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Development of mine soil quality index (MSQI) for evaluation of reclamation success: A chronosequence study

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ABSTRACT

Assessment of mine soil quality is the key parameter for evaluation of reclamation success. To investigate the effect of vegetation on mine soil development and reclamation, chronosequence sites were selected in a large opencast coal project in North Karanpura Area, Central Coalfield Limited (CCL), India. The physico-chemical and biological characteristics of chronosequence sites were compared with reference forest site. Principal component analysis (PCA) was employed to derive a mine soil quality index (MSQI) which was used for assessing the progress of reclamation. Soil organic carbon, soil CO_2 flux, dehydrogenase activity, coarse soil fraction, moisture content and base saturation are the most critical properties controlling health of reclaimed coal mine soil. The observed values of the above soil indicator parameters were converted into a unitless score (0–1.00) and the scores were integrated into MSQI. The MSQI values were validated by regression analysis with the plant growth parameters (aerial height, diameter at breast height and canopy cover). The contribution of each soil indicator parameter on calculated MSQI was analysed, which gives an insight into the cause for the measured MSQI. The calculated MSQI varied from 0.220 in 2 years old reclaimed dump to 0.670 in 17 years old reclaimed dump. More the MSQI value better is the reclamation status of the mine soil. Mine soil with MSQI > 0.500 may be considered as ecologically sustainable or reclamation is satisfactory. Age of reclamation has been found to have a significant effect on the nutritional and microbial properties of the mine soils. Progressive build up of adequate nutrient pool in 17 year site may be sufficient for ecosystem maintenance in this region.

1. Introduction

Globally, surface mining destroys the landscape and aesthetics by creation of huge overburden dumps and voids. These overburden material mostly consists of large boulders and loose rocks fragments, devoid of organic matter and nutrients which are left unmanaged and creates environmental pollution, commonly known as "mine spoil". Once the mine spoils are physically reclaimed and utilized to support plant growth (either with or without topsoil), they are considered to be "mine soils" (Sencindiver and Ammons, 2000; Shrestha and Lal, 2011). The properties of these mine spoils are directly controlled by the physical and geochemical properties of the rock strata from which they are derived. Mine soils are pedogenically young soils that are developing from mixtures of fragmented and pulverized rock material (i.e., anthropogenic soil). During reclamation development of mine soil process is accelerated by addition of topsoil, amendment, afforestation or plantation. In course of time natural succession also accelerates the soil forming process. This soil development process can be studied by considering reclaimed mine soil chronosequence sites. Chronosequence based approaches are useful ways of assessing rates and direction of changes in various pedological characteristics (Brentley, 2008; Chaudhuri et al., 2013).

Soil quality assessment of chronosequence sites is important to estimate the reclamation time. To evaluate the progress and success of reclamation of the mine soils, identification of soil quality indicators are essential which will be used to determine quantitatively the health of the reclaimed mine soils. Based on 'soil quality indicator parameters' an integrated 'mine soil quality index'

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could be developed to ascertain the stage of recovery of ecosystem and mine soil characteristics. In management perspective mine owners/stakeholders always desire to know the health of reclaimed area and time required for the development of self-sustaining forest cover. Therefore, it is essential to monitor the physico-chemical and biological characteristics of chronosequence mine soil sites, which will help to understand the progress of mine soil development.

Many authors have attempted to develop soil quality indicators by measuring various soil characteristics and relating these two different management practices, productivity, or environmental quality. Arshad and Martin (2002) have suggested several indicators for assessing soil quality, namely organic matter, topsoil depth, infiltration, aggregation, pH, electrical conductivity, suspected pollutants, and soil respiration. Dickinson et al. (2005) proposed biological descriptors of soil health for use in reclamation of Brownfield land in U.K. They emphasized that assessment of soil health can be based on measures of biodiversity or functional processes. Růžek et al. (2001) reported that although there were clear relationships between age of restoration and increase in soil microbial biomass; distinctly different algorithms had to be developed for reclaimed sites in the Czech Republic and Germany because both organic matter content and the textural characteristics are different at the initial stage of reclamation. Chronosequence study carried out by Šourková et al. (2005) in 5 reclaimed sites ranging from 8 to 40 year old in the lignite mine spoil (Germany and Czech Republic) showed that vegetation type and litter quality have greater importance for development of soil microbial activity than the substrate quality. Chodak and Niklinska (2010) emphasized that establishment of microbial community is essential for successful reclamation of post-mining degraded land.

Soil enzymes respond to changes in soil management more quickly than other variables and therefore may be useful as early indicators of biological changes (Bandick and Dick, 1999; Masciandaro et al., 2004). Soil microbial biomass (Carter et al., 1999) is highly responsive to changes in carbon inputs to the soil and can provide a measurable change before any such change in the total soil organic matter. The microbial biomass can provide one of the most satisfactory estimates of the restoration of soil microbial populations; it provides a measure of organic matter dynamics. Important microbial properties such as increase in soil microbial biomass carbon (MBC), mycorrhizal association and soil respiration are used as indicator parameters to assess the health of reclaimed land (Brookes, 1995).

Though there are specific indicators, many authors (Nannipieri et al., 2002) have proposed the combined use of a number of parameters as early indicators of stress or soil restoration. According to Gil-Sotres et al. (2005) soil indicators can be used both individually, as simple indices, or as an integrated index of these indicators. Integrated indices are thought to be highly suitable for estimating soil quality, although their use is limited to the area and situation in which they have been described. Integrated soil quality indices based on a combination of mine soil properties provide a better indication of reclamation status of coalmine degraded land than individual properties. Moreover an integrated index is essential for quantitative comparison of soil from different aged reclaimed dumps. A number of soil quality and fertility indices have been proposed (Karlen et al., 1997; Trasar-Cepeda et al., 1998; Andrews et al., 2002; Velasquez et al., 2007; Rossi et al., 2009); but only few have addressed on mine soil (Sinha et al., 2009; Asensio et al., 2013; Mukhopadhyay et al., 2013; Zhao et al., 2013). Very little attempt has been taken regarding soil quality indicator studies in a chronosequence of reclaimed coal mine soil. Thus the objective of this study is to assess the status of reclamation with time by identifying key soil quality indicators and to develop a mine soil quality index (MSQI).

2. Materials and methods

2.1. Study area

This study was conducted at the reclaimed mine soil chronosequence sites of North Karanpura Area (NK Area), Central Coalfield Limited (CCL), India, (latitudes 23°39′53″–23°42′30″N and longitudes 84°59′15″–85°0′3″E). The general topography of this area is characterized by flat terrain with gentle undulation having maximum elevation of 467 m above mean sea level. The average annual rainfall is around 1100 mm to 1600 mm with a maximum monthly rainfall of 545 mm, 89% precipitation occurs during rainy season (July-October). The climate is tropical with summer (March–May) temperature as high as 45 °C. The minimum winter (November–February) temperature is around 1 °C.

To assess the changes in mine soil properties due to tree plantation, the present study was conducted at different aged (2, 5, 7, and 17 years) reclaimed mine sites. These sites were selected according to their availability. An adjoining undisturbed natural sal (*Shorea robusta*) forest area and a fresh un-reclaimed overburden were selected as reference sites.

2.2. Vegetation

The plantations were raised on overburden dumps because natural colonization is very slow. Six month old nursery raised seedlings of different tree species were used for plantation by the Mander Social Forestry Division, Ranchi in previously dug pits (40 cm^3) at a spacing of 2 m × 2 m during the onset of monsoon. During pit plantation, no fertiliser or external topsoil was added; however watering was done manually in the summer months for the first year. Approximately 20 different tree species were planted during reclamation. At the time of sampling (2010), along with the planted tree species, natural colonisation of *Lantana camara*, *Leonotis nepetifolia*, *Eupatorium odoratum*, *Hyptis suavelons*, *Pennisetum pedicellatum*, *Saccharum spontaneum* and *Zizyphus jujube* were observed.

The reference site was a natural forest, which is mixed dry deciduous type, dominated by Shorea robusta (sal tree), along with *Terminalia tomentosa*, *Butea monosperma*, *Dalbergia sisoo*, *Madhuca indica*, *Terminalia arjuna*, *Pongamia pinnata*, and *Azadirachta indica*. Ground vegetation consists of sapling of *S. robusta*, and other shrubs (*L. camara*, *E. odoratum*, *Leonotis neptifolia*) and herbaceous plants (*Xanthium strumarium*, *S. spontaneum*, *Tridex procumbence* and *Evolvulus* sp).

In each site, six quadrates of 10 m × 10 m area were laid and average number of trees of a particular species, in each quadrate was recorded. The relative density (RD) of each tree species was calculated using the following formula:

$$\text{Relative density}\,(\%) = \frac{\text{no. of individuals of particular species}}{\text{no. of individuals of all species}} \times 100$$

Relative density (RD) of tree species growing in the reclaimed mine soil chronosequence sites is shown in Fig. 1, except for the 17 years old site which was reclaimed by *Cassia siamea* plantation only. In all the other three sites (2, 5 and 7 years), maximum RD was observed for *D. sissoo* (38–52%). The girth of each tree species was measured at the height of 1.37 m above the ground level (i.e., diameter at breast height, DBH). All trees in the 100 m^2 plot were recorded and their canopy covers measured by the line intercept method (Johnson and Skousen, 1995). Canopy cover for each species was recorded in cm/1000 cm and summed to determine total canopy cover. These totals were normalized between 0 to 100%. A value of 0% indicates no canopy cover, 100% reflects

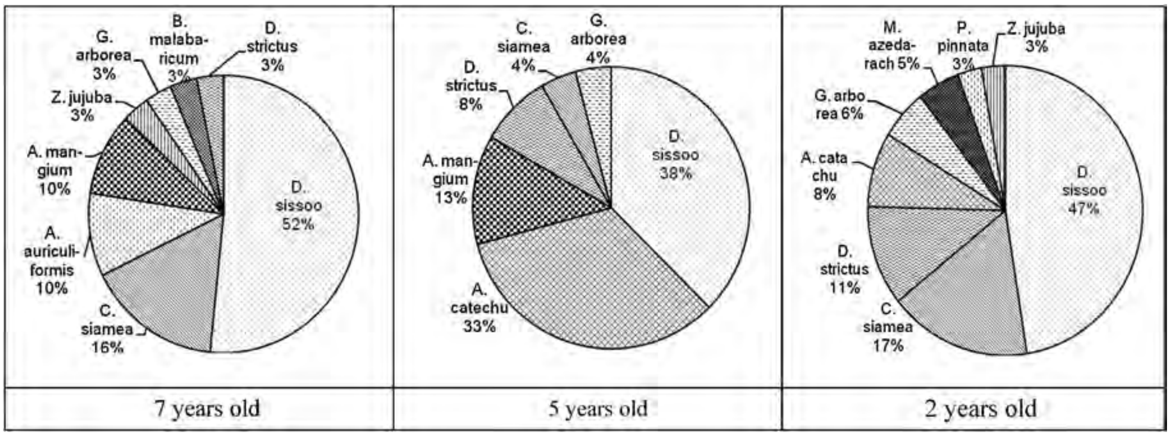

Fig. 1. Tree species growing in the reclaimed mine soil chronosequence sites along with relative density (17 years old site has only *Cassia siamea*, as it was a mono-species plantation).

complete canopy cover, and values >100% signifies an overlapping canopy.

2.3. Collection and analyzes of mine soil samples

At each site, six quadrates (10 m × 10 m) were laid down, and from each quadrate 5 mine soil samples were collected (0–10 cm depth) and mixed thoroughly and reduced the weight approximately to 0.5 kg by conning-quartering method to yield one composite sample per quadrate. Therefore six composite samples were collected from each site. Similar sampling procedure also followed for the collection of soil samples from natural sal forest. After collection, the samples were air dried at room temperature (30–35 °C) and lightly crushed with a mortar and pestle, and passed through a 2 mm sieve. For analysis of soil biological properties, field moist soil samples were taken in ice boxes, transported to laboratory and stored at +4 °C till their analysis. The physico-chemical and biological properties of the samples were analyzed as per standard procedures (Table 1).

2.4. Mine soil quality index (MSQI)

The method described by Bastida et al. (2006), Masto et al. (2008), Sinha et al. (2009), Mukhopadhyay et al. (2013) was followed to develop mine soil quality index (MSQI). PCA was used to select the appropriate properties and their weighing factors. Principal components (PCs) with eigen value ≥1 (Kaiser, 1960) and explained at least 5% of the variation of the data were examined (Wander and Bollero, 1999). Under a particular principal component (PC), only the variables with high factor loadings were retained for indexing. High factor loadings were defined as having absolute values within 10% of the highest factor loading (Andrews et al., 2002). When more than one variable are retained under a single PC, correlation was employed to determine if the variables could be considered as redundant and, therefore eliminated from the MSQI (Masto et al., 2008). If the highly loaded factors were not correlated then each was considered important, and thus, retained in the MSQI. Among well-correlated variables, the variable with the highest factor loading (absolute value) was chosen for the MSQI. The final PCA based MSQI equation is as follows:

$$\mathrm{MSQI} = \sum_{i=1}^{n} W_i S_i \tag{1}$$

where, W is the PC weighting factor, S is the indicator score for each variable.

To convert the real values of mine soil parameters into scores (S), the following equation was used that defined a sigmoidal type (Bastida et al., 2006; Masto et al., 2008), with an asymptote tending to 1 and another tending to 0.

$$S = \frac{a}{\left[1 + \left(x/x_0\right)^b\right]} \tag{2}$$

where x is the soil parameters value, a is the maximum score (=1.00) of the soil property, x_0 is the mean value of each parameter corresponding to the different aged reclaimed coalmine dump, b is the value of the slope of the equation. The slope was −2.5 for the 'more is better curve' and 2.5 for the 'less is better curve' to obtain a sigmoidal curve tending to 1 for all the proposed properties.

After calculating the S values for all the indicator parameters, each property was weighted using the PCA results. Each PC explained a certain amount (%) of the variation in the total data set. This percentage, when divided by the total percentage of variation explained by all the PCs with eigen values >1.0, provided the weighting factor (W) for the variables chosen under a given PC. Having determined the values of S and W, the MSQI for each site was then calculated using Eq. (1). Higher index scores mean better mine soil quality or superior performance of soil functions. To validate the MSQI, the observed MSQI values were regressed with end point variable like canopy cover, DBH and height of tree species (Mukhopadhyay et al., 2013).

2.5. Statistical analysis

One-way ANOVA (analysis of variance) was carried out to compare the means of soil characteristics with respect to reclaimed mine soil chronosequence sites. Differences between individual means were tested using DMRT (Duncan's multiple range test), at $P < 0.05$ significance level. For PCA, regression equations and scoring functions; Microsoft Excel and SPSS Statistics 20.0 (South Asia Private Limited) were used.

3. Results and discussion

3.1. Soil physico-chemical characteristics

Soil physical properties varied considerably between reclaimed mine soil chronosequence sites. The characteristics of mine soils under different aged plantations were compared with fresh mine spoils and reference forest soil adjacent to the study area (Table 2). Highest coarse fraction (>2 mm size) was found in fresh mine spoils

Table 1
Standard procedures followed for analysis of physico-chemical and biological parameters of mine soils.

Soil quality parameters	Analytical procedures	Apparatus used	Reference
(a) Physical parameters			
Coarse fraction	Sieving method	Sieves of different sized mesh	Gee and Bauder (1986)
Texture analysis	International pipette method	–	Gee and Bauder (1986)
Bulk density	Soil core method	Soil sampling tube	Sobek et al. (1978)
Porosity	Determined from bulk density with an assumed particle density of 2.65 $Mg\,m^{-3}$	–	Sobek et al. (1978)
Moisture content	Gravimetric method	Hot air oven	Dakshinamurthi and Gupta (1968)
(b) Chemical parameters			
pH	Soil:water suspension (1:1 w/v)	pH meter (Cyberscan 510, Merck)	Thomas (1996)
Electrical conductivity (EC)	Soil:water suspension (1:1, w/v)	Digital conductivity meter 611 (EI)	McLean (1982)
Organic carbon	Rapid dichromate oxidation technique	-	Nelson and Sommers (1996)
Available N	Alkali-permanganate method	Kjeldahl assembly	Subbiah and Asija (1956)
Available P	Bray's method for acidic soils and Olsen's method for neutral and alkaline soils	UV–Visible spectrophotometer (UV-265, Shimadzu)	Bray and Kurtz (1966), Watanabe and Olsen (1965)
Exchangeable Na, K, Ca	1 N ammonium acetate extraction method	Flame photometer (128, Systronics)	Jackson (1973)
Exchangeable Mg	1 N ammonium acetate extraction method	Atomic Absorption Spectrophotometer (Avanta, GBC)	Jackson (1973)
Cation exchange capacity (CEC)	Sodium saturation method	Flame photometer (128, Systronics)	Jackson (1973)
Base saturation	Calculated as the proportion of the CEC occupied by basic cations	–	Thomas (1982)
(c) Biological parameters			
Dehydrogenase activity	2,3,5-triphenyltetra-zolium chloride (TTC) as substrate	UV–Visible spectrophotometer (UV-265, Shimadzu)	Casida et al. (1964)
Soil microbial biomass carbon	Chloroform fumigation and extraction method	Vacuum descicator	Vance et al. (1987)
Soil respiration	Soil CO_2 flux method	Automated Soil CO_2 Flux System (LICOR-8100)	LI-8100, Instruction manual (2007)

(62.2%) and lowest in forest (12.9%), while in reclaimed chronosequence sites it was found between 39% to 47%. The observed data is in agreement with Andrews et al. (1998) and Rodrigue and Burger (2004). In the reclaimed site coarse fraction was <50% indicating a better environment for plant growth as coarse fraction >50% is rated as poor quality of mine soils, which retards plant growth (Hu et al., 1992). Coarse fraction is an important parameter that affects the soil productivity of the coal mined land because excessive amount of coarse fragments limit the fine earth volume available for root proliferation, water-holding capacity, and long-term nutrient availability (Mukhopadhyay et al., 2013; Maiti, 2013). Though many researchers have reported a reduction of coarse fractions with time in surface horizons due to weathering processes (Haering et al., 1993; Johnson and Skousen, 1995; Daniels and Zipper, 1997), no significant difference was observed in the present study probably due to greater site variability and heterogeneous nature of mine soil.

Sand percentage was higher in fresh mine soil (88.6%) compared to other chronosequence sites (67–83%); while silt and clay percentages were higher in reclaimed sites than fresh mine spoil. Highest silt content was found in forest soil. Particle size distribution is a major factor governing successful re-vegetation on

Table 2
Physico-chemical characterization of reclaimed mine soil chronosequence sites, natural sal forest and fresh overburden dumps (values are mean, standard errors are reported in italic, $n = 6$).

Soil quality parameters		Years after reclamation				Natural sal forest	Fresh overburden
		17-year	7-year	5-year	2-year		
Coarse soil fraction (>2 mm) (%)		42.06b[*] *7.77*	46.70b *4.31*	39.36b *3.33*	45.35b *4.39*	12.87c *1.05*	62.17a 3.48
Sand (%)		67.12c *2.13*	73.70c *2.46*	75.68b *2.1*	83.33a *2.46*	74.23bc *1.33*	88.58a 3.09
Silt (%)		18.43a *0.73*	14.18b *0.67*	13.65b *0.83*	9.63c *0.74*	20.34a *0.62*	8.15c *0.69*
Clay (%)		14.45a *0.61*	12.12b *0.72*	10.67b *0.62*	7.10c *0.58*	5.43c *0.42*	3.53d *0.37*
Texture		Sandy loam	Loamy sand	Loamy sand	Loamy sand	Loamy sand	–
Bulk density ($Mg\,m^{-3}$)		1.39ab *0.07*	1.55a *0.06*	1.51a *0.08*	1.56a *0.09*	1.24b *0.01*	–
Porosity (%)		47.40ab *2.73*	41.42b *2.41*	43.11b *5.77*	40.25b *3.32*	53.38a *0.48*	–
pH (1:1; w/v)		5.80ab *0.19*	5.33bc *0.19*	4.91c *0.08*	5.20bc *0.05*	5.90a *0.27*	5.52ab *0.15*
EC ($dS\,m^{-1}$) (1:1; w/v)		0.187b *0.071*	0.179b *0.047*	0.133bc *0.022*	0.115bc *0.028*	0.038c *0.001*	0.39a *0.062*
Organic carbon (%)		2.25a *1.13*	0.98cd *0.02*	1.15c *0.05*	0.31d *0.02*	1.65b *0.02*	–
Available N ($mg\,kg^{-1}$)		135.72a *8.21*	32.46c *5.46*	50.78bc *6.19*	25.89d *5.24*	84.04b *4.37*	–
Available P ($mg\,kg^{-1}$)		13.72a *1.43*	7.69c *0.93*	10.92c *0.98*	3.56d *0.35*	12.70b *0.43*	1.25d *0.14*
Available K ($mg\,kg^{-1}$)		18.40a *4.69*	6.86b *1.57*	3.03c *0.53*	1.11c *0.49*	3.64c *0.25*	17.27a *1.75*
CEC [cmol(+)/kg soil]		21.20a *1.82*	12.2b *0.82*	10.56b *0.96*	6.57cd *0.61*	9.43bc *0.68*	3.53d *0.4*
Exchangeable cations [cmol(+)/kg soil]	Ca	4.23a *1.12*	2.30b *0.21*	0.61c *0.09*	0.43c *0.07*	0.52c *0.1*	1.60bc *0.39*
	Mg	1.63a *0.023*	0.92b *0.018*	0.24d *0.017*	0.22d *0.024*	0.26d *0.011*	0.64c *0.028*
	K	0.52a *0.092*	0.22b *0.029*	0.08c *0.012*	0.03c *0.011*	0.09c *0.006*	0.46a *0.21*
	Na	0.21a *0.006*	0.18a *0.028*	0.18a *0.002*	0.18a *0.002*	0.18a *0.009*	0.22a *0.005*
Base saturation (%)		31.04b *0.58*	29.61b 0.42	10.55c *0.56*	13.16c *0.53*	11.23c *0.43*	82.56a *1.14*

[*] Different letters in the same row indicates significant differences between different sites at $P < 0.05$.

Table 3
Soil CO_2 flux, soil surface CO_2 conc., soil temperature, moisture and relative humidity in the reclaimed mine soil chronosequence sites and natural sal forest (values are mean ± standard deviation (min–max), $n = 6$).

Site	Soil CO_2 flux (μmol CO_2 m^{-2} s^{-1})	Soil surface CO_2 conc. (ppm)	Soil temperature (°C)	Soil moisture (%)	Relative humidity (%)
17-yr old	5.41 ± 1.22a* (4.23–7.50)	491 ± 33.02 (455–559)	36.44 ± 2.75 (34.08–39.75)	5.79 ± 0.98 (4.89–7.59)	62.80 ± 1.94 (60.12–64.88)
7-yr old	3.05 ± 0.83b (2.19–4.91)	472 ± 31.91 (443–531)	31.11 ± 1.43 (29.29–32.91)	4.45 ± 1.40 (2.56–5.93)	52.69 ± 0.76 (51.93–53.70)
5-yr old	3.14 ± 0.39b (2.82–3.79)	416 ± 1.84 (414–418)	36.78 ± 2.51 (34.56–38.79)	4.96 ± 1.09 (3.88–7.53)	47.46 ± 10.88 (32.28–61.22)
2-yr old	2.47 ± 0.23c (2.12–2.82)	401 ± 29.21 (357–462)	36.12 ± 2.33 (34.52–38.31)	5.16 ± 1.03 (4.04–6.82)	48.34 ± 5.62 (36.63–59.14)
Natural sal forest	5.34 ± 0.52a (4.87–6.14)	441 ± 7.68 (435–450)	31.33 ± 3.22 (26.63–33.87)	3.86 ± 1.64 (1.15–4.40)	50.65 ± 10.25 (40.80–63.19)

* Different letters indicate significant differences between soil CO_2 flux in different aged reclaimed dumps at $P < 0.05$.

reclaimed land as it influences water holding capacity, bulk density, soil moisture availability and nutrient contents as well as availability. Mine soils texture vary from dump to dump depending upon the overburden materials excavated from different depth and also upon the parent material from which the soil is developing (Sencindiver and Ammons, 2000).

Soil bulk density was higher (1.56 Mg m^{-3}) in the recently reclaimed mine soils, compared to the 17 years old mine soil (1.39 Mg m^{-3}) and lowest in the forest soil (1.24 Mg m^{-3}). The bulk density differences were attributed to mining equipment and organic inputs on older sites. New mine soils had a slightly higher bulk density than the native soils due to the differences in mining method rather than pedogenic processes. In a similar study, root system development, addition of biomass, and little anthropogenic perturbation after 15 to 20 years of reclamation improved soil structure, decreased bulk density, and increased porosity (Thomas et al., 2000). The bulk density decreased with increase in age of reclamation (Table 3). Izquierdo et al. (2005) also observed a sharp decrease in bulk density after planting of trees in the degraded mining sites. In a study comparing mine soils of different ages, bulk density of the old mine soil (~50 years) was equal to or less than the native soil (Schafer et al., 1980). Akala and Lal (2001) also showed that growth and development of roots over time incorporates soil organic carbon and loosens up the soil, thus decreasing soil bulk density. In relation with bulk density, porosity was significantly higher in natural forest and 17-year old dumps compared to other reclaimed sites (Table 3). Profile porosity was considered the fourth most influential variable on mine soil quality and higher porosity resulted in higher site productivity (Rodrigue and Burger, 2004).

The pH of the mine soil was acidic in all sites and no significant trend was found with the increasing age of reclaimed sites (Table 3). The pH (1:1) values ranged between 4.91 to 5.80, which is lower than natural forest (5.90) and showed significant variations among the reclaimed mine soil chronosequence sites ($P < 0.05$). The study indicates that soil pH of this regions were slightly acidic which favours the growth of natural sal forest and leguminous trees. The parent material of the overburden dump decides the mine soil pH depending on the amount of acid-producing or acid-neutralizing material present in it (Daniels and Zipper, 1997; Mukhopadhyay and Maiti, 2011). The gradual increase in pH from 5.52 (fresh overburden) to 5.80 was due to plantations and inputs of organic matter that modifies the pH of the soil. Since the plant species are dicotyledonous, they may release more base cations like Ca^{2+} into the soil (highest Ca^{2+} was found in 17 and 7 year old mine soil) thus increase the pH of the soil more than the fresh mine soils.

The soil EC values were lower in the mine soils, varying from 0.115 to 0.187 dS m^{-1} and reduced significantly in natural forest; however significantly high value was found in fresh overburden materials. Soluble salts are an influential variable in the survival and growth of tree seedlings, and site productivity decreases with an increase in soluble salt concentration (Rodrigue and Burger, 2004; Torbert et al., 1988). The variation of EC values are attributed by leaching, composition of parent materials and plants uptake. The observed EC is within the plant growth limit. Soluble salt concentrations of >1–3 dS m^{-1} were unfavourable for plant growth and tree survival (McFee et al., 1981).

The highest soil organic carbon (OC) content was in the 17-year old mine soil (2.25%) and the lowest in the 2-year old mine soil, while in forest soil, the OC was 1.65%. This higher OC in the oldest site is due to the accumulation of leaf litter and its decomposition to form humus. Available N and P also followed the same trend as organic matter (Table 2). OC, 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., 1998). Increase in concentration of available N with increase in age of plantation has been observed. Low available N stock in the younger reclaimed sites 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, and phosphorus content is determined by the organic matter, pH of the soil substrate and weathering process (Andrews et al., 1998). Several chronosequence studies (Akala and Lal, 2000; Schwenke et al., 2000; Maharaj et al., 2007; Shrestha and Lal, 2010) have reported accumulation of C and N pools over time in reclaimed soils. Available *P* varied along the chronosequence and there were significant differences among sites, with the highest levels of *P* in the 17-year old reclaimed mine soil. Development of vegetation cover enhanced the natural soil cycle and thus showed higher values of available P compared to fresh mine spoil (Torbert et al., 1988). Šourková et al. (2005) studied the accumulation of carbon (C), nitrogen (N) and phosphorus (P) and their vertical distribution in the soil profile in relation to site age in a chronosequence of 19 sites on reclaimed spoil heaps from open-cast coal mining, near Sokolov (Czech Republic) and compared them to a semi-natural alder forest in the vicinity of the mining area. Rapid accumulation of C and N in the soil profile was registered within 15 years after reclamation.

A significant change in exchangeable cations with the age of reclaimed sites was observed (Table 3). In mined site, base saturation and cation nutrition are highly dependent on the parent material (Czapowskyj, 1978). Generally, CEC is used as a measure of soil fertility and nutrient retention capacity. In forest soil and 2-year old mine soil, the concentration of cation nutrients was lower because of higher leaching caused by porous texture of the soil. In case of 17-year old site, concentrations of cations were found higher due to low leaching and higher clay content. In the fresh overburden, base saturation was higher (82.6%) due to high concentration of bases (Ca, Mg, K, Na) in the parent materials. With increase in age of reclamation, content of these ions decreased as they are exposed to natural weathering process, followed by leaching. In initial stage of reclamation, due to low clay content and lower CEC, bases are continuously leached, which is evidenced in 2 and 5 year reclaimed sites having 10.6–13% base saturation. However, the base saturation was higher for the 17 year site (31%). In course

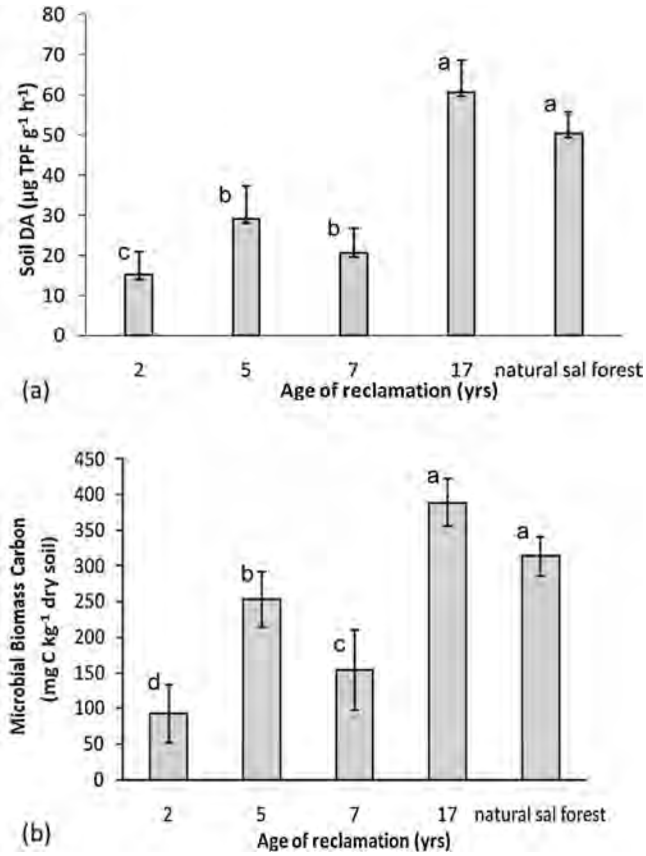

Fig. 2. Change in (a) soil dehydrogenase activity (DA) (μg TPF g^{-1} soil h^{-1}) and (b) microbial biomass carbon (mg C kg^{-1} dry soil) with age of reclamation. (Error bar represents standard deviation of six replicates; bars with same letters are not significant at $P < 0.05$).

of time as dumps get stabilized, with the increase in clay content, base saturation also increases.

3.2. Soil biological parameters

3.2.1. Soil dehydrogenase activity

Soil dehydrogenase activity (DA) was highest in 17 year mine soil (60.72 μg TPF g^{-1} h^{-1}) followed by the forest soil (50.36 μg TPF g^{-1} h^{-1}) > 5 year mine soil (29.15 μg TPF g^{-1} h^{-1}) >7 year mine soil (25.70 μg TPF g^{-1} h^{-1}) and least in 2 year mine soil (15.06 μg TPF g^{-1} h^{-1}) (Fig. 2a). The DA activity increased with increase in the age of reclamation due to the relatively higher vegetation cover and organic carbon content in older sites. Apart from reclamation age, the heterogeneity of the dump materials and nature of the plant species will affect the carbon accumulation and accordingly the DA activity. Harris and Birch (1989) studied soil microbial activity in opencast coal mine restoration sites and observed DA ranged from 140 to 580 μg TPF g^{-1} 24 h^{-1} in undisturbed soils, whereas in disturbed soils activities reduced to 10 to 220 μg TPF g^{-1} 24 h^{-1}, with the lowest activities being recorded in the stored and most recently reinstated soil, indicating that disturbance has depressed microbial activity.

3.3. Soil microbial biomass carbon

Soil microbial biomass carbon (MBC) acts as a source of plant nutrients in mine soils (Singh et al., 1989), which increases progressively with age of reclamation. Accumulation of labile carbon during reclamation helps in a rapid increase in MBC. A general

Table 4
Results of principal component analysis of soil parameters from reclaimed mine soil chronosequence sites.

Principal components	PC-1	PC-2	PC-3
Eigen values[a]	**9.61**	**3.22**	**1.52**
Variation (%)	56.54	18.95	8.92
Cumulative variation (%)	56.54	75.49	84.41
Eigen vectors[b]			
Coarse soil fraction (>2 mm)	−0.472	**0.782**	0.210
Sand	−0.837	−0.213	0.310
Silt	0.827	−0.298	−0.110
Clay	0.469	0.687	−0.403
Bulk density	−0.736	0.528	0.124
Moisture content	0.488	**0.739**	−0.384
pH (1:1; w/v)	0.570	−0.260	0.574
EC (1:1; w/v)	1.616E − 02	0.696	0.163
Organic carbon	**0.948**	4.148E − 02	−7.30E − 02
Available N	0.817	7.207E − 02	9.678E − 02
Available-P	0.813	−9.55E − 02	−0.226
Exchangeable K	0.800	0.305	0.378
CEC	0.761	0.539	0.117
Base saturation	0.467	0.328	**0.661**
Soil CO_2 flux	**0.938**	−0.267	0.112
Microbial biomass carbon	0.811	−0.185	−8.70E − 02
Dehydrogenase activity	**0.936**	−0.123	5.388E − 02

[a] Boldface eigen values correspond to the PCs examined for the index.
[b] Boldface-underlined factors correspond to the parameters included in the index.

increasing trends of MBC was observed from a low level in the more recently reclaimed sites (92 mg C kg^{-1} soil) to a higher level at 5 (254 mg C kg^{-1} soil), 7 (155 mg C kg^{-1} soil), and 17 (388 mg C kg^{-1} soil) year of reclamation. Lower MBC was observed in the 7-year site than 5 years may be due to impoverished conditions of the site, sparse ground vegetation and low tree density. Clayton et al. (2009) also observed a general trend of increasing MBC from a low level in the more recently reclaimed sites (131–138 mg C kg^{-1} soil) to a high level in the 16–20 year (280 mg C kg^{-1}) and 38–42 year sites (244 mg C kg^{-1}) in coal mine reclaimed soils of South-western Virginia, USA.

The MBC level in the 17-year old reclaimed sites was found higher than the forest site, which indicates the recovery of soil microbial communities with time (Fig. 2b). Anderson et al. (2008) reported that it usually takes 20 years or more for microbial biomass and diversity in disturbed soils to reach the levels of native soils in the semiarid mined lands of Wyoming (USA). Similar observations were also reported by Banning et al. (2008) and Singh et al. (2004). Microbial biomass thus provides one of the most satisfactory estimates of the restoration of soil microbial populations (Ross et al., 1990). A continuous increase in microbial biomass with age in our study indicates continuous soil redevelopment on mine soils. A rapid development of microbial biomass in the mine spoil is an indication of the efficient restoration potential of the growing tree plantation. Obviously, the younger sites are in developing stage and it will take time to reach soil nutrient levels comparable to nearby natural forests.

3.4. Soil respiration (in situ soil CO_2 flux)

In reclaimed mine soil, organic matter and microbial activity progressively increased with time due to growth of vegetation. Soil organic carbon quality is assessed by microbial biomass carbon and microbial CO_2 respiration activity (Ananyeva et al., 2008). The variation of soil CO_2 flux was studied during the winter months in the reclaimed chronosequence sites (Table 4). Level of soil moisture in the reclaimed sites ranged from 4.5% to 5.8%; temperature and relative humidity varied between 31 and 36.8 °C and 47–63%, respectively. The ambient soil surface CO_2 concentration was between 416 and 490 ppm. Average CO_2 flux was highest in the

Table 5
Correlation between the variables of PC-1.

Parameter	Organic carbon	CO_2 flux	Dehydrogenase activity
Organic carbon	1.00		
Soil CO_2 flux	0.958**	1.00	
Dehydrogenase activity	0.953**	0.951**	1.00

** Correlation is significant at $P < 0.01$ (2 tailed).

17-year reclaimed site due to higher accumulation of organic matter and greater microbial activity. No significant difference in CO_2 flux was observed between 5 and 7-year reclaimed site. Higher soil CO_2 flux in 17 year reclaimed sites and forest soils were attributed to high soil organic carbon and microbial biomass than younger dumps. Time series analysis by Wiseman and Seiler (2004) also revealed that stand age had a significant effect on soil CO_2 flux rate. The increasing trend of CO_2 flux was observed with increase in age of reclaimed sites due to increase in moisture holding capacity, organic matter, root density and microbial activity. The most influential factors affecting soil CO_2 flux during the study were soil temperature, soil moisture and stand age (Wiseman and Seiler, 2004; Mukhopadhyay and Maiti, 2012). Rochette et al. (1999) reported that CO_2 flux in moist soils is 2 to 3 times greater than in drier soils. Ding et al. (2007) suggested that soil moisture may affect soil respiration indirectly by modifying soil temperature, and both may be interdependent in their effects on soil respiration. Chodak and Niklinska (2010) reported that soil texture has a greater influence than planted vegetation on basal respiration rate, which was found higher in loamy sand than sandy soil. Thus the improvement in the soil physico-chemical properties (Table 2) in turn favourably enhanced the soil biological quality.

3.5. Mine soil quality index (MSQI) based on principal component analysis

The soil characteristics of chronosequence sites and reference site (sal forest) of NK Area was subjected to PCA to identify the critical soil parameters that can be considered as "soil quality indicators of reclaimed mine soil". The first three PCs had eigen values > 1.0 (Table 4). The highly weighted variables under PC-1 were organic carbon, soil CO_2 flux and dehydrogenase activity. Organic carbon was highly correlated with the other parameters i.e., soil CO_2 flux and dehydrogenase activity (Table 5). Since the sites were reclaimed by coalmine soil, the coal particles will significantly contribute to SOC. So it is not advisable to depend heavily on soil organic carbon alone for assessing MSQI. So the next two highly weighted variables soil CO_2 flux and dehydrogenase activity were also included in the MSQI, and the weights among the soil parameters were decided as per the factor loadings. Under PC-2, coarse soil fraction and moisture content were highly weighted. As coarse soil fraction and moisture content were not well correlated, both were retained for calculating index. Likewise base saturation was highly weighted in PC-3. Thus soil indicator parameters finally selected by PCA were, soil organic carbon, soil CO_2 flux, dehydrogenase activity, coarse soil fraction, moisture content and base saturation. Weights for selected variables were determined by the per cent variation in the data set explained by the first three PCs. Within a particular PC, the weights were distributed among the correlated variables as per the factor loading; for non-correlated variables the full weights were assigned.

$$\text{Mine soil quality index (MSQI)} = 0.5654 \ (\text{organic carbon}/CO_2\text{flux}/\text{dehydrogenase}) + 0.1895 \ \text{coarse fraction} + 0.1895 \ \text{moisture} + 0.0892 \ \text{base saturation}$$

The MSQI values were normalized to a 0 to 1 scale by dividing each weighing factors by the total weighing factor (1.0336) and the final normalized MSQI is given below:

$$\text{Final MSQI} = 0.18234 \times S(CO_2 \ \text{flux}) + 0.18234 \times S(\text{organic carbon}) + 0.18234 \times S(\text{dehydrogenase}) + 0.18334 \times S(\text{coarse fraction}) + 0.18334 \times S(\text{moisture}) + 0.0863 \times S(\text{base saturation}) \quad (3)$$

where S is the score for the individual variables, and the coefficients are the weighing factors obtained from the results of PCA.

The different parameters for the scoring curves are presented in Table 6. The variables in Eq. (3) are considered the most critical indicators to express the overall soil health of mine soil and the subsequent performance of the tree species. The PCA infers that these six important soil parameters could be used to derive MSQI that will indicate health of reclaimed coal mine soil. Several researchers also considered these properties as important soil quality indicators for different types of degraded land.

Soil organic carbon (SOC) is a much reliable soil quality indicator and its monitoring over time indicates the quality of the land, whether aggrading, degrading or stable (Chaudhuri et al., 2013). Rajan et al. (2010) has reported that SOC is the most discriminating and reliable quality indicator which can be used singly for monitoring the status of land degradation due to soil erosion. Bodlák et al. (2012) concluded that SOC content is an appropriate tool for evaluating the soil quality in a reclaimed post-mining landscape. Soil CO_2 flux describes the level of microbial activity, soil organic matter content and its decomposition and used as an early indicator of stress or soil restoration to determine the reclamation status of coalmine degraded sites (Šourková et al., 2005; Chodak and Niklinska, 2010). Coarse fraction has been identified as one of the most influential mine soil property affecting site quality and forest productivity (Rodrigue and Burger, 2004). Soil moisture is used as an indicator parameter in studies on restoration of degraded land (Dutta and Agrawal, 2002; Mukhopadhyay and Maiti, 2012). Littlefield et al. (2006) studied carbon and nutrient dynamics in reforested mine sites by considering soil CO_2 respiration, organic

Table 6
Parameters for scoring curves for reclaimed mine soil chronosequence sites.

Sl. no.	Parameter	Organic carbon	CO_2 flux	Dehydrogenase activity	Coarse fraction	Moisture	Base saturation
1	Curve type	More is better	More is better	More is better	Less is better	More is better	More is better
2	Mean (x_0)	1.27	3.89	35.18	37.27	4.22	21.44
3	Slope (b)	−2.50	−2.50	−2.50	2.50	−2.50	−2.50
4	R^2	0.662	0.935	0.777	0.990	0.934	0.759
5	F significance	0.000	0.000	0.000	0.000	0.000	0.000

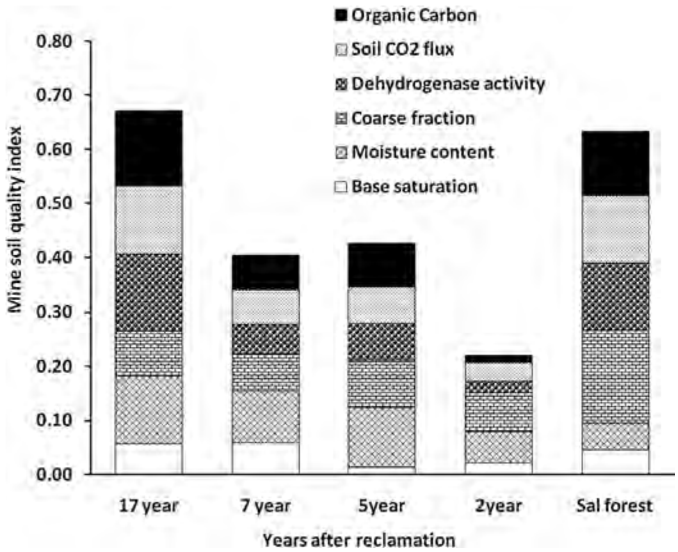

Fig. 3. Contribution of each soil indicator parameter on calculated MSQI with age of reclamation.

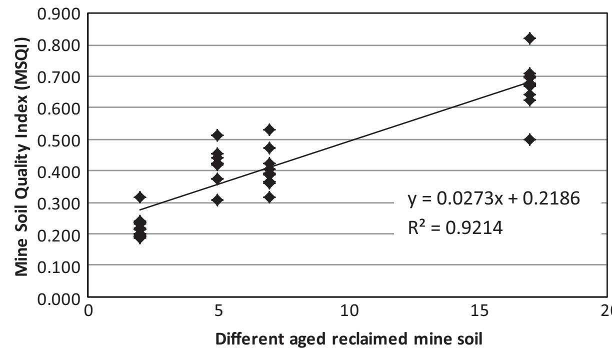

Fig. 4. Relation between mine soil quality index and age of reclamation.

matter, soil moisture, decomposition, litterfall, and microbial biomass. Rodrigue and Burger (2004) reported BS ranged from 13 to 100% in reclaimed mine soils and found higher than that of the non-mined sites; and correlated with forest productivity.

The MSQI obtained using the PCA is presented in Fig. 3, where the contribution of each soil indicator parameter on calculated MSQI is also shown, which gives an insight into the cause for the measured MSQI. Lowest MSQI observed in 2 years old reclaimed dump was due to the lesser score for all the six parameters included in the MSQI. The calculated MSQI varied from 0.220 in 2 years old reclaimed dump to 0.670 in 17 years old reclaimed dump (Fig. 3). A positive correlation between mine soil quality index and age of reclamation is depicted in Fig. 4. Now, in order to evaluate the MSQI, regression analyses have been done with end point variables like canopy cover, DBH and height of tree species. The details of vegetation analysis of few dominant tree species growing in the different aged reclaimed sites are given in Table 7. The canopy cover ($R^2 = 0.99$), DBH ($R^2 = 0.87$) and height ($R^2 = 0.82$) of tree species are highly correlated with the MSQI (Fig. 5). These regression results support the practical utility of the MSQI.

The MSQI recorded for the 17 years old site (0.670) is slightly higher than that of the sal forest (0.633), which indicates the recovery of soil with time. Anderson et al. (2008) reported that it usually takes 20 years or more for disturbed soils to reach the levels of native soils in the semiarid mined lands. More the MSQI value better is the reclamation status of the sites. So it is recommended that ecorestored mine soil sites with MSQI > 0.500 could be considered as ecologically sustainable or reclamation is satisfactory. In other words at least 50% of the soil functions are restored in these sites. Age of reclamation has been found to have a significant effect on the nutritional and microbial properties of the mine soils. Progressive build up of adequate nutrient pool in 17 years site may be sufficient for ecosystem maintenance in this region. All the indicator parameters (except soil coarse fraction) scores and MSQI are positively related with the year of reclamation (Fig. 6). A progressive amelioration of soil CO_2 flux, organic carbon,

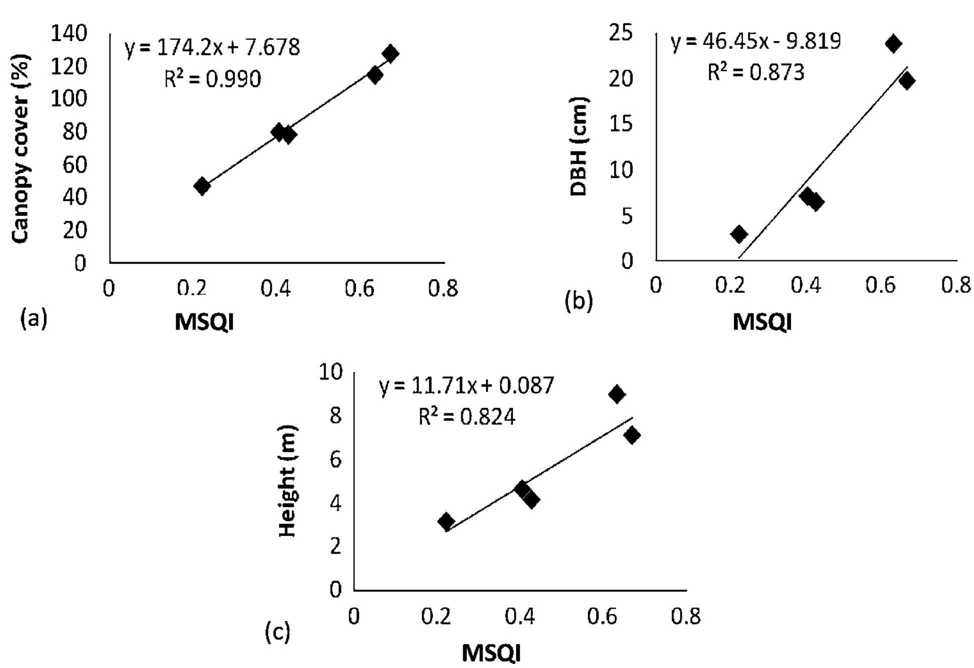

Fig. 5. Correlation between mine soil quality index and plant growth parameters (a) canopy cover (b) DBH (c) tree height.

Table 7
Vegetation analysis of the dominant trees growing in the different aged reclaimed sites.

Age of reclaimed sites	Dominant tree species	DBH (cm)	Height (m)	Canopy cover (%)
17-year	*C. siamea*	19.76 ± 2.35 16.86–24.18	7.1 ± 0.61 6.4–7.6	128
7-year	*D. sissoo*	9.09 ± 2.19 5.73–13.36	5.12 ± 0.75 4.5–5.7	86
	C. siamea	8.97 ± 2.12 6.36–11.77	4.2 ± 0.68 3.9–4.5	88
	A. auriculiformis	5.41 ± 0.64 4.77–6.14	5.1 ± 0.82 4.7–5.4	65
	A. mangium	6.47 ± 1.29 5.73–7.95	4.1 ± 0.51 3.9–4.5	82
5-year	*D. sissoo*	7.81 ± 1.51 5.73–10.5	4.91 ± 0.71 3.5–5.8	85
	A. catechu	4.97 ± 1.75 2.23–7.00	3.09 ± 0.80 1.9–4.1	72
2-year	*D. sissoo*	3.82 ± 1.18 1.91–5.73	3.76 ± 0.67 2.4–4.5	48
	C. siamea	2.23 ± 0.12 2.01–2.38	2.45 ± 0.47 1.8–3.4	46

dehydrogenase activity, moisture, and base saturation with increase in age of reclamation is depicted in Fig. 6. The coarse fraction of the mine soil is not increasing with reclamation age, it may require many more years for its weathering depending on the physical, chemical, and biological conditions of the soil. Thus, the MSQI estimated based on the soil indicators, CO_2 flux, organic carbon, dehydrogenase, coarse fraction, soil moisture, and base saturation could be employed as a tool for evaluation of the

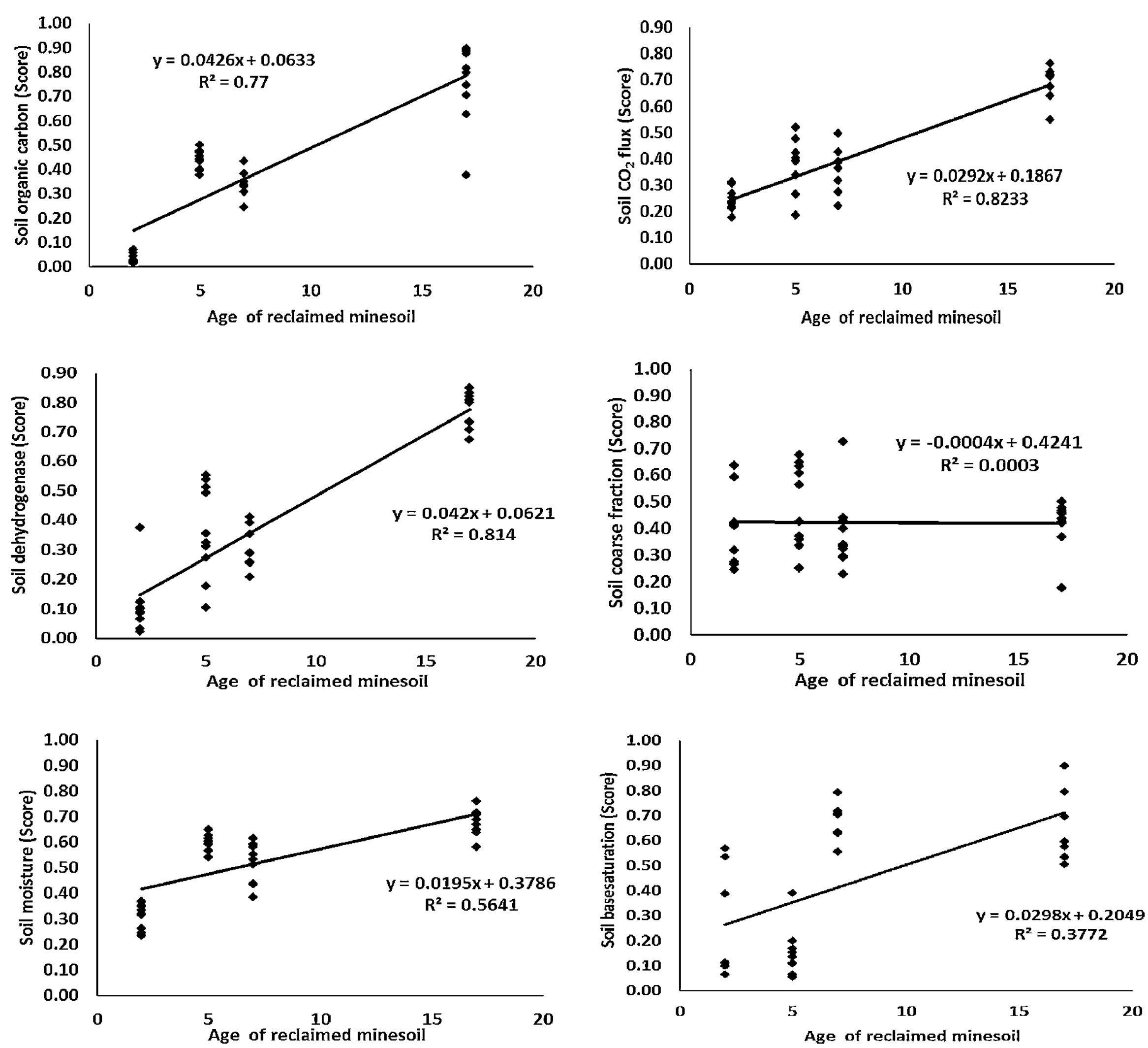

Fig. 6. Relation between the soil quality indicator scores and the age of reclamation.

success and changes in mine soil reclamation process. This MSQI may be applied to other mining sites, although we recommend a validation in each site.

4. Conclusion

Soil physico-chemical and biological characteristics of chronosequence mine soil sites, were assessed to evaluate the progress of mine soil development leading to sustainable reclamation. PCA was used to create the mine soil quality index (MSQI). MSQI increased with increase in the age of reclamation. The soil quality at 17 years old site is comparable to that of a undisturbed forest. More the MSQI value better is the reclamation status of the mine soil. So it is recommended that mine soil with MSQI > 0.500 should be considered as ecologically sustainable or reclamation is satisfactory. Besides assessment of reclamation status of the mine soil, this indexing approach can be useful as a tool for selection of plant species and role of amendments on the improvement of soil function which will meet the ecorestoration goals.

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