Catena 141 (2016) 100–108

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Rhizosphere soil indicators for carbon sequestration in a reclaimed coal mine spoil

Sangeeta Mukhopadhyay [a], Reginald E. Masto [a,*], Artemi Cerdà [b], Lal C. Ram [a]

[a] Environmental Management Division, CSIR–Central Institute of Mining and Fuel Research, Digwadih Campus, Dhanbad 828108, India
[b] Departament de Geografia, Universitat de València, Blasco Ibàñez, 28, Valencia 46010, Spain

ARTICLE INFO

Article history:
Received 22 August 2015
Received in revised form 8 January 2016
Accepted 26 February 2016
Available online 10 March 2016

Keywords:
Coal mine spoil
Tree species
Carbon sequestration
Microbial biomass
Carbon accumulation index

ABSTRACT

Re-vegetation of mine spoil enhances carbon storage in both above-ground plant biomass and mine soil. The current study was conducted at the coalmine overburden dumps of Jharia Coalfield (India), with the aim to evaluate the effect of different tree species on the rhizosphere soil properties and to identify key rhizosphere soil indicators that influence tree biomass and carbon density. Rhizosphere soil samples were collected from five tree species (*Acacia auriculiformis*, *Albizia lebbeck*, *Cassia siamea*, *Delonix regia*, and *Dalbergia sissoo*) of the same age. An area without ground vegetation was selected as a non-rhizosphere soil. The carbon density was higher for *D. sissoo* and *A. auriculiformis* (39.6–43.7 kg C/tree) and lowest for *A. lebbeck* (20.7 kg C/tree). Except for *C. siamea* (4.38%), the total C (TC) content was lower in the rhizosphere than the non-rhizosphere soil. About 50% reduction in TC was observed for *A. auriculiformis* and *A. lebbeck* and 75% for *D. sissoo*. Labile C and microbial biomass carbon (MBC) were significantly higher in the rhizosphere than the non-rhizosphere soil. Dehydrogenase enzyme activity was higher in all the rhizosphere soils with the maximum activity under *C. siamea* (88.48 μg/TPF/g/24 h) and *D. sissoo* (71.95 μg/TPF/g/24 h). Three types of carbon accumulation indices (CAI) were calculated: CAI-1, based on TC and labile C; CAI-2, TC, and MBC; and CAI-3, TC, labile C, and MBC. CAIs depending on rhizosphere effect were generally higher for *D. sissoo* and *C. siamea*. Principal component analysis showed that the tree carbon density is closely associated with CAI-3, CAI-2, carbon lability index (CLI), available N, and MBC. Thus, an integrated rhizosphere carbon accumulation index (CAI-3, based on rhizosphere effects) and N could be considered as indicators for carbon sequestration in reclaimed mine spoils.

1. Introduction

Globally, two-thirds of terrestrial carbon is stored as organic matter in soils (Köchy et al., 2015; Prescott, 2008). The amount of carbon stored in global soils is higher than the global carbon stored in biomass and the atmosphere (Scharlemann et al., 2014). Carbon contribution by terrestrial plants into the soil is the primary source of soil organic matter. About one-third to half of total plant C is allocated belowground (Whipps, 1990). Subsequently, 15–25% of belowground C is extruded from roots into the soil, which enhances microbial density and results in fast C turnover in the vicinity of the roots (Kuzyakov, 2002). However, this may be less in case of the trees as the stem is the major sink for C in trees, and a major portion also goes to leaves (Kuzyakov and Domanski, 2000). Thus, tree litter could be the major source for belowground carbon in reclaimed mine spoil (Brevik, 2013). Further, the rhizosphere influences the above-ground performance of the tree species in mine spoils (Sinha et al., 2009). These rhizosphere processes initiate nutrient cycling in soils; this is especially true for initially forming soils and highly practical for the reclaimed coal mine spoils, where the planted tree species and the natural vegetation trigger soil nutrient cycling (Thomas et al., 2015). A favorable root-soil interaction may result in sustained survival of the planted tree species in the mine spoils and enhance carbon sequestration. Biomass production and C accumulation are strongly related (Filcheva et al., 2000; Jagodziński and Kałucka, 2010; Poorter et al., 2012; Uri et al., 2014). The accumulation of carbon in the mine spoil depends on the quality of the litter fall and its mineralization and bioturbation in the mine spoil (Frouz et al., 2013). The importance of rhizosphere processes on global C stocks has recently been emphasized by Finzi et al. (2015) and Smith et al. (2015). In this context, a better understanding of the relationship between rhizosphere parameters and above-ground carbon density of tree species growing in the coal mine spoils is desirable.

Huge quantities of Earth's stored carbon are lost due to coal mining and the debris left after mining possess severe environmental issues. However, the spoils may be reclaimed through selective plantations (Akala and Lal, 2000; Chatterjee et al., 2009; Mukhopadhyay et al., 2013; Shukla and Lal, 2005; Tripathi et al., 2014; Zhao et al., 2013) using a variety of amendments (Dutta et al., 2015; Ram and Masto, 2010; Ram and Masto, 2014). Carbon sequestration in reclaimed mine

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* Corresponding author at: Environmental Management Division, CSIR–Central Institute of Mining and Fuel Research, Digwadih Campus, P.O. FRI, Dhanbad 828108, India.
E-mail addresses: sangeeta.dccs@rediffmail.com (S. Mukhopadhyay), mastocfri@yahoo.com (R.E. Masto).

http://dx.doi.org/10.1016/j.catena.2016.02.023
0341-8162/

soils could partly mitigate C emissions associated with coal mining (Dixon-Coppage et al., 2005; Jacinthe and Lal, 2009). The estimated carbon sequestration potential of one coal mine in India amounts to 3.64 Mg C/ha/year (Tripathi et al., 2014). In US reclaimed coal mines, the C sequestration potential ranged from 0.1 to 3.1 Mg/ha/year and from 0.7 to 4 Mg/ha/year in grass and forest ecosystems, respectively (Shrestha and Lal, 2006).

For the targeted use of tree species to sequester soil C, identifying the specific soil–plant processes related to C accumulation is a must (Vesterdal et al., 2013). In a chronosequence study, the rate of carbon storage in mine spoils decreased with age of the spoil (Bartuska and Frouz, 2015). A life cycle assessment with carbon in reclaimed mine spoil showed that conversion of cool-season forage grasses to tallgrass prairie resulted in a significant net sink for atmospheric CO_2 (Guzman et al., 2014). As root derived C is stored at deeper layers in the soils, it is protected against mineralization and contribute significantly to the soil C storage (Tefs and Gleixner, 2012). Garcia et al. (2005) found that *Stipa tenacissima*, *Retama sphaerocarpa*, and *Rhamnus lycioides* had higher rhizosphere soil C and these species had increased plant biomass and root elongation and hence were suitable for soil restoration. Rhizosphere microbial activity has been reported to be different among plant species and differences in root exudation among species are assumed to be the major reason (Van der Krift et al., 2001; Warembourg et al., 2003). The colonization pattern of tree species on mine spoil is affected by fine-scale variations in abiotic factors, such as pH, P, light, K, N, C/N, organic matter, and soil moisture (Milder et al., 2013). Recent research on carbon fluxes in the rhizosphere is mostly restricted to field crops (Cheng and Gershenson, 2007). Mukhopadhyay and Maiti (2014) found that the CO_2 flux from reclaimed mine spoil was about 50% less than in natural grass land. Information on the rhizosphere processes of tree species and their affect on organic carbon stocks of mine spoil is limited. Below ground carbon fluxes in the rhizosphere significantly influence above-ground tree growth. Increase in belowground carbon allocation of tree species is correlated significantly with aboveground tree growth (Raich et al., 2014). It is important to establish desirable vegetation and preserve soil aggregates to improve long-term nutrient supply, physical soil properties, and C-sequestration in reclaimed soils (Wick et al., 2014).

Different carbon indices have been used to assess C accumulation in the soils (Blair et al., 1995; Guimarães et al., 2014; Silva et al., 2014). The original carbon management index developed by Blair et al. (1995) is based on total and labile C. In the present study, we explored the 'rhizosphere effects' to develop a sensitive C index and to identify the key rhizosphere soil parameters influencing tree biomass and carbon density.

2. Materials and methods

2.1. Study site

The study was carried out in the reclaimed coalmine overburden (OB) dumps of Chandan opencast project (N 23°40′, E 86°24′), Jharia Coalfields (JCF) operated by Bharat Coking Coal Limited (BCCL), Dhanbad, Jharkhand, India. The experimental area is characterized as tropical with a mean annual precipitation of about 1598 mm, most of the rain falling between June and October. The relative humidity during monsoon (July–September) varies between 60% and 100%, while in relatively warmer periods (April–June), it decreases to as low as 20–25%. The summer and winter average temperatures are 44.5 °C and 20 °C, respectively. The annual average temperature ranges from 25 to 30 °C. The elevation of the area is 227 m above mean sea level. In JCF, severe land degradation has been caused by opencast mining methods resulting in huge OB dumps and deep voids. The mining is generally carried out by shovel–dumper combination. The average height of dumps is 20–30 m with a quarry depth of approximately 40–50 m.

Multipurpose, fast growing, leguminous hardy tree species (*Acacia auriculiformis*, *Albizia lebbeck*, *Cassia siamea*, *Delonix regia*, and *Dalbergia sissoo*) were found to be growing in the reclaimed mine spoil with sparse ground vegetation. The total study area was approximately 4 ha, and the total tree density was 319 trees/ha. The mine soil was a huge heap of large boulders and loose rocky materials; wherever possible, proper leveling and dozing were done and fenced with barbed wire in order to prevent the entry of cattle/animals. Pits (size: 60 × 60 × 60 cm) were made during the onset of monsoon in July 2000. Different amendments were added to the pits. The amendments include pesticides, good earth and cow dung manure, and NPK fertilizers (40:40:20 g/pit as urea, diammonium phosphate and muriate of potash). One-year-old saplings of selected tree species were planted in the pits.

2.2. Estimation of tree carbon density

All individual trees having a circumference at breast height (1.37 m) (CBH) ≥ 30 cm, or diameter at breast height (DBH) ≥ 9.5 cm, were counted and measured. Heights of these trees were measured by a hypsometer (Nikon Forestry Pro, Japan). Wood samples for the estimation of specific gravity were collected at 1.3 m height using a stem borer. The volume of fresh wood samples was measured by the water displacement method, and the samples were dried at 80 °C until a constant weight was achieved (Chaturvedi, 2010).

Stem biomass (kg) was obtained using the equation given by (King et al., 2006; Singh et al., 2014):

$$\text{Stem biomass} = 0.5 \times (\pi) \times \text{WSG} \times (\text{DBH})^2 \times \text{H} \times 0.025 \tag{1}$$

where 0.5 is the form factor, defined as the ratio of stem volume to the volume of a cylinder; H is height (m); DBH is the diameter at breast height (cm); and WSG is the wood-specific gravity (g/cm^3) (Chaturvedi et al., 2011).

Carbon density was calculated for each tree by assuming that the carbon content of the biomass was 50% (Dixon et al., 1994; Schroeder, 1992). Direct estimation of root biomass is difficult because of the problems in sampling woody roots of trees. However, the growth of structural roots depends on the above-ground biomass. The below-ground biomass was calculated by assuming that root biomass was 25% (for hardwood species) of the total above-ground biomass ((Fonseca et al., 2011); IPCC (2006)). Although there are limitations of using a constant factor for calculation of root biomass (Brown et al., 1989; Cairns et al., 1997; Vitousek and Sanford, 1986), 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; Gerhardt and Fredriksson, 1995). The use of constant factor may over/under estimate the total C stock (Cairns et al., 1997); however, in the present study, our interest for tree carbon data is to correlate it with soil data for indicator development.

2.3. Soil sampling and analyses

Rhizosphere soil samples from different tree species were collected from the reclaimed coalmine OB dumps of Chandan OCP, JCF. Sampling was carried out during November–December 2013. The soil strongly adhering to roots and within the space explored by roots was considered as rhizosphere soil (Garcia et al., 2005). The reclaimed site was dominated by an evenly distributed mixed plantation of five tree species. Ten random samples were collected from the rhizosphere of each tree species. Non-rhizosphere soil samples were collected from ten different spots free from ground vegetation. The non-rhizosphere soil samples were collected in such a way that it represents the entire mine spoil unaffected by reclamation. For analysis of soil biological properties, field moist soil samples were taken in ice boxes, transported to the laboratory and stored at 4 °C until their analysis. For other physical and chemical analyses, a portion of the sample was air dried at room