Soil organic carbon – the most reliable indicator for monitoring land degradation by soil erosion

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Degradation due to erosion, salinity, waterlogging, contamination, etc. reduces the quality of land. Soil and water resources are affected initially then the bio-resources. Uncontrolled degradation processes lead to desertification of land and the ecosystem functions are disturbed. In India, soil erosion has produced maximum degraded lands due to mismanagement and indiscriminate use of land resources. Monitoring of land degradation status is essential to take appropriate and timely soil-conservation measures. Numerous soil and land-quality indicators are used to assess the degradation status. In this study, an attempt has been made to select a few reliable indicators using multivariate statistical tools. Eroded land of southern Karnataka was selected for the study using remotely sensed satellite imageries. Soil samples were collected depth-wise in profiles at different landforms and land uses. There were 24 soil quality indicators estimated from eroded lands to select few indicators for monitoring degradation status. Principal component analysis was employed for the reduction of 24 indicators. Out of the 24 principal components formed, only seven accounted for maximum variance. Twelve soil quality indicators were selected from the seven components based on the highest loadings. Linear discriminant analysis was employed to obtain the most discriminating soil quality indicators from among the 12 selected. Soil organic carbon (SOC) emerged as the most discriminating soil quality indicator with maximum loadings (–2.43). Apart from SOC, there were four other indicators with loadings > 1.0. Electrical conductivity (1.95), available soil water (1.45), micro-aggregates (–1.18) and dehydrogenase activity (1.08) have also gained considerable importance along with SOC in monitoring degradation status of land by soil erosion.

Keywords: Erosion, quality indicators, land degradation, multivariate analysis, soil organic carbon.

THE productivity of land declines due to degradation. In degraded lands, soil, water and bio-resources are in a disturbed state compared to productive lands. Erosion is defined as the detachment of soil particles from one place and deposition elsewhere through water, wind, coastal wave, snow, gravity and other factors. Selective removal of finer particles from the soil results in land and environmental degradation. Erosion due to ecological balance, known as geological erosion, will not cause any detrimental effect on the natural resources, whereas that due to mismanagement and indiscriminate use of soil and land resources causes accelerated erosion, which is disastrous to the natural resources. It leads to decline in crop production and sustainable productivity in agriculture. In India, out of 187.8 mha of degraded lands, 162.53 mha is affected by soil erosion which is 49.4% in total geographical area (328 mha) and 86.4% among degraded land. Loss of top fertile soil by erosion is estimated to be about 5334 mt/yr, out of which 29% is lost permanently to the sea, 10% deposited in reservoirs and 59% deposited as alluvium at different places[1]. Accelerated erosion is continuous if proper conservation measures are not adopted. It is also influenced by land uses and landforms. Hence, wide variation is present in the soil and land resources and also in their quality. Assessment of degraded lands for quality is done through some selected quality indicators. There are several quality indicators available, but it is tedious and time-consuming to consider all of them. An attempt was made to arrive at some reliable indicators to monitor land degradation by erosion.

The National Bureau of Soil Survey and Land Use Survey National Remote Sensing Agency and Karnataka State Remote Sensing Application Centre reported that large tracts of degraded land exist in the southern parts of Karnataka. According to these reports, Kolar district is severely affected by erosion; hence, this district was selected for the present study. The climate is semi-arid tropical monsoon with an annual rainfall of about 733 mm. Maximum rainfall is received during August through October. The mean annual temperature is 24.4°C. Satellite imageries of the entire district in the 1 : 50,000 scale (57G/15, 57G/16, 57K/03, 57K/04 and 57K/08) were interpreted in conjunction with the respective toposheets, based on tonal variations, texture and pattern. Lowlands and uplands were demarcated. The upland areas were further divided into summits and midlands. Gullies were observed with light tones in irregular patches in the midlands. The other areas showed regular pattern of either increasing or decreasing tones. Very pale yellow tones and the same tones with streaks were demarcated as severely eroded land. Yellow to light brown tones were demarcated as moderately eroded land and light brown to brown tones as slightly eroded land. It showed that the uplands are in different phases of erosion. Many places in the uplands were observed with white patches in the imageries and they were identified as gravelly or boulder lands from the toposheets. Two imageries, namely 57G/15 and 57K/03 were selected for the characterization of erosion status in the district. These two

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imageries cover the major areas of Sidlaghatta, Chinthamani and Srinivaspur taluks of the district. Based on the variation in tone and pattern, three transects were selected covering both uplands and lowlands. All transects were traversed in detail in the field. The first transect is located in Sidlaghatta taluk near Jangamakote village, the second transect is also located in Sidlaghatta taluk near Bhaktarahalli village and the third transect is located in Srinivaspur taluk near Bagalahalli village. Representative areas were selected, nine profiles were opened and the pedons were exposed (Table 1). Soil samples were collected from each pedon, horizon-wise, for laboratory analysis during April 2008. The samples were air-dried and passed through a 2 mm sieve. These processed soil samples were preserved and used for the quantification of soil physical, chemical and biological indicators using standard procedures (Table 2). Descriptive statistics of the soil physical indicators is given in Table 3, soil chemical indicators in Table 4 and soil biological indicators in Table 5.

Principal component analysis (PCA) was done with all the 24 quality indicators. It was then reduced to few indicators, which explains maximum variance using eigen value. The indicators selected from the PCA were used for discriminant analysis. In the selected principal components (PCs), the measured indicators with maximum loadings were selected. Soil indicators with higher loadings were selected from each PC. In order to identify the most discriminating indicators, a pre-determined group is needed. In the study area there are two types of soil, viz. red and laterite soils under erosion. The dataset was arranged separately for the two soils under erosion and linear discriminant analysis was used to obtain the most discriminating soil quality indicator. The analysis was performed with Statistical Package for Social Sciences (SPSS) software. There were seven PCs with the eigen value more than one. These were responsible for 82% of the total variation created by erosion (Table 6). The remaining 17 components accounted for only 18% variance and therefore were rejected. The first component accounted for 17.8% variance ($Y\text{pc}_1$) and the highest loadings were found with micro-aggregates followed by available soil water, bulk density and clay. This was termed as 'structural factor' as most of the indicators are important for soil structural function. Contribution from the second component ($Y\text{pc}_2$) to the total variance was 15.0% and the highest loading was found with biomass carbon, biomass nitrogen and available phosphorus which can be named as 'biomass factor'.

$$Y\text{pc}_1 = 0.92\ (\text{micro-aggregates}) - 0.77\ (\text{bulk density}) + 0.75\ (\text{available soil water}) + 0.69\ (\text{clay}) + \ldots$$

The third component accounted for 13.7% variance ($Y\text{pc}_3$). There were two indicators found with higher loadings, viz. organic carbon and dehydrogenase activity, which can be named as 'biological factor'. The fourth PC accounted for 11.0% variance ($Y\text{pc}_4$) and the maximum

Table 1. Site characteristics and pedon locations in Kolar district

Taluk	Transect location	Pedon no.	Location of pedon	Landforms	Land use	Slope (%)	Run-off	Erosion	Surface stoniness (cm)	Depth of soil (cm)
Sidlaghatta	Jangamakote	1	Lat.: 13°16′36.71″N Long.: 77°51′26.79″E	Very gently sloping upland	Current fallow	1–3	Medium	Moderate	2–7.5	80
		2	Lat.: 13°16′53.49″N Long.: 77°52′02.71″E	Very gently sloping upland	Scrub forest	1–3	Slow	Slight	< 2	> 150
		3	Lat.: 13°17′08.49″N Long.: 77°52′00.20″E	Very gently sloping upland	Eucalyptus forest	3–5	Medium	Moderate	< 2	119
		4	Lat.: 13°17′13.17″N Long.: 77°51′59.84″E	Moderately sloping upland	Eucalyptus forest	5–10	Very rapid	Severe	7.5–25	55
		5	Lat.: 13°17′17.89″N Long.: 77°52′04.94″E	Very gently sloping lowland	Cultivable land	1–3	Slow	Slight	< 2	> 150
	Bhaktarahalli	6	Lat.: 13°19′47.88″N Long.: 77°50′57.07″E	Very gently sloping upland	Cultivable land	1–3	Slow	Moderate	< 2	> 150
		7	Lat.: 13°19′51.41″N Long.: 77°50′50.46″E	Gently sloping upland	Eucalyptus forest	3–5	Rapid	Moderate	2–7.5	126
Srinivaspur	Bagalahalli	8	Lat.: 13°17′20.26″N Long.: 78°05′43.88″E	Very gently sloping upland	Current fallow	1–3	Moderate	Moderate	2–7.5	> 150
		9	Lat.: 13°17′28.87″N Long.: 78°06′01.91″E	Very gently sloping upland	Cultivable land	1–3	Slow	Slight	< 2	> 150

Table 2. Analytical procedures for different soil quality indicators

Soil quality indicator	Methodology
Physical indicators	
Sand (%)	International pipette method[5]
Silt (%)	
Clay (%)	
Bulk density (mg m^{-3})	Core method[6]
Available soil water (cm)	Pressure plate apparatus[6]
Micro-aggregates (%)	According to Sarma and Das[7]
Total porosity (%)	Keen's cup[8]
Clay dispersion (%)	According to Rengasamy *et al.*[9]
Chemical indicators	
pH or soil reaction (1 : 2.5 soil : water suspension)	Potentiometry[6]
Electrical conductivity (EC; 1 : 2.5 soil : water saturation extract) (dSm^{-1})	Conductivity bridge[6]
Cation exchange capacity (CEC; cmol (p+) kg^{-1})	NH_4OAc method[10,11]
Available nitrogen (kg ha^{-1})	Alkali–permanganate method[12]
Available phosphorus (kg ha^{-1})	Bray's method for acidic soils[13] and Olsen's method for neutral and alkaline soils[14]
Available potassium (kg ha^{-1})	Neutral normal ammonium acetate extract method[6]
Available copper (mg kg^{-1})	DTPA extraction method[6]
Available iron (mg kg^{-1})	
Available manganese (mg kg^{-1})	
Available zinc (mg kg^{-1})	
Biological indicators	
Organic carbon (g kg^{-1})	Walky and Black method as described by Jackson[6]
Carbon dioxide evolution (μg CO_2–C g^{-1} day^{-1})	Alkali trap method[15]
Dehydrogenase activity (μg of TPF g^{-1})	According to Casida *et al.*[16]
Urease activity (μg of NH_3 activity g^{-1})	According to Tabatabai and Bremner[17]
Soil microbial biomass carbon (μg g^{-1})	According to Carter[18]
Soil microbial biomass nitrogen (μg g^{-1})	

Table 3. Descriptive statistics of soil physical quality indicators

	Soil quality indicator							
Statistical parameter	Sand (%)	Silt (%)	Clay (%)	Bulk density (mg m^{-3})	Available soil water (cm)	Micro-aggregate (%)	Porosity (%)	Clay dispersion (%)
Mean	46.5	14.2	39.3	1.5	31.3	12.8	38.8	6.3
Median	45.5	12.2	39.6	1.4	28.0	12.7	39.6	2.9
Minimum	33.1	0.7	22.3	1.3	7.5	1.7	22.3	2.9
Maximum	69.10	69.1	38.6	57.1	1.8	69.8	29.2	49.6
Standard error	1.41	1.4	1.3	1.3	0.1	2.1	1.2	0.7
Standard deviation	9.35	9.4	8.9	8.6	0.1	14.2	8.1	4.9

loading was found with available nitrogen and pH. This can be named as 'nutrient factor'.

$Y\text{pc}_2$ = 0.92 (biomass carbon) + 0.92 (biomass nitrogen) + 0.66 (available phosphorus) + 0.63 (available potassium) + . . .

$Y\text{pc}_3$ = 0.92 (dehydrogenase) + 0.86 (organic carbon) + 0.79 (CO_2 evolution) + 0.68 (urease) + . . .

The fifth and sixth components contributed 8.7% and 8.1% of the total variance respectively. Manganese from the fifth component and sand from the sixth component were found with highest loadings. These can be named as 'micronutrient factor' and 'textural factor' respectively.

$Y\text{pc}_4$ = 0.76 (available nitrogen) – 0.73 (pH) + . . .

$Y\text{pc}_5$ = 0.86 (manganese) + 0.63 (iron) + . . .

$Y\text{pc}_6$ = 0.92 (sand) – 0.75 (silt) + . . .

$Y\text{pc}_7$ = 0.72 (electrical conductivity) + 0.67 (clay dispersion) + . . .

The seventh component accounted for 7.7% of the total variance ($Y\text{pc}_7$) and the maximum loadings were with electrical conductivity and clay dispersion. This can be named as 'electrolyte factor'. Seven PCs were observed with one dominating and other associating soil quality indicators[2]. In each component, the loading values for

Table 4. Descriptive statistics of soil chemical quality indicators

Statistical parameter	Soil quality indicator									
	pH	EC (dSm^{-1})	CEC (cmol (p+) kg^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Cu (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Zn (mg kg^{-1})
Mean	5.93	0.38	11.42	128.22	26.96	69.02	0.90	5.15	27.78	0.51
Median	5.97	0.32	11.33	128.60	15.20	59.50	0.83	4.40	23.10	0.42
Minimum	4.59	0.16	4.50	40.80	1.30	33.00	0.22	0.60	3.00	0.26
Maximum	7.67	1.19	16.30	238.30	189.80	166.00	2.22	20.80	62.44	1.48
Standard error	0.13	0.03	0.33	5.39	5.54	4.09	0.07	0.63	2.41	0.04
Standard deviation	0.88	0.22	2.20	35.75	36.77	27.11	0.49	4.19	16.01	0.23

Table 5. Descriptive statistics of soil biological quality indicators

Statistical parameter	Soil quality indicator					
	Organic carbon (g kg^{-1})	CO_2 evolution (μg CO_2–C g^{-1} day^{-1})	Dehydrogenase activity (μg of TPF g^{-1})	Urease activity (μg of NH_3 activity g^{-1})	Biomass carbon (μg g^{-1})	Biomass nitrogen (μg g^{-1})
Mean	3.19	14.88	13.88	25.01	308.86	34.63
Median	3.04	15.25	7.92	20.36	300.14	32.81
Minimum	2.00	8.20	1.00	1.90	85.26	10.25
Maximum	6.00	24.40	85.05	77.78	741.03	86.45
Standard error	0.14	0.64	2.86	3.32	27.57	3.14
Standard deviation	0.90	4.05	18.11	21.02	174.35	19.89

Table 6. Rotated principal components of soil quality indictors

Soil quality indicator	Principal components						
	1	2	3	4	5	6	7
Sand	–0.17	–0.11	0.04	0.25	–0.02	**0.92**	–0.02
Silt	–0.41	–0.16	–0.15	0.26	0.08	–0.75	–0.08
Clay	**0.69**	0.28	0.11	–0.54	–0.06	–0.23	0.09
Bulk density	**–0.77**	–0.16	0.17	–0.14	0.11	0.25	–0.05
Available soil water	**0.75**	–0.30	–0.18	–0.02	–0.20	0.13	–0.06
Micro-aggregates	**0.92**	–0.12	–0.02	0.18	0.00	0.04	0.08
Porosity	0.59	0.04	0.49	–0.20	–0.29	0.02	–0.08
Clay dispersion	0.42	–0.05	0.46	–0.01	–0.07	–0.01	0.67
pH	–0.33	0.26	–0.10	–0.73	–0.35	–0.08	–0.06
EC	0.14	0.54	–0.04	–0.22	0.09	0.02	**0.72**
CEC	0.62	0.15	–0.07	–0.20	–0.08	0.28	0.04
Available nitrogen	–0.02	0.14	0.13	**0.76**	–0.11	0.01	–0.17
Available phosphorus	–0.17	**0.66**	–0.01	0.46	0.38	–0.08	0.27
Available potassium	–0.14	0.63	–0.07	0.19	0.35	0.28	0.22
Copper	0.29	0.12	–0.13	0.35	0.45	–0.06	–0.64
Iron	–0.17	–0.02	–0.04	0.60	0.63	–0.10	–0.21
Manganese	–0.26	–0.02	0.07	–0.03	**0.86**	–0.05	–0.02
Zinc	–0.40	0.46	–0.14	0.35	0.34	0.15	0.42
Organic carbon	0.23	–0.10	**0.86**	–0.02	0.00	0.26	0.17
CO_2 evolution	–0.25	–0.18	0.79	0.02	0.17	0.01	0.01
Dehydrogenase activity	–0.10	0.12	**0.92**	0.11	–0.10	0.05	0.09
Urease activity	–0.27	0.37	0.68	0.17	0.05	–0.33	–0.14
Biomass carbon	0.09	**0.92**	0.02	–0.13	–0.12	–0.06	–0.02
Biomass nitrogen	0.08	0.92	0.04	–0.08	–0.13	–0.06	–0.04
Eigen value	4.27	3.60	3.30	2.64	2.10	1.95	1.84
Percentage variance	17.8	15.0	13.7	11.0	8.7	8.1	7.7
Cumulative variance	17.8	32.8	46.6	57.6	66.3	74.4	82.0

Corresponding soil quality indicators in bold letters were selected for discriminant analysis.

each indicator were examined. In the first PC, a highest loading was observed with micro-aggregates. The next higher loadings were for closely related indicators of micro-aggregates. The components contributing to maximum variance will always become first PC and hence, more quality indicators were selected from this component. In this case, four quality indicators were selected for discriminant analysis. Two each were selected from the second and third components with highest loadings. One quality indicator each from the fourth, fifth, sixth and seventh PCs was selected with highest loading. Selection of quality indicators from each PC decreased because the contribution had reduced and the total number of quality indicators became 12. The most discriminating soil quality indicator was selected from 12 indicators. Linear discriminant analysis was employed (Y_{df}).

$$Y_{df} = -2.43 \text{ (organic carbon)} + 1.95 \text{ (electrical conductivity)} + 1.45 \text{ (available soil water)} - 1.18 \text{ (micro-aggregates)} + 1.08 \text{ (dehydrogenase activity)} + 0.88 \text{ (biomass carbon)} + 0.71 \text{ (bulk density)} + \ldots$$

According to the standardized linear discriminant function coefficient, the highest value was observed with organic carbon (–2.43) followed by electrical conductivity (1.95), available soil water (1.45), micro-aggregates (–1.18) and dehydrogenase activity (1.08). SOC emerged as the most discriminating soil quality indicator in the eroded land (Table 7). SOC concentration is more in the surface layer and of low density; soil organic matter is preferentially removed by surface run-off[3]. Frequent tillage and different land uses under the eroded lands might have created much variation in the distribution of SOC[4]. Organic carbon is an integral part of the physical, chemical and biological properties of the soil. In any soil ecosystems, a change in its content affects other soil properties. Therefore, SOC is a much reliable soil quality indicator and its monitoring over time indicates the quality of the land, whether aggrading, degrading or stable. Twelve soil quality indicators were selected from the seven components based on the highest loadings. Linear discriminant analysis was employed to obtain the most discriminating soil quality indicators from among the 12. SOC was the most discriminating soil quality indicator with the maximum loadings (–2.43) and accounted for 36% of the total loadings. There were four other indicators with loadings > 1.0. Electrical conductivity was the second highest indicator (1.95) and accounted for 23% of the total loadings. Next was available soil water (1.45) with 13% loadings. Micro-aggregates (–1.18) and dehydrogenase activity (1.08) were the fourth and fifth, accounting for 9% and 7% respectively. Two indicators from physical, one indicator from chemical and two indicators from biological properties have emerged with highest loading, which accounted for 75% of the total loadings. 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. Electrical conductivity, available soil water, micro-aggregates and dehydrogenase activity can also be used along with SOC.

Table 7. Linear discriminant analysis for selected soil quality indicators

Soil quality indicator	Coefficient of linear discriminant function
Sand	0.02
Clay	0.34
Bulk density	0.71
Available soil water	**1.45**
Micro-aggregates	**–1.18**
EC	**1.95**
Available nitrogen	0.02
Available phosphorus	–0.54
Manganese	0.57
Organic carbon	**–2.43**
Dehydogenase activity	**1.08**
Biomass carbon	0.88

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