.1–0.5	Akala and Lal (2001)
			15–30	7.8–37.8	1.9–0.4	
	Forest (with top soil)	0–21	0–15	14–48.4	2.3–07	
			15–30	8.4–14.5	0.4–0.3	
	Pasture (No top soil)	30–40	0–15	60–67	–	
			15-30	34–40		
	Forest (No top soil)	30–50	0–15	50-70	–	
			15–30	27-47		
Reclaimed mine soil, Central Appalachian, USA	Mixed hardwood forest	40	0–10	–	4.0	Burger (2004)
Reclaimed minesoil, Ohio USA	Hardwood forest	–	–	81	–	Jacinthe et al. (2004)
	Grassland			71		
Reclaimed minesoil Appalachian, USA	Pine stands	–	–	11	–	Amichev et al. (2008)
	Hardwood stands			13		
	Mixed stands			17.7		
Reclaimed minesoil, northern Europe (Estonia)	Forest (Scots pine)	14	O- and A-horizon (0.2.8)	0.1 & 0.2	0.33 & 0.51	Karu et al. (2009)
		21		4.6 & 0.4		
		36		12.3 & 19.0		
Reclaimed mine soils, Poland	Scots pine (*Pinus sylvestris*)	12–30	–	0.73[a]	1.45	Pietrzykowski and Krzaklewski (2010)
				2.17[b]		
				5.26[c]		
Reclaimed minesoil of Ohio, USA	Forest	25	0–15	38	1.52	Shrestha and Lal (2010)
	Pasture	25	0–15	35	1.4	
Reforested coal mine sites, Appalachian, USA	Mixed plantation[1]	5	–	7.02	–	Avera et al. (2015)
		11		13.52		
		21		21.35		
		30		16.62		
		Unmined		42.85		
Central Himalayan Tarai, India	*D. sissoo* monoculture plantation	10	0–30	36.3	–	Kanime et al. (2013)
Temperate forests Kashmir, India	Broad leaved species and conifers	Natural forest	0–30	39.1–91.4	–	Dar and Sundarapandian (2015)
Revegetated coal mines, Singrauli, India	Afforest site	19	0–30	22.9	1.20	Tripathi et al. (2014)
Reclaimed coalmine, site, Jharia coalfields	Afforest site	4	0–15	16.33 ± 1.04 (14.96–17.25)	4.08	Present study
	Forest (reference)	–	0–15	35.5 ± 5.8 (30.4–42.5)		

[a] Poorest sandy soils

[b] Sandy-clayish soils

[c] Carboniferous substrate soils

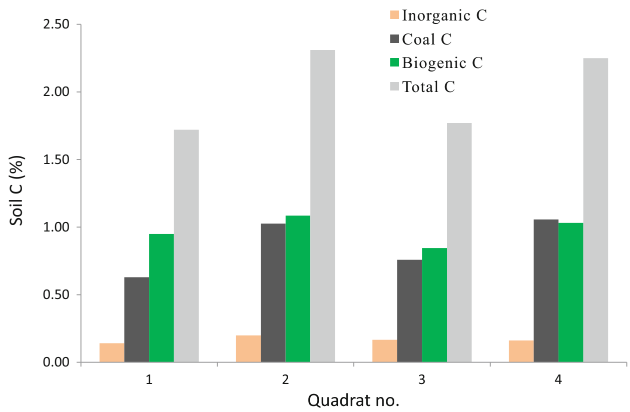

Fig. 11 Distribution of total carbon (%), inorganic carbon (%), coal carbon (%) and biogenic carbon (%) of different reclaimed mine soil samples

spp) was derived from decomposing plant material. Ussiri and Lal (2008) determined the coal C content of RMS restored with topsoil application using radiocarbon analysis and chemi-thermal method, observed that coal C accounted for 2 % to 40 % of the total OC in the top 30 cm soil layer, while in the subsoil (below 30 cm depth) coal C accounted up to 92 % of the total organic C. Overall, the reviewed data suggests that the distribution of coal C in coal-contaminated RMS can be highly variable; therefore, intensive sampling is necessary in order to obtain adequate measure of SOC in restored ecosystems (Ussiri et al. 2014).

3.7 Total C stock in reclaimed site and CO_2 sequestration

Total C stock of the study area was calculated 30.3 Mg C ha^{-1}.equivalent to 111 Mg CO_2 sequestered ha^{-1}. Total C stock in biomass, understorey vegetation and litter and mine soil is given in Fig. 12. In reference forest site, total C stock was estimated as 103 Mg C ha^{-1}, which is higher than RMS. More than 98 % of C-stock contributed by biomass and soil organic carbon in reference forest site, which is also similar to the RMS. Differences in C stock between RMS and reference forest site attributed to the biomass C stock. Tripathi et al. (2014) reported total C sequestration potential of 69.21 Mg C ha^{-1} in 19 years old RMS of Singrauli, India, (equivalent to 253.96 Mg ha^{-1} capture of atmospheric CO_2 and C sequestration rate of 3.64 Mg ha^{-1} year$^{-1)}$ which indicates that mine spoil can act as a significant sink for atmospheric CO_2 through revegetation. Amichev et al. (2008) estimated total C sequestration (all ecosystem components of RMS of Midwestern and Appalachian coalfields of USA) in pine, hardwood and mixed stands as 148, 117 and 130 Mg C ha^{-1} respectively. Another study by Shrestha and Lal (2010) reported total ecosystem C sequestration potential and average rate of RMS (Ohio USA, 25 years age) as 107 Mg ha^{-1} (5.1 Mg ha^{-1} year^{-1}) and 21 Mg ha^{-1} (1.0 Mg ha^{-1} year^{-1}) in forest and pasture ecosystems respectively.

3.8 Future projection of C stock

Climate, soil conditions and species composition have major influence on accretion of C stock in reclaimed mine soil. Similarly, the rate of C stock accretion for a particular site depends on site characteristics (texture, soil fraction, water holding capacity, bulk density, soil fertility), prevailing climatic conditions and types of species. Vogt et al. (1995) reported 40 %–62 % of total ecosystem C contained in living biomass, and SOM contained 33 %–50 % of the total. Rate of accumulation of total biomass C stock was found 3.25 Mg C ha^{-1} year^{-1}, which is close to the study of Shrestha and Lal (2010) and Singh et al. (2011) and it will take about 17 years to reach the level of C stock of reference forest site (Table 9). Most noticeable amount of tree C increased from 5-year stands (0.3 Mg C ha^{-1}) to 11-year stands (53.8 Mg C ha^{-1}) (Avera et al. 2015) and decreases gradually. The present rate of accumulation is

Table 8 Contribution of coal C (geogenic C) in total organic carbon (TOC) in the reclaimed coalmine soils

Post land use (age)	Age (yrs)	Depth (cm)	Coal C (g/kg)	Coal C (% of TOC)	Reference
Red Oak	30	–	37–56	25–96	Rumpel et al. (1998, 2000)
Old Pine	15–36	(O-horizon)	8–71	79–91	Rumpel et al. (2003)
Grassland	28	–	0–24.4	0–92	Ussiri and Lal (2008)
Reclaimed coal mines	0–22	0–6	0.6–1.76	2.5–14	Chaudhuri et al. (2013)
Reforested coalmine site	10	0–10	35.97	47.4	Das and Maiti (2016)
Unreclaimed (Reference site)	10	10–20	14.4	24.2	
		0–10	36.60	68.5	
		10–20	19.15	55.9	
Reclaimed coal mines	4	0–10	8.7	43	Present study

Table 9 Prediction recovery of C stock (biomass and minesoil) in reclaimed minesoil to reference forest site

Study site	Total biomass C accumulation rate (Mg C ha^{-1} $year^{-1}$)	Predicted year	SOC accumulation rate in reclaimed mine soil (Mg C ha^{-1} $year^{-1}$)	Predicted year	Reference
Reclaimed coal mine, Singrauli, India	1.658 (0.87–2.34)	32	1.20	16	Tripathi et al. (2014; 2016)
Reforested coal mine, USA	2.5875 (0.50–5.04)	20.5	1.05	18.3	Avera et al. (2015)
Reclaimed minesoil (forest), USA	3.365	15.8	1.52	12.6	Shrestha and Lal (2010)
Reclaimed mine soil, Poland	–	–	1.45	13.2	Pietrzykowski and Krzaklewski (2010)
Reclaimed coal mine, Singrauli, India	3.7075 (2.18–5.65)	14.32	–	–	Singh et al. (2004)
Reclaimed minesoil (forest), Ohio USA	–	–	1.484	13	Akala and Lal (2000)
Reclaimed coal mine, Jharia coalfields, India	3.25	16.4	4.08[a] 1.305[b]	5[a] 15	Present study

[a] Rate of SOC accumulation initially calculated is very high, but with time, SOC accumulation going to be decreased and reported in the range of 1.305 (1.05–1.52) Mg C ha^{-1} $year^{-1}$

[b] Assumed average rate

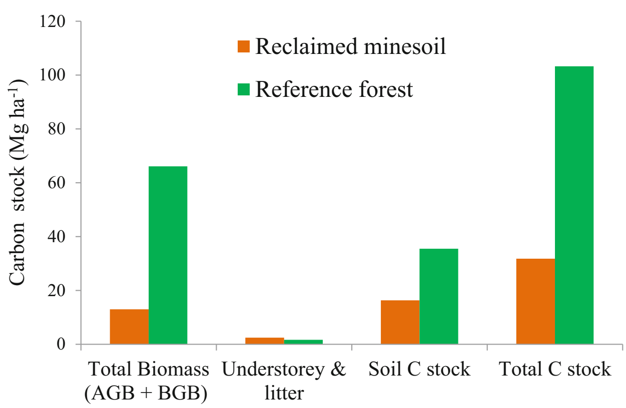

Fig. 12 Comparison of distribution of C stock (Mg ha-1) in various components of reclaimed coalmine site and reference forest site

much higher than the reported values of 1.658 Mg C ha^{-1} $year^{-1}$ (Singrauli, Tripathi et al. 2014, 2016), which is due to the younger age of site, however, it is expected that, rate of accumulation will decrease with age. Based on rate of SOC accumulation rate, C stock of RMS will reach close to the level of reference forest site is predicted as 15 years.

Alka and Lal (2001) stated that SOC increased rapidly over the first 20 years following reclamation and then accumulated at lower rates between 20 and 30 years. Based on 0–25 year reclaimed sites chronosequence data, Akla and Lal (2000, 2001) predicted that, it may take 100–150 years for SOC stock to reach an equilibrium state in RMS. The accumulation of C stock will also increase in biomass and minesoil components, with the gradual increase in age of reclamation and this accumulation of C stock is expected to increase highest in the biomass component. Avera et al. (2015), while studying the chronosequence reforested surface-mined lands in the Central Appalachian Coal Basin (USA) reported that, total ecosystem C increased from 9.5 Mg C ha^{-1} in the 5-year stands to 83.5 Mg C ha^{-1} in the 30-year stands and after 30 years, reforested surface-mined lands contains 47 % of the total C of the unmined ecosystem C (179 Mg C ha^{-1}). Aboveground tree C was the greatest proportion of ecosystem C, accounting for an average of 73 % of the total ecosystem C. SOC content tripled from the 5-year to the 11-year stands, with the most rapid SOC sequestration rate of 0.7 ± 0.1 Mg SOC ha^{-1} $year^{-1}$ measured in the 11-year stands. Amichev et al. (2008) reported similar results of at least 75 % of total ecosystem C contributed by aboveground tree C on reforested mined land.

Reclamation by development of 3-tier canopy over is better alternative than simple plantation, because it leads to reinstatement of ecosystem in the degraded site. It not only stabilizes and minimizes pollution but also act as potential sink of CO_2. Thus, reclaimed coalmine sites can be a viable alternative to sequester carbon both in soil and vegetation and can be useful for combating climate change and global warming issues. The widespread problem of land degradation and soil erosion is growing at an exponential rate due to opencast mining activities in agriculture based countries like India, where resources are limited. Concurrently, reclamation of those sites through forestry development approach is a common practice. Interpretation of carbon sequestration will be worthwhile since they can be used to create carbon credits which can be generate significant source of income to fulfill the demands of ever increasing pressure of population.

4 Conclusions

Reclamation process is an integral part of mining operation aimed to stabilize mine degraded sites which resulted carbon sequestration. C stock in reclaimed mine soil is dependent on the nature and type of soil and vegetation; age and geo-climatic conditions. Out of total C stock was 30.3 Mg C ha^{-1}, 43 % is stored in biomass and 53 % as soil organic matter. Coal C contributes a significant amount of organic carbon in reclaimed mine soils, and for better assessment of C stock, fractionation study is recommended. Limited field studies data is available on accretion of C stock in reclaimed minesoil in Indian conditions (only Singrauli and Jharia coalfields) along with very little work of USA and European conditions. Based on the present study, the C stock will tentatively reach similar to the reference forest site in 17 years, as the rate of carbon accumulation decreases with age. As species composition, climate conditions and nature of mine soils is site specific, this study will a guidelines for a specific geo-climatic conditions.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest in any concern or context in the present study.

Ethical standards All the experiments are conducted in this study following local, national or international guidelines and comply with the current laws of the country, India. No permission or license was required for the study.

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