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Assessment of Seasonal and Site-Specific Variations in Soil Physical, Chemical and Biological Properties Around Opencast Coal Mines

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ABSTRACT

Coal mining adversely affects soil quality around opencast mines. Therefore, a study was conducted in 2010 and 2011 to assess seasonal and site-specific variations in physical, chemical, and biological properties of soil collected at different distances from mining areas in the Jharia coalfield, India. Throughout the year, the soil in sites near coal mines had a significantly higher bulk density, temperature, electrical conductivity, and sulfate and heavy metal contents and a significantly lower water-holding capacity, porosity, moisture content, pH, and total nitrogen and available phosphorus contents, compared with the soil collected far from the mines. However, biological properties were site-specific and seasonal. Soil microbial biomass carbon (MBC) and nitrogen (MBN), MBC/MBN, and soil respiration were the highest during the rainy season and the lowest in summer, with the minimum values in the soil near coal mines. A soil quality index revealed a significant effect of heavy metal content on soil biological properties in the coal mining areas.

Key Words: heavy metal, microbial biomass, mining area, soil property, soil quality index, soil respiration

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Environmental consequences associated with coal mining practices have been highlighted worldwide. In the process of coal mining and thereafter, numerous alterations occur in physical, chemical, and biological properties of the soil as a result of mining and storage (Mukhopadhyay *et al*., 2014; de Quadros *et al*., 2016). The causes of land degradation during mining are the removal of vegetation cover and topsoil, excavation, dumping of overburden materials, subsidence, mine fires, dynamite blasting, and use of large scrapers, excavators, and dump trucks (Maiti, 2013). The topsoil in mining areas is affected by the blending of overburden materials through surface wind strokes, which ultimately leads to variations in its physicochemical properties (Rai *et al*., 2010).

Huge amounts of dump rocks that accumulate in coal mining areas are of great environmental concern due to their potential for causing acidic and metal-rich drainage (Wong, 2003). Coal particles and burning of coal give rise to airborne compounds such as fly ash and bottom ash that may contain heavy metals (HMs), which settle down or are washed out from the atmosphere into the land and contaminate the soil (Rout *et al*., 2014). The physical and chemical properties of the metal-contaminated soils tend to inhibit soil-forming processes and plant growth (Pandey *et al*., 2014a). The loss of vegetation cover in coal mining areas further causes soil erosion, compaction, wide temperature fluctuations, a lack of soil-forming fine materials, a shortage of essential nutrients, and the loss of microbial communities in the soil (de Quadros *et al*., 2016).

Coal mining activities affect soil physical quality, which may disturb soil development. Variability in soil chemical properties affects nutrient cycling, bioavailability and toxicity of metals to the biota, and ecology and physiology of soil microflora (Mukhopadhyay *et al*., 2013; de Quadros *et al*., 2016). Soil biological properties affect soil microbial diversity and populations, thereby influencing root growth and soil microbes (de Quadros *et al*., 2016).

The maintenance of soil biological properties, *i.e.*, microbial biomass carbon (MBC) and nitrogen (MBN), soil respiration, and MBC/MBN, is of central importance in improving soil function in coal mining areas, because soil microbes and their enzymatic activity play important roles in maintaining soil fertility, productivity, and nutrient cycling (Mukhopadhyay *et al*., 2014;

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de Quadros *et al.*, 2016). As soil biological properties are sensitive to small changes in soil condition, changes in soil physical and chemical properties and HM contents can provide information on the factors that govern soil biological properties, helping maintain the overall quality of soil in coal mining areas.

Effective soil improvement processes require a healthy ecosystem that is self-sustaining and interacts and functions in balance with a combination of physical, chemical, and biological components (Maiti, 2013). Assessing soil in terms of these properties, and how they change with time, is important. As soil function depends on a large number of parameters (physical, chemical, and biological), it is very difficult to interpret overall soil quality (Liu *et al.*, 2014). Integrated indices based on physical, chemical, and biological properties of soil can provide a good indication and quantitative comparison of variations in soil quality in coal mining areas (Sinha *et al.*, 2009).

The specific objectives of the present study were 1) to investigate seasonal and site-specific variations in soil physical, chemical, and biological properties in coal mining areas and 2) to identify indicator parameters and develop soil quality indices (SQIs).

MATERIALS AND METHODS

Study area and sample collection

The Jharia coalfield selected for this study is situated in Dhanbad District of Jharkhand State, India and is the most exploited coalfield in India because of its high-grade coking coal reserves. It lies 23°39′–23°48′ N and 86°11′–86°27′ E with an above sea level of 222 m, and covers an area of about 450 km^2. The Jharia coalfield contains about 100 mines, in which 68 mines are operating, while 25 mines have been closed due to mine fires. This coalfield has had about 70 mine fires, spread over an area of approximately 18 km^2 (Pandey *et al.*, 2014a). The region experiences a sub-tropical climate. It is cool during the winter (from November to February). The month of May is the hottest, and it remains hot until the monsoon starts in the middle of June. The rainy season runs from July to October.

Characteristics of the sampling sites and their status in respect to the species richness of herbaceous and woody vegetation are given in Table I. The sites were selected from near to 10 km away from mines. Two sites (MA and MB) were selected close (0.5 to 1 km) to the coal mines, two sites (NA and NB) were 2–3 km away from the coal mines, and one site (CK) was about 10 km away from the coal mines (Fig. 1). At each site, five sub-sites were selected. Soil samples were randomly collected from three places at each sub-site. Aboveground herbaceous vegetation was removed, and soil up to 15 cm depth was collected using an auger and placed in marked polythene bags. Soil samples were collected every four months in the summer (May–June), rainy season (August–September), and winter (November–December) for two consecutive years from 2010 to 2011.

Assessment of species richness

Species richness measurements were conducted at five sub-sites of each site where soil samples were collected. For the herbaceous layer, 1 m × 1 m quadrats were used, and for the woody layer, 20 m × 20 m quadrats were used, after calculating species area curves. Details of the vegetation sampling procedure are given in Pandey *et al.* (2014b). Species richness (Margalef, 1958) was calculated using the following equation:

$$\text{Species richness} = S - 1/\log N \tag{1}$$

where S is the number of species and N is the number of individuals.

Analyses of soil physical and chemical properties

Soil temperature (T_{soil}) was monitored at three ra-

TABLE I

Characteristics of the sampling sites selected in Jharia coalfield in Dhanbad District of Jharkhand State, India

Site[a)]	Activities	Species richness
CK	Good plantation, institutional area	6.13 (herbaceous), 8.97 (woody)
NA	Vehicular movement, transport of coal, domestic coal burning, and residential activities	5.07 (herbaceous), 8.27 (woody)
NB	Vehicular movement, transport of coal, domestic coal burning, and residential activities	5.03 (herbaceous), 8.12 (woody)
MA	Mining activities, coal-handling plant, vehicular movement, transport on paved and unpaved roads, haul road, exposed dump, and industrial activity	4.66 (herbaceous), 7.42 (woody)
MB	Mining activities, coal-handling plant, vehicular movement, transport on paved and unpaved roads, haul road, and exposed dump/exposed pit surface	4.09 (herbaceous), 7.36 (woody)

[a)] Site CK was selected about 10 km away from the coal mines; sites NA and NB were 2–3 km away from the coal mines; sites MA and MB were close (0.5 to 1 km) to the coal mines.

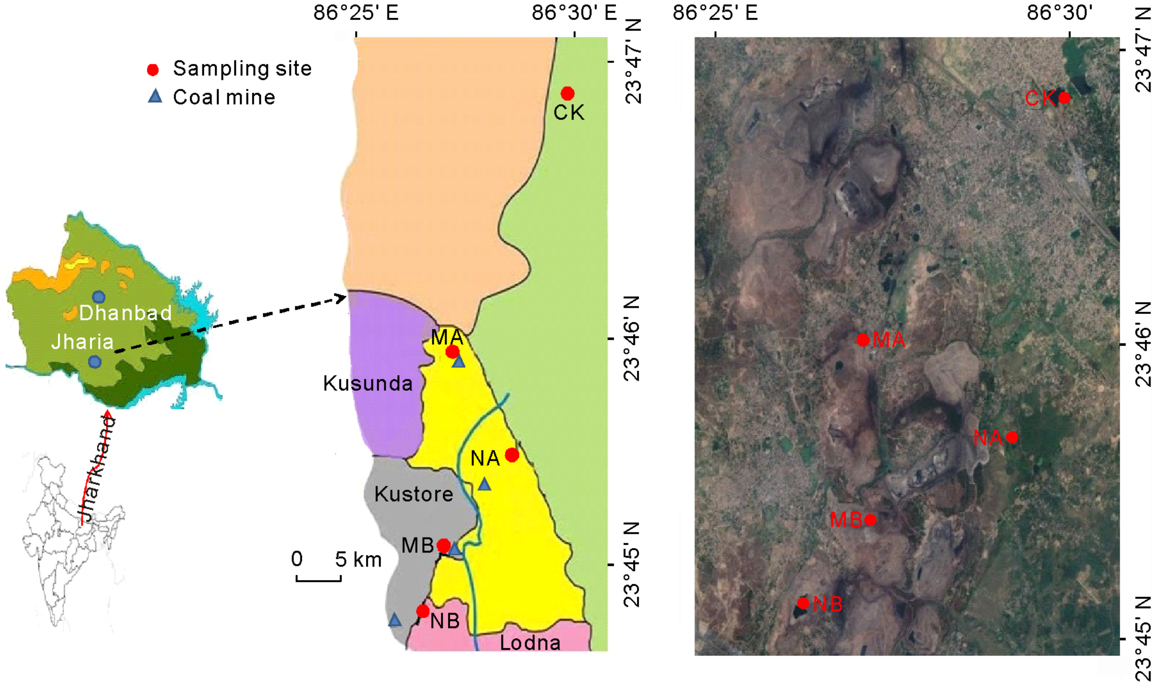

Fig. 1 Map and Landsat image of the study area showing sampling sites in Jharia coalfield in Dhanbad District of Jharkhand State, India. See Table I for the detailed descriptions of the sampling sites CK, NA, NB, MA, and MB.

ndomly selected points at each sub-site by a probe connected to an LICOR 6400 infrared gas analyzer (IRGA) (LI-COR, USA). Bulk density (ρ_b) and water-holding capacity (WHC) were determined using the method described by Pandey *et al.* (2014b). Soil moisture was determined by drying the soil core (6.5 cm diameter) at 105 °C for 24 h. Total porosity was calculated from ρ_b, assuming a particle density of 2.65 g cm^{-3} and 98% saturation (Maiti, 2013).

Soil pH and electrical conductivity (EC) were determined just after collecting the samples, and the rest of soil was air-dried and ground to pass through a 2-mm sieve. Soil total organic carbon (TOC) was determined using a modified method of Walkley and Black (1947). Total nitrogen (TN) in the soil was determined using a Gerhardt automatic N analyzer (Model KB8S, Frankfurt, Germany). Available phosphorus (AP) was extracted following Olsen *et al.* (1954) and estimated by the method of Dickman and Bray (1941). Soil sulfate (SO_4-S) content was estimated following Williams and Steinbergs (1959).

Analyses of HMs

An air-dried sample (1.0 g) was digested with a mixture of HNO_3 and $HClO_4$ at a ratio of 9:4 (volume:volume) at 80 °C until a clear transparent solution was obtained (Tyler, 1974). The solution was filtered through Whatman No. 42 filter paper and made up to 25 mL with double-distilled water. This solution was stored in an inert glass vessel until analysis. The HM concentrations in the filtrate were determined using an atomic absorption spectrophotometer (Model AAnalyst 800, Perkin-Elmer, USA).

The precision and accuracy of the HM analyses were assured through the repeated analysis of samples against the National Institute of Standards and Technology standard reference material for all of the HMs. The results were found within ± 2% of the certified values. Quality control measures were taken to assess contamination and reliability of the data. Blank and drift standards (Sisco Research Laboratories, India) were run after five determinations to calibrate the instrument. A coefficient of variation of the replicated analyses was determined for analytical precision. Variations lower than 10% were considered acceptable.

Analyses of biological properties

The MBC and MBN were determined using the chloroform fumigation and extraction method (Brookes *et al.*, 1985). Fresh soil samples were fumigated under chloroform vapors in a vacuum desiccator for 24 h. Differences in carbon and ninhydrin-reactive nitrogen contents between the fumigated and unfumigated samples were determined following the methods of Walkley and Black (1947) and Joergensen and Brookes (1990), respectively. Soil respiration (SR) was measured using an LICOR 6400 IRGA connected to a 6400-09-type soil chamber (LI-COR, USA).

SQIs

To ascertain the effects of coal mining on different soil components, SQIs were calculated using physical, chemical, and biological properties, as well as HM contents, based on an approach proposed by Liu *et al.* (2014). For the development of SQI, the real value of a parameter (p) of soil quality was first converted into a score (S_p) using the following equation that defines a non-linear scoring function, characterized by a sigmoidal-type curve with an asymptote inclining to 1 and another inclining to 0 (Sinha *et al.*, 2009; Mukhopadhyay *et al.*, 2014):

$$S_p = \frac{1}{1+\left(\frac{x}{\bar{x}}\right)^b} \qquad (2)$$

where x is the value of soil property, $\bar{x}$ is the average value of each property corresponding to different sites, and b is the slope of the equation for each soil property. The slope was taken as negative for the "more is better curve", positive for the "less is better curve", and a combination of both for the "optimum curve", in order to obtain a sigmoidal curve tending to 1 for all of the indicator properties (Sinha *et al.*, 2009).

Once the score for each parameter was calculated, a principal component analysis (PCA) was performed to identify the variables that most affected the soil properties. Only components with eigen values of above 1 were considered for further analysis. Firstly, variables with the maximum loading values (*i.e.*, having absolute values inside 10% of the highest loading value) and the weakest correlations with the other parameters were identified (Mukhopadhyay *et al.*, 2014). Once all of the indicator parameters had been identified, the weight of each indicator variable (W_p) was calculated based on the percentage variance of each component representing the indicator variable in the total dataset. This value was normalized by dividing it by the values of all the principal components obtained (eigen value > 1), and this value gave the final W_p for each indicator variable. Subsequently, the final SQI was calculated using the following equation:

$$\mathrm{SQI} = \sum_{p=1}^{n} W_p \cdot S_p \qquad (3)$$

High index values indicate high soil quality and superior soil function. Based on the SQI results, percentiles of 0.33 and 0.67 were established for different levels of soil quality. An SQI ≤ 0.40 indicated a severely affected soil, an SQI of 0.41–0.70 indicated a moderately affected soil, and an SQI ≥ 0.70 indicated a least affected soil.

Statistical analyses

Soil physical, chemical, and biological parameters and HM contents were analyzed using one-way analysis of variance (ANOVA) to ascertain site effects on the different parameters. Duncan's multiple range test was performed as a *post-hoc* test for various measurements after the one-way ANOVA. All of the soil parameters were analyzed by three-way ANOVA to ascertain the effects of site, season, and year. A regression analysis of the calculated indices with species richness was performed to validate the approach used for categorizing different soil qualities, and a multiple linear regression was performed to investigate differential responses of the biological properties to soil physical and chemical properties, as well as the HM contents. All of the statistical analyses were performed using IBM SPSS Statistics 20 software.

RESULTS

Soil physical properties

Soil physical properties varied significantly with season and site, while yearly variations were insignificant (Fig. 2). In all seasons, the highest values of T_{soil} and ρ_{b} were recorded at site MB, followed by sites MA, NB, NA, and CK (Fig. 2). T_{soil} and ρ_{b} were 10.8% and 30% higher, respectively, at MA and 11.2% and 32% higher, respectively, at MB than at CK for the entire study period. Soil moisture, total porosity, and WHC followed an opposite trend to ρ_{b} with respect to the sites. The WHC, soil moisture, and total porosity were 36%, 57%, and 26% lower, respectively, at MA and 36.4%, 59%, and 27% lower, respectively, at MB than at CK for the entire study period.

Soil chemical properties

Soil pH was lower in the sites near the coal mining areas (Fig. 3), with the minimum values at site MB during the rainy season of 2011 and the maximum values at site CK during the summer of 2011 (Fig. 3). The pH values were 23%, 21%, 9.9%, and 9% lower at sites MB, MA, NB, and NA, respectively, than at site CK for the entire study period. The EC, TOC, and SO_4-S values were the highest at MB. The minimum values of EC and SO_4-S were recorded at CK, while that of TOC was recorded at NA (Fig. 3). The EC and SO_4-S were the highest during the summer and the lowest during the rainy season at all sites except CK, at which EC was the lowest in winter (Fig. 3). The TOC was the hi-

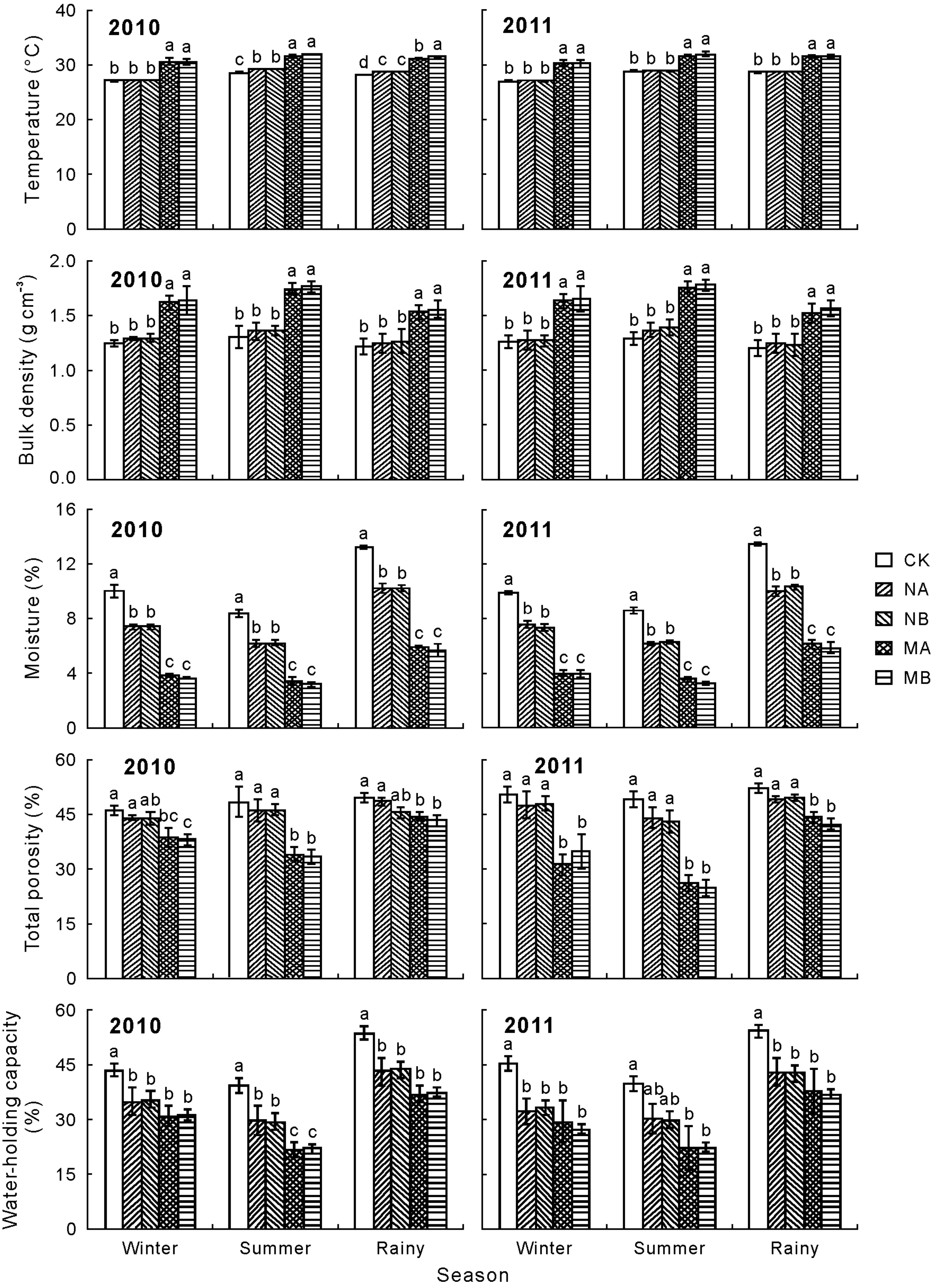

Fig. 2 Seasonal and site-specific variations in soil physical properties in 2010 and 2011 at the study sites in Jharia coalfield in Dhanbad District of Jharkhand State, India. Vertical bars indicate standard errors of the means ($n = 15$). Bars with the same letter(s) within each season are not significantly different at $P < 0.05$. See Table I for the detailed descriptions of the study sites CK, NA, NB, MA, and MB.

ghest during the rainy season at all sites, and the lowest during the summer at CK, NA, and NB, while MA and MB did not exhibit a definite seasonal trend for TOC (Fig. 3). The TOC was 79% and 75% higher, respectively, at MA and MB than at CK in summer. The TN and AP contents at CK were 52% and 45% higher,

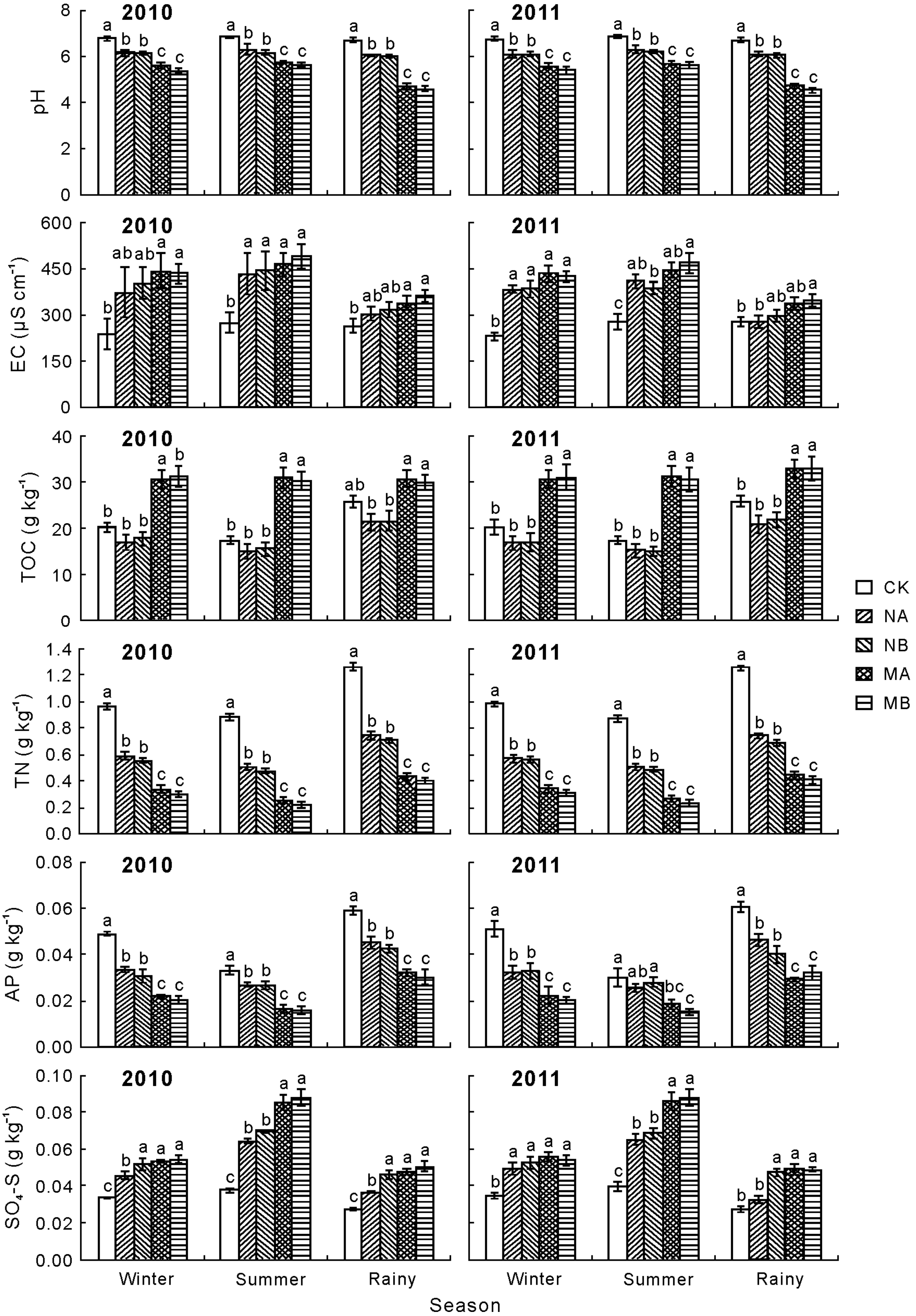

Fig. 3 Seasonal and site-specific variations in soil chemical properties, including pH, electrical conductivity (EC), total organic carbon (TOC), total nitrogen (TN), available phosphorus (AP), and sulfate (SO_4-S), in 2010 and 2011 at the study sites in Jharia coalfield in Dhanbad District of Jharkhand State, India. Vertical bars indicate standard errors of the means (n = 15). Bars with the same letter(s) within each season are not significantly different at $P < 0.05$. See Table I for the detailed descriptions of the stduy sites CK, NA, NB, MA, and MB.

respectively, than at MA and 34% and 17% higher, respectively, than at NA during the summer (Fig. 3). The highest mean TN and AP contents were recorded during the rainy season, and the lowest during the summer. The variations in soil chemical properties were more or less similar in both years of the study (Fig. 3). Among the chemical parameters, soil pH, TN, AP, and SO_4-S were significantly affected by site, season, and the interaction between site and season, while EC and TOC were significantly affected by site and season (Table II).

Soil HMs

Among soil HMs analyzed, Pb, Mn, Fe, Zn, and Cd showed the highest values at MB, while Ni, Cu, and Cr showed the highest values at NB. All of the HMs had their maximum values during the summer, followed by winter and the rainy season (Table III). The trend in average annual HM contents at NA, NB, MA, and MB was Fe > Mn > Zn > Cu > Ni > Cr > Pb > Cd, while it was Fe > Mn > Zn > Ni > Cu > Pb > Cr > Cd at CK. The Pb, Fe, Zn, and Cd contents were significantly affected by site and season, while the Ni, Cu, and Cr contents were significantly affected by site, season, and their interaction. The Cr was significantly affected by year, while Mn was only significantly affected by site. With increasing distance from the mines, the percent reductions in HM contents were the greatest for Cu, followed by Ni, Cr, Cd, Fe, Mn, and Zn.

Soil biological properties

Soil MBC, MBN, MBC/MBN, and SR were the highest at site CK in all three seasons, followed by NA, NB, MA, and MB. The highest values of these parameters were recorded during the rainy season, and the lowest during the summer (Fig. 4). The MBC and MBN were significantly affected by site, season, and site × season, while MBC/MBN and SR were significantly affected by site and season (Table II). The maximum percent reductions in MBC, MBN, and SR were 58%, 32%, and 79%, respectively, in summer at site MB, compared to site CK.

The PCA explained 93.35%, 79.6%, 91.5%, and 98.7% of the variation in soil physical properties, chemical properties, HM contents, and biological properties, respectively. The WHC and T_{soil} had high loading values for soil physical properties, TN and pH had high loading values for soil chemical properties, MBN and

TABLE II

Results of a three-way analysis of variance on the effects of site, season, and year on soil physical, chemical, and biological properties and heavy metal contents

Parameter$^{a)}$	Site	Season	Year	Site × season	Site × year	Season × year	Site × season × year
T_{soil}	280.28***	133.73***	0.02NS$^{b)}$	0.89NS	0.49NS	1.72NS	0.25NS
Moisture	776.67***	626.67***	0.30NS	9.73***	0.23NS	0.03NS	0.24NS
ρ_{b}	42.19***	10.51***	0.00NS	0.35NS	0.03NS	0.04NS	0.03NS
Total porosity	45.90***	28.13***	1.39NS	3.96***	3.90**	4.20*	0.54NS
WHC	29.05***	56.40***	0.13NS	0.20NS	0.13NS	0.34NS	0.07NS
pH	214.04***	60.09***	0.00NS	11.54***	0.03NS	0.11NS	0.10NS
EC	18.82***	19.05***	0.98NS	1.61NS	0.20NS	0.16NS	0.07NS
TOC	80.27***	15.71***	0.28NS	1.82NS	0.17NS	0.28NS	0.09NS
TN	789.13***	157.57***	0.40NS	4.76***	0.10NS	0.11NS	0.09NS
AP	109.96***	148.81***	0.02NS	4.54***	0.03NS	0.13NS	0.48NS
SO_4-S	140.30***	312.67***	0.28NS	13.97***	0.19NS	0.40NS	0.28NS
MBC	613.39***	457.02***	0.36NS	9.30***	0.16NS	0.12NS	0.18NS
MBN	76.96***	190.71***	1.04NS	4.21***	0.13NS	0.03NS	0.15NS
MBC/MBN	499.63***	96.90***	0.22NS	1.15NS	0.02NS	0.13NS	0.07NS
SR	1 506.73***	1 093.28***	2.52NS	13.36***	5.22**	0.87NS	1.03NS
Pb	142.56***	86.94***	0.41NS	1.06NS	0.38NS	0.61NS	0.81NS
Ni	219.13***	345.98***	0.01NS	5.53***	0.88NS	0.53NS	0.99NS
Cu	375.38***	187.16***	0.98NS	6.44***	0.16NS	0.00NS	1.11NS
Mn	21.63***	2.88NS	0.01NS	0.15NS	0.10NS	0.22NS	0.15NS
Fe	301.05***	185.99***	0.09NS	2.01NS	0.44NS	0.17NS	0.14NS
Zn	5.05***	6.34**	2.03NS	0.15NS	0.36NS	0.50NS	0.10NS
Cd	94.29***	10.49***	1.14NS	0.19NS	0.03NS	1.67NS	0.21NS
Cr	292.82***	373.42***	4.88*	17.97***	0.31NS	1.48NS	1.68NS

*, **, ***Significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

[a)] T_{soil} = soil temperature; ρ_{b} = bulk density; WHC = water-holding capacity; EC = electrical conductivity; TOC = total organic carbon; TN = total nitrogen; AP = available phosphorus; MBC = microbial biomass carbon; MBN = microbial biomass nitrogen; SR = soil respiration.

[b)] Not significant.

TABLE III

Seasonal variations in soil heavy metal contents in 2010 and 2011 at the study sites[a] in Jharia coalfield in Dhanbad District of Jharkhand State, India

Heavy metal	Year	Season	CK	NA	NB	MA	MB
Pb (mg kg^{-1})	2010	Winter	17.0 ± 0.9[b]	21.2 ± 1.1	20.7 ± 0.8	30.1 ± 1.7	30.9 ± 1.5
		Summer	20.8 ± 0.4	23.7 ± 2.1	24.5 ± 1.3	34.9 ± 1.3	35.1 ± 0.9
		Rainy	11.7 ± 0.6	17.5 ± 1.1	17.6 ± 0.7	25.0 ± 1.7	25.8 ± 1.0
	2011	Winter	16.3 ± 0.7	20.3 ± 1.0	22.3 ± 1.5	33.1 ± 1.8	31.1 ± 1.9
		Summer	19.8 ± 0.6	24.4 ± 1.9	23.5 ± 0.9	32.6 ± 2.6	36.5 ± 1.3
		Rainy	13.0 ± 1.4	17.5 ± 0.6	18.4 ± 0.8	23.9 ± 0.8	28.3 ± 1.3
	Average		16.4 ± 1.5	20.8 ± 1.2	21.2 ± 1.1	29.9 ± 1.9	31.3 ± 1.6
Ni (mg kg^{-1})	2010	Winter	21.5 ± 1.1	61.8 ± 1.3	66.4 ± 1.9	46.1 ± 1.4	48.3 ± 2.1
		Summer	32.6 ± 1.8	76.6 ± 2.4	85.5 ± 3.7	60.9 ± 2.5	64.9 ± 2.1
		Rainy	13.2 ± 1.0	41.9 ± 5.7	44.5 ± 3.9	32.9 ± 1.5	36.0 ± 1.8
	2011	Winter	23.4 ± 1.4	54.0 ± 1.7	71.0 ± 4.9	43.0 ± 2.1	50.2 ± 2.3
		Summer	35.3 ± 1.3	73.1 ± 2.1	87.2 ± 5.7	63.5 ± 3.4	67.9 ± 1.6
		Rainy	11.4 ± 0.7	43.6 ± 3.8	39.0 ± 2.6	31.3 ± 1.1	37.6 ± 1.2
	Average		22.9 ± 4.0	58.5 ± 6.0	65.6 ± 8.3	46.3 ± 5.6	50.8 ± 5.5
Cu (mg kg^{-1})	2010	Winter	20.1 ± 1.2	69.5 ± 3.5	78.6 ± 4.0	62.3 ± 0.9	65.6 ± 1.4
		Summer	24.7 ± 1.2	74.5 ± 4.3	82.5 ± 4.7	72.4 ± 0.8	77.1 ± 2.4
		Rainy	14.3 ± 1.2	51.4 ± 2.2	56.9 ± 3.5	47.1 ± 1.9	51.0 ± 1.3
	2011	Winter	22.4 ± 1.5	65.0 ± 2.0	82.5 ± 4.5	64.8 ± 2.1	66.9 ± 1.2
		Summer	25.5 ± 1.5	76.3 ± 4.1	86.6 ± 5.4	69.1 ± 1.5	78.1 ± 2.1
		Rainy	17.9 ± 0.9	53.8 ± 2.4	51.0 ± 2.1	50.0 ± 0.8	52.3 ± 1.7
	Average		20.8 ± 1.7	65.1 ± 4.3	73.0 ± 6.2	61.0 ± 4.2	65.2 ± 4.8
Mn (mg kg^{-1})	2010	Winter	393.5 ± 27	429.4 ± 42	451.4 ± 49	605.3 ± 52	592.2 ± 52
		Summer	422.0 ± 29	474.0 ± 48	466.1 ± 47	638.8 ± 68	642.3 ± 80
		Rainy	339.4 ± 25	404.1 ± 40	432.5 ± 49	575.5 ± 47	574.9 ± 51
	2011	Winter	390.7 ± 21	458.5 ± 43	457.9 ± 48	630.0 ± 54	603.4 ± 50
		Summer	431.0 ± 21	457.3 ± 46	474.0 ± 50	643.4 ± 54	550.0 ± 39
		Rainy	330.2 ± 22	415.8 ± 45	427.5 ± 42	565.3 ± 44	581.7 ± 33
	Average		384.5 ± 17	439.9 ± 11	451.6 ± 8	609.7 ± 14	590.7 ± 13
Fe (g kg^{-1})	2010	Winter	23.6 ± 0.9	35.0 ± 1.6	34.8 ± 1.0	41.8 ± 1.3	44.4 ± 0.5
		Summer	28.3 ± 1.4	38.2 ± 1.7	39.4 ± 1.2	45.3 ± 1.4	47.2 ± 1.2
		Rainy	16.9 ± 0.6	27.9 ± 1.2	27.6 ± 0.9	37.4 ± 1.2	39.6 ± 0.7
	2011	Winter	21.6 ± 1.1	35.2 ± 1.2	36.0 ± 1.8	42.0 ± 0.6	44.0 ± 0.6
		Summer	29.1 ± 0.7	38.6 ± 2.2	40.5 ± 0.9	45.6 ± 1.3	46.8 ± 1.5
		Rainy	16.5 ± 0.3	28.1 ± 1.2	28.4 ± 0.5	37.6 ± 0.8	39.2 ± 0.7
	Average		22.7 ± 2.2	33.6 ± 1.9	34.4 ± 2.2	41.6 ± 1.4	43.5 ± 1.4
Zn (mg kg^{-1})	2010	Winter	96.1 ± 6.1	110.1 ± 11.8	113.0 ± 10.6	123.0 ± 9.6	124.9 ± 10.5
		Summer	101.5 ± 8.8	126.1 ± 14.2	126.3 ± 13.6	139.3 ± 15.0	141.4 ± 17.0
		Rainy	90.3 ± 6.5	103.6 ± 12.6	108.3 ± 12.2	110.0 ± 13.0	115.7 ± 14.7
	2011	Winter	98.1 ± 5.7	106.3 ± 11.7	108.5 ± 11.6	123.7 ± 10.7	118.7 ± 10.2
		Summer	102.6 ± 10.2	108.8 ± 7.2	121.2 ± 10.1	124.2 ± 7.0	121.3 ± 15.4
		Rainy	94.7 ± 6.6	102.9 ± 10.4	98.8 ± 8.2	109.6 ± 7.2	105.1 ± 6.1
	Average		97.2 ± 1.9	109.7 ± 3.5	112.7 ± 4.0	121.6 ± 4.5	121.2 ± 4.9
Cd (mg kg^{-1})	2010	Winter	0.2 ± 0.01	0.3 ± 0.01	0.4 ± 0.03	0.4 ± 0.02	0.5 ± 0.03
		Summer	0.2 ± 0.02	0.4 ± 0.03	0.4 ± 0.03	0.5 ± 0.06	0.5 ± 0.03
		Rainy	0.2 ± 0.01	0.4 ± 0.02	0.4 ± 0.04	0.5 ± 0.06	0.5 ± 0.04
	2011	Winter	0.2 ± 0.01	0.3 ± 0.02	0.4 ± 0.03	0.5 ± 0.04	0.5 ± 0.04
		Summer	0.2 ± 0.02	0.4 ± 0.01	0.4 ± 0.03	0.5 ± 0.05	0.6 ± 0.03
		Rainy	0.2 ± 0.02	0.3 ± 0.01	0.4 ± 0.04	0.4 ± 0.03	0.5 ± 0.02
	Average		0.2 ± 0.01	0.3 ± 0.01	0.4 ± 0.02	0.5 ± 0.02	0.5 ± 0.01
Cr (mg kg^{-1})	2010	Winter	13.0 ± 1.1	35.3 ± 2.9	40.0 ± 1.8	32.0 ± 0.9	34.2 ± 0.8
		Summer	18.4 ± 0.4	47.5 ± 1.9	57.8 ± 2.7	42.8 ± 1.0	48.2 ± 0.6
		Rainy	10.2 ± 0.5	26.9 ± 1.1	24.1 ± 0.8	26.6 ± 1.4	28.7 ± 0.9
	2011	Winter	14.0 ± 0.7	35.5 ± 1.2	44.5 ± 2.0	35.4 ± 1.0	35.5 ± 1.3
		Summer	18.0 ± 0.7	51.1 ± 2.2	55.1 ± 1.7	40.9 ± 1.0	49.1 ± 0.9
		Rainy	12.6 ± 0.9	23.9 ± 2.4	28.6 ± 1.8	28.7 ± 0.8	31.5 ± 3.0
	Average		14.4 ± 1.3	36.7 ± 4.4	41.7 ± 5.6	34.4 ± 2.7	37.8 ± 3.5

[a] See Table I for the detailed descriptions of the study sites CK, NA, NB, MA, and MB.

[b] Means ± standard errors ($n = 15$).

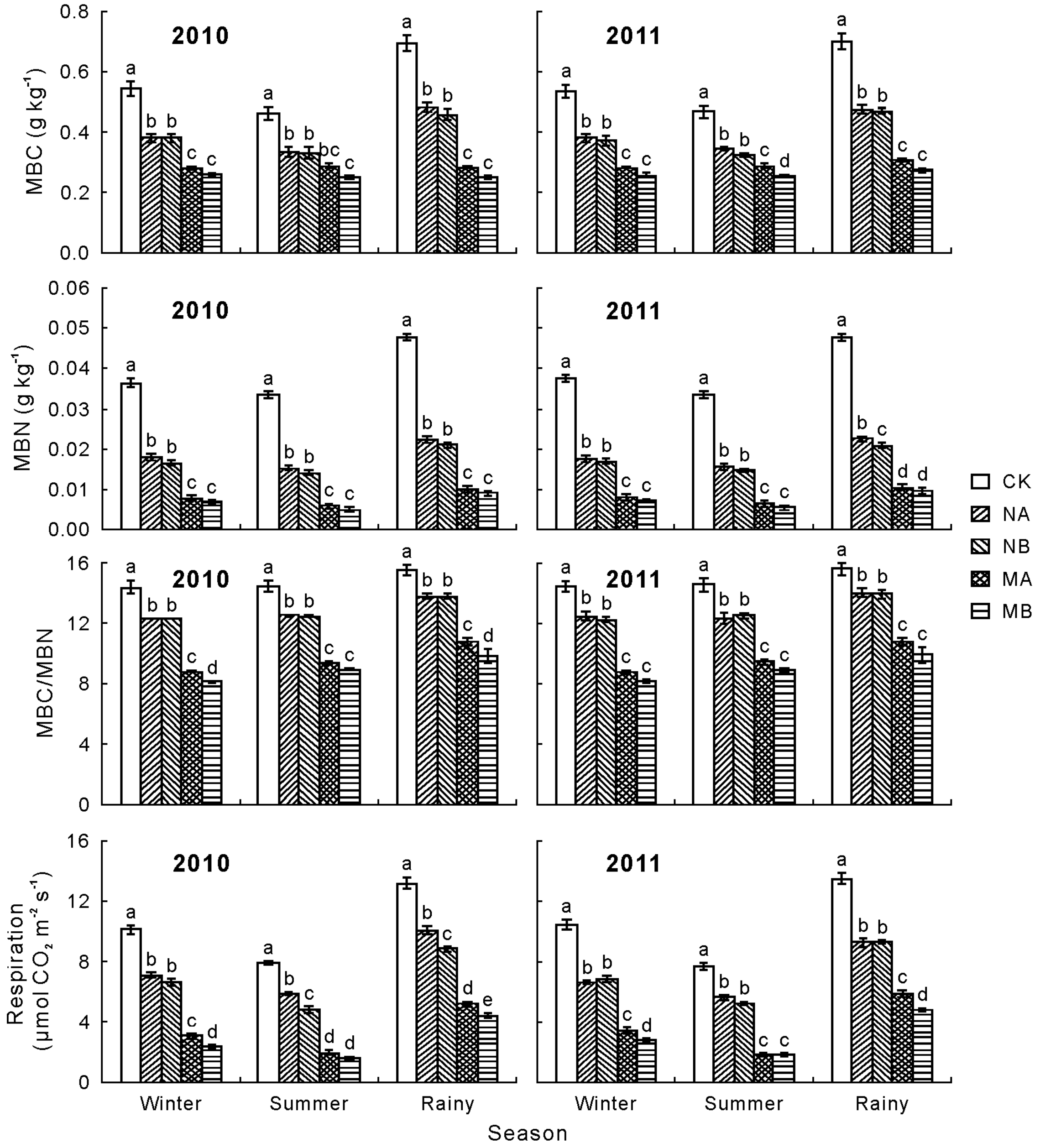

Fig. 4 Seasonal and site-specific variations in soil biological properties, including microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), MBC/MBN, and soil respiration (SR), in 2010 and 2011 at the study sites in Jharia coalfield in Dhanbad District of Jharkhand State, India. Vertical bars indicate standard errors of the means ($n = 15$). Bars with the same letter(s) within each season are not significantly different at $P < 0.05$. See Table I for the detailed descriptions of the study sites CK, NA, NB, MA, and MB.

SR had high loading values for soil biological properties, and Ni and Zn had high loading values for soil HM contents (Table IV).

SQIs

The SQIs gradually improved with increasing distance from the coal mines. Site CK had the highest values for all of the SQIs throughout the year. The SQI general trend was CK > NA > NB > MA > MB. Site-specific and seasonal patterns of soil physical quality index (SPQI), soil chemical quality index (SCQI), soil biological quality index (SBQI), and soil metal quality index (SMQI) are presented in Table V. All of the SQIs had the maximum values during the summer and the minimum values during the winter. A positive, significant correlation was found between the different SQIs and species richness (trees and herbs). The SCQI had the strongest correlation with species richness for trees ($R^2 = 0.998$), and the SPQI had the weakest correlation with species richness for herbs ($R^2 = 0.822$) (Table IV). The stepwise multiple linear regression revealed significant, positive correlations between SBQI and the

TABLE IV

Results of a principal component (PC) analysis on soil heavy metal (HM) contents and physical, chemical, and biological properties[a)]

Item	Physical property	PC 1	PC 2	PC 3	Chemical property	PC 1	PC 2	HM	PC 1	PC 2	PC 3	Biological property	PC 1	PC 2
	ρ_b	−0.841	−0.274	0.387	pH	0.313	0.877	Pb	0.260	0.842	0.248	MBC	0.724	0.683
	ρ_total	0.860	0.382	−0.299	EC	−0.822	−0.048	Ni	0.954	0.178	0.130	MBN	0.339	0.939
	WHC	0.309	0.914	−0.106	TOC	−0.046	−0.868	Cu	0.872	0.384	0.162	SR	0.948	0.610
	T_soil	−0.319	−0.190	0.913	TN	0.914	0.464	Mn	0.049	0.441	0.866	MBC/MBN	0.771	0.305
	Moisture	0.334	0.722	−0.502	AP	0.822	0.288	Fe	0.475	0.802	0.248			
					SO_4-S	−0.825	−0.128	Zn	0.266	0.101	0.938			
								Cd	0.258	0.840	0.164			
								Cr	0.892	0.355	0.172			
Eigen value		1.76	1.61	1.30		2.97	1.91		2.90	2.57	1.85		2.13	1.82
Variance (V, %)		35.12	32.27	25.96		49.42	30.18		36.23	32.12	23.15		53.32	45.40
Cumulative V (%)		35.12	67.39	93.35		49.42	79.60		36.23	68.35	91.50		53.32	98.72
Soil quality index (SQI)	$\mathrm{SQI} = (0.35S\rho_\mathrm{total}{}^{\mathrm{b)}} + 0.32S_\mathrm{WHC} + 0.26S_{T_\mathrm{soil}})/0.93$				$\mathrm{SQI} = (0.49S_\mathrm{TN} + 0.30S_\mathrm{pH})/0.79$			$\mathrm{SQI} = (0.36S_\mathrm{Ni} + 0.32S_\mathrm{Pb} + 0.23S_\mathrm{Zn})/0.93$				$\mathrm{SQI} = (0.53S_\mathrm{SR} + 0.45S_\mathrm{MBN})/0.98$		
Normalized SQI[c)]	$\mathrm{SPQI} = 0.38S\rho_\mathrm{total} + 0.38S_\mathrm{WHC} + 0.28S_{T_\mathrm{soil}}$				$\mathrm{SCQI} = 0.62S_\mathrm{TN} + 0.38S_\mathrm{pH}$			$\mathrm{SMQI} = 0.40S_\mathrm{Ni} + 0.35S_\mathrm{Pb} + 0.25S_\mathrm{Zn}$				$\mathrm{SBQI} = 0.54S_\mathrm{SR} + 0.46S_\mathrm{MBN}$		
Correlation with species richness	$y = 2.4477x + 6.726$ ($R^2 = 0.952^{***}$) for trees, $y = 2.5514x + 3.6389$ ($R^2 = 0.822^{**}$) for herbs				$y = 2.0315x + 7.087$ ($R^2 = 0.998^{***}$) for trees, $y = 2.1934x + 3.98$ ($R^2 = 0.925^{***}$) for herbs			$y = 2.5767x + 6.8469$ ($R^2 = 0.993^{***}$) for trees, $y = 2.8242x + 3.7015$ ($R^2 = 0.948^{***}$) for herbs				$y = 3.4302x + 6.1923$ ($R^2 = 0.888^{**}$) for trees, $y = 3.9435x + 2.8856$ ($R^2 = 0.933^{***}$) for herbs		

[a)] ρ_b = bulk density; ρ_total = total porosity; WHC = water-holding capacity; T_soil = soil temperature; EC = electrical conductivity; TOC = total organic carbon; TN = total nitrogen; AP = available phosphorus; SO_4-S = sulfate; MBC = microbial biomass carbon; MBN = microbial biomass nitrogen; SR = soil respiration.

[b)] Score value for each parameter of soil quality (S_p), where p stands for ρ_total, WHC, T_soil, *etc.*

[c)] SPQI = soil physical quality index; SCQI = soil chemical quality index; SMQI = soil metal quality index; SBQI = soil biological quality index.

TABLE V

Soil quality indices (SQIs) in different seasons at different study sites in Jharia coalfield in Dhanbad District of Jharkhand State, India

Site[a)]	Season	SQI[b)]			
		Physical	Chemical	Metal	Biological
CK	Winter	0.78	0.92	0.80	0.75
	Summer	0.91	0.94	0.90	0.88
	Rainy	0.84	0.93	0.83	0.83
NA	Winter	0.57	0.51	0.41	0.41
	Summer	0.72	0.59	0.63	0.66
	Rainy	0.65	0.58	0.54	0.55
NB	Winter	0.60	0.47	0.39	0.34
	Summer	0.74	0.56	0.56	0.64
	Rainy	0.64	0.54	0.54	0.54
MA	Winter	0.19	0.18	0.31	0.11
	Summer	0.35	0.17	0.50	0.34
	Rainy	0.26	0.17	0.46	0.30
MB	Winter	0.16	0.13	0.29	0.09
	Summer	0.35	0.12	0.47	0.24
	Rainy	0.22	0.14	0.38	0.18

[a)] See Table I for the detailed descriptions of the study sites CK, NA, NB, MA, and MB.

[b)] An SQI value $\leq$ 0.40 indicates a severely affected soil, an SQI value of 0.41–0.70 indicates a moderately affected soil, and an SQI value $\geq$ 0.70 indicates a least affected soil.

other SQIs. The SMQI explained 59% of variance in the SBQI, whereas only 24% and 17% were explained by the SCQI and SPQI, respectively (Table VI).

DISCUSSION

Seasonal variations in T_{soil} can be explained by the fact that T_{soil} tracks the changes in the surrounding air temperature. The high T_{soil} at MA and MB can be attributed to the presence of underground mine fires near these sites. Underground coal fires are known to increase T_{soil} through conductive or convective heat (Kuenzer and Stracher, 2012). The ρ_{b} is a parameter describing soil compactness; if soil is compacted, ρ_{b} increases and the total porosity correspondingly decreases. High ρ_{b} values were found near the mining sites, probably because of compaction caused by the heavy vehicles that transport coal and overburden materials near MA and MB (Maiti, 2013; Mukhopadhyay *et al.*, 2014).

TABLE VI

Stepwise multiple linear regression between soil biological quality index (SBQI) and soil physical, chemical, and metal quality indices (SPQI, SCQI, and SMQI, respectively)

SQI[a)]	R^2		Variance	Percentage explained
	Total	Without corresponding SQI		
				%
SPQI	0.849	0.861	0.033	24
SCQI	0.849	0.826	0.023	17
SMQI	0.849	0.770	0.079	59
Total			0.135	

[a)] Soil quality index.

Soil WHC indicates the maximum amount of water that can be held in saturated soil, while soil moisture indicates the amount of water stored in soil pores. Both depend on soil porosity and the size distribution of pores in the soil. With mining activities, soil WHC decreases, because this parameter is dependent on soil organic matter, soil texture, the density of soil minerals, vehicular traffic, and natural processes (*e.g.*, drying/wetting and freezing/thawing cycles), which are involved with soil consolidation and structure regeneration (Carter, 1990). As soil texture is extremely difficult, if not impossible, to alter in a short period of time and at short distances under natural conditions, the use of heavy vehicles and the deposition of particulate matter seem to be responsible for the seasonal and spatial variations in ρ_{b}, total porosity, and WHC in the coal mining areas (Mohapatra and Goswami, 2012; Mukhopadhyay *et al.*, 2014; Rout *et al.*, 2014).

The higher ρ_{b} values at NA and NB than at CK can be explained by the soil organic matter content. The decomposition and transformation of above- and belowground plant detritus (litter) are the main processes by which soil organic matter is formed (Cotrufo *et al.*, 2013). Organic matter, being light and porous, improves soil structure. Due to reduced vegetation cover at NA and NB there was an insufficient amount of litter, so these sites had a lower organic matter content and lower soil microbial activities than site CK (Pandey *et al.*, 2014b; de Quadros *et al.*, 2016). An increase in ρ_{b} and a decrease in total porosity reduce soil infiltration and WHC (Li *et al.*, 2007). A high ρ_{b} and low total porosity and WHC in summer, followed by winter and the rainy season, can be explained by the fact that soil expansion and contraction are dependent on soil moisture. Humus in soil forms gel reinforced by organic and inorganic particles, which may increase the volume of the matrix after absorption of moisture (Mora and Lázaro, 2014).

Coal mining typically exposes sulfur-containing pyrites that oxidize to sulfuric acid when exposed to oxygen, water, and certain aerobic bacteria, resulting in a low soil pH (Gitt and Dollhopf, 1991). During the rainy season, when the conditions for pyrite oxidation are optimal (Bell *et al.*, 2001), acidic air pollutants wash out of the atmosphere into the soil, and thus reduce soil pH (Singh and Agrawal, 2008). High ρ_{b} and low total porosity play further role in reducing surface soil pH by restricting infiltration (Yang and Zhang, 2011). During the rainy season, organic debris rapidly decomposes and generates CO_2, which reacts with water to form carbonic acid and other mild organic acids (humic and fulvic) during litter humification and may reduce soil pH in the non-coal mining areas (Good *et al.*, 2014). The EC indicates the soluble salt content in soil, and the high EC found at the coal mining sites can be attributed to the large deposits of anions (NO_3 and SO_4) and cations (Na, K, and NH_4) present in the coal mining areas (Singh *et al.*, 2007). Summer provides the greatest potential for deposition, so had the highest EC. Low dispersion and deposition may account for the low EC observed in winter, while during the rainy season, the solubility of salts in water and their infiltration may explain the low EC values recorded (Pariente, 2001).

High TOC values at MA and MB were probably caused by fossilized organic substances present in the soil of coal mining areas (Pandey *et al.*, 2014b). The TOC enters soil through the decomposition of plant and animal residues, root exudates, living and dead microorganisms, and soil biota (de Quadros *et al.*, 2016). High microbial biomass and decomposition rate in the rainy season may be responsible for the high TOC levels, and the differences among NA, NB, and CK were due to high plant residue and root exudate levels at CK. The lower soil N content at the coal mining sites than at CK may be caused by an insufficient amount of mineralizable organic nitrogen, lower mineralization and nitrification rates, reduced vegetation cover, and lack of microbial activity (Maiti, 2013). In acidic soil, phosphorous forms insoluble Fe and Al phosphates (dos Santos *et al.*, 2013); consequently, its available form is reduced in the soil near coal mines.

Dutta and Agrawal (2002) also reported maximum ammonification and nitrification rates during the rainy season and minimum values during the summer in mine-spoil soils of an opencast coal mine in India. Increases in AP during the rainy season may be caused by waterlogging, increased mineralization of soil organic P, or a combination of both (Chen *et al.*, 2003). Seasonal and site-specific fluctuations in the SO_4-S content can result from changes in the balance between microbial activity, leaching, surface run-off, atmospheric inputs, and plant uptake of sulfate (Ghani *et al.*, 1990). The seasonal and site-specific results suggest that the soil SO_4-S content in coal mining areas is mainly affected by atmospheric deposition.

During the process of coal mining, huge quantities of mine spoil and dust are produced along with coal, which may be responsible for the high HM levels observed in the Jharia coalfield (Rout *et al.*, 2014). Natural weathering may degrade these exposed, coal-mine spoils into small, clay-sized particles. Through this process, large amounts of fine particles enriched in HMs are released into the environment within the course of a few weeks (Masto *et al.*, 2011). The high Fe, Mn, and Zn contents in the area may be attributed to the minerals associated with geological formations (Singh *et al.*, 2012); however, the considerable spatial variations in HM contents suggest that anthropogenic activities related to coal mining and mine fires have played a role. Two main factors can be responsible for the site-specific variations in soil HM contents: vegetation cover and distance from the coal mine (Mukhopadhyay *et al.*, 2013). The high vegetation cover at site CK may be the reason for the relatively low HM content at this site. High concentrations of Ni, Cu, and Cr in the soils at NB and NA can be attributed to the associations of these HMs with coal particles, their transportation and deposition behaviors, and their integration into soil upper layers (Rai *et al.*, 2010).

Seasonal variations in soil HM levels depend on variations in metal deposition rates, soil physical, chemical, and biological properties, soil-metal interactions, and metal behavior due to weather conditions. The sorption of metals on soil organic matter and oxyhydroxides of Fe, Mn, and clay minerals depends upon soil pH (Alloway, 2013). During the summer, pollutants are deposited at a high rate, and due to a relatively high pH, low total porosity, and high ρ_b, the vertical movement of HMs in the soil is restricted. The low HM contents in the topsoil during the rainy season can be attributed to a lower deposition of HMs, washout, and the subsequent leaching of metals to greater depths in the soil.

Microbial biomass gives estimates of the net flux of carbon and nitrogen through microbial pools, and thus reflects the contribution of soil microorganisms both as a source and a sink of C and N in soil ecosystems (de Quadros *et al.*, 2016). Acidic air pollutants and HMs released during coal mining activities can alter the microbial biomass after deposition on soil surface (Asensio *et al.*, 2014). Soil physicochemical characteristics have a great impact on microbial biomass and microbial activity (Maiti, 2013). The high MBC and MBN values observed during the rainy season may be caused by nutrient immobilization by microbes from decomposing litter. Decomposition rate of litter and microbial activities are reported to be at their peak during this season (Ngatia *et al.*, 2014). Low MBC and MBN values in the winter may be due to low activities of microorganisms and slow decomposition rate of litter in dry and cool winter.

Site-specific and temporal variations in the ratio of MBC/MBN may be due to low levels of microbe-available organic matter at the sites near coal mining areas, as carbon mineralization from fossilized organic matter is lower than that from soil organic matter (Waschkies and Hüttl, 1999). The availability of organic matter further reduces during dry season (Ngatia *et al.*, 2014). The spatial variability of SR rates among the sites near the coal mines and the non-mining sites may be affected by the spatial distribution of fine roots (Saiz *et al.*, 2006). There are few fine roots in coal mining areas because of the sparse vegetation cover. The SR was the greatest during the rainy season, probably because root growth and microbial activity are the highest under wet conditions (Qi *et al.*, 2010).

The PCA revealed that total porosity, WHC, T_{soil}, pH, TN, MBN, SR, Ni, and Zn were the most reliable indicators for developing SQIs at our study sites. All of the SQIs indicated that site CK was the least affected by mining activities in all the seasons. Sites NA and NB were moderately affected during all the seasons, except for SPQI in summer. Sites MA and MB were severely affected by coal mining in all the seasons, except for SMQI in winter and the rainy season. The differential gradation among the sites and seasons reflect the variability of soil physical, chemical, biological, and metallic components. Strong correlations with the species richness of woody and herbaceous vegetation confirm the practical utility of SPQI, SCQI, SMQI, and SBQI. Stepwise multiple linear regression between SBQI and the other SQIs revealed that the variation in SBQI was largely determined by SMQI, suggesting that SBQI can be used as an indicator to assess HM pollution in soil around coal mines.

CONCLUSIONS

Significant seasonal and site-specific variations in soil physical, chemical, and biological properties were observed in the coal mining areas studied. The T_{soil} and ρ_{b} were the highest, while total porosity, WHC, and soil moisture were the lowest at the sites closest to the coal mines. Soil pH was inversely related to EC, with low pH values at the sites close to coal mines. The TOC and SO_4-S levels were the highest near coal mines; however, the N and P levels were the highest far from the coal mines. Soil biological properties (*i.e.*, MBC, MBN, MBC/MBN, and SR) showed decreasing trends with increasing HM contents at the sites close to coal mines. The results of PCA suggest that T_{soil}, TN, and SR may be used as indicators of soil quality in coal mining areas; Ni, Pb, and Zn were the most important HMs contributed by the coal mining activities. Multiple linear regression revealed that soil biological properties are mostly influenced by soil HM contents in coal mining areas, followed by soil physical and chemical properties.

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