PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol x(x): xx–xx
https://doi.org/10.14719/pst.4607

HORIZON
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RESEARCH ARTICLE

Soil quality assessment and mapping in basaltic terrain of Central India for sustainable soil and crop management using integrated PCA and GIS

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OPEN ACCESS

ARTICLE HISTORY

Received: 11 June 2024
Accepted: 23 August 2024

Available online
Version 1.0 : 31 August 2024

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

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Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
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CITE THIS ARTICLE

Ingle SN, Nagaraju MSS, Kumar N, Prasad J, Tiwary P, Srivastava R, Sahu N, Lal B, Das SP, Pradhan AK, Beura K, Karad GU. Soil quality assessment and mapping in basaltic terrain of Central India for sustainable soil and crop management using integrated PCA and GIS. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.4607

Abstract

Soil quality is very important and significant concept and its assessment and mapping helps to maintain the present level of soil productivity and to meet the demand of future with respect to agricultural production as well as its sustainability. A detailed survey was conducted in the Bareli watershed of Seoni district, Madhya Pradesh, at a 1:10000 scale using high-resolution satellite data and Geographic Information System (GIS) technology. The survey identified and mapped 5 soil series: Diwartola, Diwara, Bareli-1, Bareli-2 and Bareli-3. Soil quality was evaluated based on morphological, physical and chemical properties as well as fertility parameters. Key indicators for soil quality assessment included sand, silt, clay content, bulk density, hydraulic conductivity, available water capacity and coefficient of linear extensibility (COLE). Chemical properties, pH, electrical conductivity, organic carbon, cation exchange capacity and soil fertility parameters like N, P, K, Fe, Mn, Cu and Zn were considered. The SQI was calculated using integrated principal component analysis, which involved selecting a minimum data set (MDS), assigning weights and scoring indicators. The results revealed that Diwartola soils had high quality (242.7 ha, 13.5 % TGA), Bareli-1 and Bareli-3 soils were of medium quality (462.8 ha, 25.7 % TGA), while Diwara and Bareli-2 soils were of low quality (966.1 ha, 53.8 % TGA). Agro-interventions such as agri-horticulture, agro-forestry, silvi-pasture, intensive cultivation and soil and water conservation measures were recommended based on the different mapping units.

Keywords

Soil quality; MDS; PCA; bareli watershed; basalt; land recourse management

Introduction

The ongoing utilization, mismanagement and exploitation of land resources have led to their degradation and ultimate destruction (1). In order to sustain developmental processes in the long-term, it is necessary to have a judicious allocation of land for various activities according to its sustainability and capability (2-4). The sustainable productivity of land resources is widely recognized as the cornerstone of all life forms. Consequently, the management, conservation and development of these resources are warranted.

Soil stands as a pivotal natural resource, with its quality reflecting the cumulative impact of management practices on various soil properties crucial for crop productivity and sustainability (5). While the literature offers diverse definitions of soil quality, it is commonly understood as "the capability of the soil to function" (6) or soil quality refers to the capacity of soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal health (6). And delineated soil quality in phrases of 5 primary functions: sustaining biological diversity, regulating and partitioning water and solute flow, buffering and detoxifying organic and inorganic materials, storing and cycling nutrients and providing guide for socio -economic systems (7) observed that, soil quality cannot be considered in isolation but must be contextualized within specific land uses and their corresponding management practices. In the agricultural context, Soil Quality (SQ) is defined as the soil's capacity to sustain crop growth without undergoing degradation or cause impairment to the environment (8). Consequently, soil quality emerges as a critical and significant concept for agricultural production and sustainability. However, it is widely unquestioned that in semi-dry domains, crop productivity faces inactivity on account of inadequate administration practices, mainly rainfed conditions and restricted system availability (9, 10).

As soil erosion, organic matter loss, declining fertility and productivity, chemical and heavy metal contamination and air and water quality deteriorate; soil quality is becoming increasingly important. A quantitative judgment of soil quality holds promises in providing essential insights for the growing the demand of food and fibre of a growing global population. Soil quality assessment can range from basic visual observations to more intricate processes involving numerous laboratory analyses and the computation of soil quality indices (11).

Typically, soil quality evaluation involves the identification of a set of soil properties deemed indicative of soil quality. These indicators are crucial as soil functions respond sensitively to them (12), necessitating that they be easily measurable (13). To identify these minimum soil dataset (MDS) various methods have been used, including principal component analysis (PCA), expert opinion (EO) and factor analysis (14-16). PCA is employed to streamline a large volume of data by categorizing soil properties into principal components (PC), thereby facilitating indicator selection (15). Expert opinion, drawing on available literature, field experience and soil scientists' knowledge, underscores the cause-effect relationships of soil properties influenced by pedogenic processes (17-19). Once the MDS is identified, a weighted additive method is used to normalize and integrate these indicators (20). In the context of PCA, the variance explained by each component serves as the weight for that component (15, 21, 22).

The Seoni district of Madhya Pradesh is facing frequent erratic rainfall, continuous depletion of vegetative cover, increased soil erosion and low crop productivity (2). Detailed characterization of the soils, including their physical, chemical properties and fertility is essential for assessing soil quality and managing land resources to support sustainable agricultural production and hence present investigation for assessment of soil quality was carried out in the Bareli watershed of Seoni district.

Materials and Methods

Study area

The Bareli watershed 22° 29’ 39” to 22° 32’ 10” N latitude and 79° 46’ 44” to 79° 49’ 50”E longitude E (Fig. 1) covers an area of 1780 ha in the Seoni district, Madhya Pradesh With an average annual temperature of 28.4˚C and an average annual rainfall of 1100 mm, the climate is primarily dry sub -tropical. The region has a characteristic of in a typical basaltic landscape, a hyperthermic soil temperature regime and an ustic soil moisture regime. The main crops

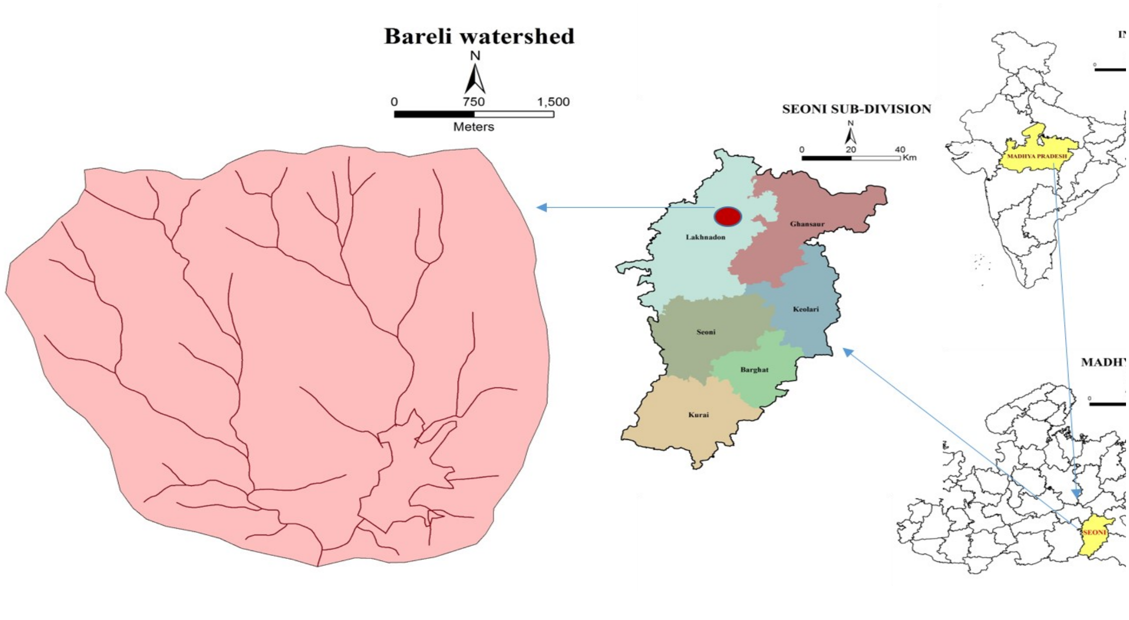

Fig. 1. Study area of Bareli watershed

grown during the monsoon season (June to September) are Sorghum (*Sorghum Bicolor* L.), pigeonpea (*Cajanus cajan* L.), maize (*Zea mays* L.), and cotton (*Gossypium hirsutum*). Groundnuts (*Arachis hypogaea* L.) is the dominant winter or post-monsoon season (October-January) having growing period (LGP) of 153 days.

Soil sampling and analysis

To delineate the different landform units and current land use/cover classes, the area was explored using interpreted maps (landforms and land use/land cover maps) derived from toposheet data (55 N/14 and 55 N/15) and satellite data (IRS-P6 LISS-IV). Twenty-eight pedon representing different landform were examined in order to comprehend the soil heterogeneity in the watershed. Slope, stoniness, erosion, colour, texture, structure and other site and soil characteristics were noted (23) and soils were classified as per Keys to Soil Taxonomy (24). There were 5 series with 24 mapping unit phases of soil series at 1:10000 rule. A representative soil sample weighing close to 2.0 kg was collected from each horizon in all of the representative pedons. The processed soil samples were analysed. For pH and electrical conductivity (EC), 1:2 soil-to-water method was used (25), potassium dichromate method was used to estimate the amount of soil organic carbon (SOC) (26). The $CaCO_3$ equivalent (%) was analysed using the rapid titration method (27). With the 1 N neutral ammonium acetate technique, the cation exchange capacity (CEC) and exchangeable cations were calculated (28, 29). Alkaline potassium permanganate ($KMnO_4$) solution was used to measure the amount of available nitrogen by measuring the amount of ammonia released (30). Available phosphorus was estimated using 0.5 M $NaHCO_3$ extractant (31) and neutral normal NH_4OAc method was used to estimate available potassium using flame photometry (32). Atomic absorption spectrophotometer was used to determine available micronutrient cations (Fe, Mn, Cu and Zn) after DTPA-$CaCl_2$ extraction at pH 7.3 (33). The particle-size distribution was estimated following International Pipette technique and the dry clod coating method was used to determine bulk density (34). The moisture retention was measured at -33 kPa and -1500 kPa using pressure plate apparatus and available moisture was calculated by taking differences at both moisture level (34). The process proposed by Schafer and Singer was adopted to determine the coefficient of linear extensibility (COLE) (35).

Soil quality assessment

By calculating the soil quality index (SQI), the quality of the soil was evaluated. A management goal was defined, indicators were chosen as the minimum data set (MDS), weights were assigned, the indicators were scored and SQI was calculated. Among the soil functions, the production function is prioritized in the current study, even though both edaphic and non-edaphic factors affect crop cultivation.

Principal component analysis was carried out to choose the indicators. Often many factors (SQ indicators) that are neither locally relevant nor mutually exclusive are employed in soil quality assessment methodologies, which prevent the production of data that have any real-world application (14, 15). Soil depth, sand, silt, clay, BD bulk density, HC hydraulic conductivity, AWC available water capacity and coefficient of linear extensibility (COLE) of soil, pH, electrical conductivity, organic carbon and cation exchange capacity and available N, P, K, Fe, Mn, Cu and Zn have been considered as indicators for soil quality assessment.

Data pre-processing: A total of 28 pedons were studied to bring out maximum variability in soils. Before the PCA analysis, the data were analyzed for sample sufficiency (36). Homogeneity (37) and normality (38).

Data sufficiency: The measure of sample adequacy (MSA) for the individual indicator is shown in the (Table 1). As recommended by (36). The variables with MSA less than 0.5 were not included for the further studies. This increased the overall MSA from 0.6 to 0.72.

Data homogeneity: Data homogeneity test (Table 2) indicated that the *p*-value of all the indicators, except HC and Fe, is not less than the significance level of 0.05. This implies that we cannot reject the null hypothesis, which posits that the variance is consistent across all treatment groups (soil types). Consequently, there is no evidence indicating that the variance in soil properties varies among the soils of five soil series in the study area.

Data normality: The normality for each variable at 5 % probability (Table 3) indicated that OC, HC, Clay, BD and Mn were not found normally distributed. However, except clay content and Mn, the variables were normally distributed at 10 % probability and were kept in the model for PCA.

Table 1. Measure of sample adequacy for individual soil quality indicators.

pH	EC	OC	BD	CEC	COLE	HC	Sand	Silt	Clay	AWC	N	P	K	Zn	Fe	Mn	Cu	Depth
0.30	0.38	0.87	0.56	0.59	0.59	0.71	0.67	0.41	0.59	0.76	0.75	0.93	0.68	0.50	0.75	0.88	0.63	0.73

Table 2. Coefficients of Bartlett's test for soil quality indicators.

Variable	K-squared	*p*-value	Variable	K-squared	*p*-value
OC	7.375	0.117	N	2.857	0.582
CEC	5.366	0.252	P	2.9867	0.560
COLE	8.868	0.065	K	6.170	0.187
HC	13.032	0.011	Zn	2.766	0.598
Sand	0.690	0.953	Mn	7.200	0.126
Clay	5.224	0.265	Fe	10.213	0.037
AWC	4.323	0.364	Cu	3.963	0.411
BD	8.463	0.076	Depth	5.113	0.276

Table 3. Coefficients of Shapiro-Wilk test for soil quality indicators.

Variable	Shapiro-Wilk Coefficient	*p*-value	Variable	Shapiro-Wilk Coefficient	*p*-value
OC	0.9073	0.0171	N	0.9599	0.3461
CEC	0.9540	0.2487	P	0.9495	0.1925
COLE	0.9212	0.0372	K	0.9505	0.2039
HC	0.9029	0.0134	Zn	0.9487	0.1837
Sand	0.9601	0.3501	Mn	0.8639	0.0018
Clay	0.8906	0.0069	Fe	0.9577	0.3065
AWC	0.9587	0.3244	Cu	0.9304	0.0631
BD	0.9302	0.0450	Depth	0.9330	0.0734

Selection of Minimum Data Sets: To identify the minimum dataset, the PCA was carried out by SPSS software (version 18.0). (Table 4) summarises the 19-soil physical, chemical and fertility parameters and the derived principal component in the present study. PCA intended to reduce the dimension of data that losing as little information as possible (39). The best representative of explaining the variability was considered on the basis of Principal components (PCs) with high Eigen values (15). However, (36) identified PCs with eigenvalues ≥1, because differences between PCs with eigenvalue ≥1 capture less variance than that was generated by one of the individual variables. In order to maximise the correlation between the PCs and the soil properties, the retained PCs (40). Went through varimax rotation to distribute the variance. Soil quality indicators for each PC were chosen below autocorrelated variables with high loading factor. In order to avoid redundancy and correlation among variables, bivariate correlation coefficients were calculated. When the variables were strongly correlated, one of the correlated variables (variable with highest factor loading - absolute value) was retained as indicator and others were dropped (14).

Assignment of weights: The weight of each indicator during PCA was determined by the variation that each indicator explained (15, 21, 22).

Calculation of SQI: SQI was computed by weighted additive method in a manner similar to closely paint (15) as follows:

$$SI = \sum_{j=1}^{n} W_j S_{ij}$$

Where, n is the number of indicators in MDS suggested by experts, W_j is the weight of j^{th} indicator which is computed using AHP and S_{ij} is the standardized scores of the i^{th} alternative against the j^{th} indicator. The standardized scores for each alternative under each indicator are calculated using linear scoring methods (15, 22).

Reclassification of soil quality index: The soil quality index has been reclassified based on a moving average graph and the inflection points as breakpoints for the classes in to different classes and generated a soil quality map using Arc GIS.

Table 4. Principal component analysis of selected variables.

PCs	**PC_1**	**PC_2**	**PC_3**	**PC_4**	**PC_5**
Total	**3.975**	**3.356**	**2.746**	**2.448**	**1.283**
% of Variance	**22.086**	**18.646**	**15.257**	**13.599**	**7.127**
Cumulative %	**22.08**	**40.73**	**55.98**	**69.58**	**76.71**
Factor loading/eigen vector					
Depth	.081	-.119	.128	.208	.198
pH	-.385	-.381	-.210	.274	.332
EC	.066	.000	-.045	-.086	-.893
OC	.888	.106	.131	-.176	-.112
BD	-.703	.008	.157	.096	.092
CEC	-.144	-.288	-.019	.801	.020
COLE	-.073	-.009	-.580	.680	-.154
HC	.122	.403	.678	-.037	.032
Sand	.105	.058	.881	-.313	-.087
Silt	.501	.187	-.764	-.115	.008
Clay	-.713	-.346	-.099	.445	.153
AWC	-.222	-.219	-.162	.676	.266
N	.749	.354	.079	.203	.134
P	-.080	-.631	.322	-.406	.422
K	-.394	-.170	-.518	.141	-.141
Zn	.177	.844	.045	-.193	.037
Fe	.890	.212	.127	-.168	-.028
Mn	.124	.835	.163	-.360	.039
Cu	.344	.862	.208	-.181	-.087

Results

Soils of the area

The detailed study of the site characteristics and landforms relationships, 5 different types of soils were identified in the area (Fig. 2). On the very gently sloping (1-3 %) and moderately sloping (5-10 %) cultivated plateau, the soils (P_1) were shallow, moderately well drained, very dark greyish brown (10YR 3/2M), clayey in texture underlain by hard basalt with moderate erosion and qualify for Lithic Haplustepts at subgroup level (P_1). On the moderately steep to steep sloping (15-25 %) escarpments under forest, soils were very shallow, well drained, very dark greyish brown (7.5YR 3/3M), clayey in texture underlain by hard basalt with moderate erosion and qualify for Lithic Ustorthents at subgroup level (P_2). Three soils series were identified on very gently sloping (1-3 %) to moderately sloping (5-10 %) pediments which were under single crop, double crop and wasteland. Soils on moderately sloping pediments under mixed uses were shallow, well drained, dark greyish brown (7.5YR 3/3M), calcareous, clay soils underlain by hard basalt with severe erosion and qualify for Typic Ustorthents at subgroup level (P_3). Soils on gently sloping (3-5 %) pediments under single crop were shallow, well drained, very dark greyish brown (10YR 3/2M), clay soils underlain by hard basalt with moderate erosion and qualify for Lithic Ustorthents at subgroup level (P_4). Soils on very gently sloping (1-3 %) pediments under intensive cultivation were moderately deep, well drained, very dark greyish brown (10YR 3/2M), clayey soils underlain by hard basalt with severe erosion and qualify for Vertic Haplustepts at subgroup level (P_5). The soil-site characteristics of typical pedons of different soil series in Bareli watershed are presented in (Table 5). While the descriptive statistics of important soil properties considered for soil quality assessment is presented in (Table 6).

Principal Component Analysis

A small number of chosen soil parameters are used as indicators of soil quality to create the Soil Quality Index (SQI). A total of 19 indicators, comprising the physical and chemical, fertility parameters state, were chosen based on the results of the tests for normalcy and sample adequacy. One could argue that the optimal soil quality index could be obtained by selecting additional soil variables or by considering the entire soil data set. However, high correlation amongst the soil variables may result in redundancy of data on soil variability (41). For this, PCA has been suggested as a data reduction tool and

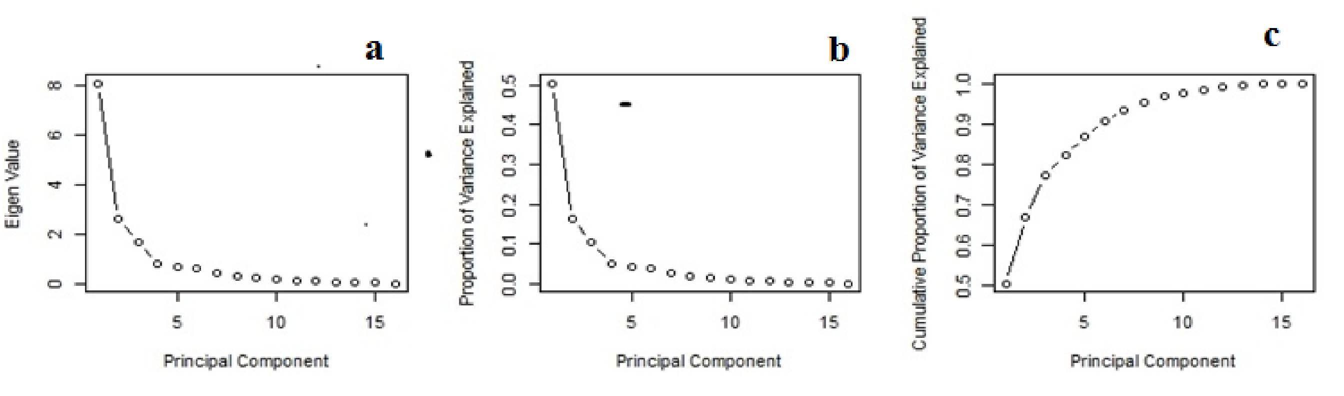

Fig. 2. Screen plot indicating a) Eigen value of the PCs, b) Variance explained by each PC and c) Cumulative variance explained.

Table 5. Soil-site characteristics of typical pedons of different soil series in Bareli - watershed.

Soil series	Landform	Soil Depth (cm)	Soil texture	Surface stoniness (%)	Coarse Fragments (%)	Slope (%)	Erosion	Drainage	Present Land use
Diwartola	Very gently, gently and moderately sloping plateau	36	clay	15-40	5-10	1-5	Moderate	Well	Single crop, Double crop
Diwara	Strongly sloping to moderately steep to steep sloping Escapement, Isolated Mound and Hills and Ridges	35	clay	3-15	5-10	10-25	Very Severe	Well	Dense Forest, Moderately Forest, Degraded Forest and wasteland
Bareli-1	Very gently sloping pediment	60	clay	<3	10-15	1-3	Moderate	Well	Single crop, Double crop
Bareli-2	Gently sloping pediment	15	clay	15-40	35-40	3-5	Moderate	Well	Single crop Wasteland
Bareli-3	Moderately sloping pediment	32	clay	15-40	35-40	5-10	Severe	Well	Single crop Double crop and Wasteland

Table 6. Descriptive statistics of soil properties.

Soil Properties	Minimum	Maximum	Mean	Standard Deviation	Coefficient of Variation
pH (1:2.5)	5.92	7.75	6.83	0.423	6.19
EC (dS m^{-1})	0.13	0.44	0.24	0.080	33.79
OC %	0.31	1.38	0.63	0.304	47.90
BD. (Mg m^{-3})	1.36	1.78	1.47	0.107	7.25
CEC cmol/kg	32.19	61.38	45.58	7.337	16.10
COLE	0.07	0.20	0.14	0.038	26.88
HC(cm hr^{-1})	0.13	2.51	0.91	0.737	81.29
Sand %	4.89	34.14	20.25	9.625	47.53
Silt %	8.45	56.73	24.62	9.535	38.73
Clay %	38.38	66.14	55.05	7.151	12.99
AWC %	10.40	15.07	12.17	1.115	9.16
N (kg ha^{-1})	140.56	432.12	245.69	82.107	33.42
P (kg ha^{-1})	18.42	38.08	28.42	4.890	17.20
K (kg ha^{-1})	56.00	492.80	257.29	127.058	49.38
Zn (mg kg^{-1})	0.27	0.90	0.50	0.182	36.53
Fe (mg kg^{-1})	6.19	27.60	12.83	6.084	47.42
Mn (mg kg^{-1})	8.45	56.25	23.93	11.395	47.62
Cu (mg kg^{-1})	2.30	11.25	5.05	2.428	48.06

identifying MDS. The results obtained from PCA indicated three PCs with eigenvalues >1 (Fig. 2) explaining more than 77 % of the total variance in the data.

The biplot analysis (Fig. 3) shows that the soils on the escarpments under forest (P_2) and the soils on moderately sloping (8-15 %) pediments under mixed uses (P_3) were clearly separable from the rest of the soils. Further, the soils on very gently sloping (1-3 %) pediments under intensive cultivation (P_5) were also separable from the soils on gently sloping (3-5 %) pediments (P_4) with minor overlap with the soils on plateau (P_1) (2).

Selection of MDS

Soil parameters pH, OC, BD, clay, available nitrogen and available iron were selected from PC_1 (Fig. 3). Nonetheless, the transformation among these parameters presented a high degree of correlation (Fig. 4) with OC has the highest factor loading was selected in MDS. Zinc availability was selected based on mantel test for PC_2 and from PC_3, available copper, sHC, silt and available potassium were chosen. Sampling site was selected as indicator by mantel test from PC_3. CEC, COLE and AWC were selected from PC_4 but with a higher factor loading/eigen vectors. The chosen parameters were not linearly independent. CEC was correlated with COLE and AWC; therefore, it was chosen for the MDS due to having the highest loading factor in PC_4. Similarly, EC was selected from PC_5.

Soil Quality Index

The normalized values of the chosen MDSs were integrated into SQIs using a weighted additive method using weights produced by PCA. The linear scoring approach recommended was used for normalization (42). Indicators were ranked according to whether a greater value was regarded as "good" or "bad" in terms of soil function in order to assign the soil variable. The greatest observed value was used to divide each observation. In the "more is better" scenario so that the highest observed value received a score of 1. Each observation was divided by the lowest observed value (in the denominator) in the numerator to arrive at a score of 1 for the "less is better" principle. Weights were assigned to each variable in the

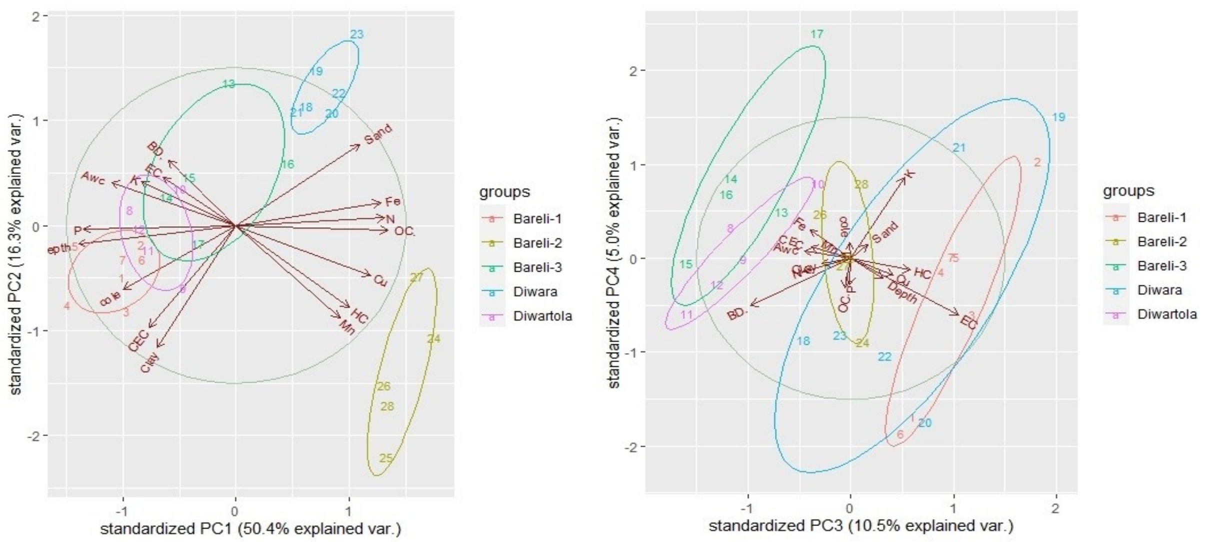

Fig. 3. Biplots of PCA analysis

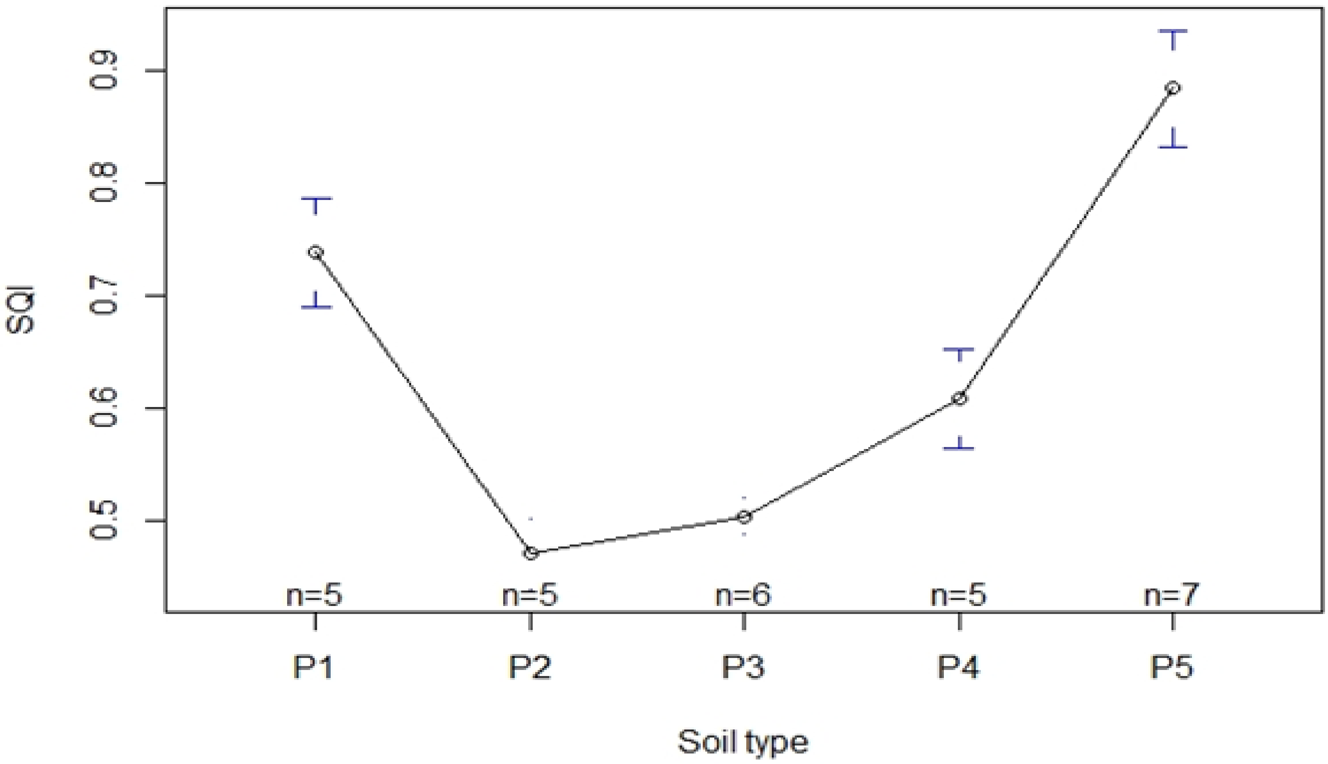

Fig. 4. Mean SQI of different soil types

parameter as percent of total variation explained by the selected PCs (Eigen value≥1) (Table 4). In case of more than one parameter selected from a single PC, the weights were divided equally as recommended (42). The depth of the soil was given a weight of 0.66, followed by 0.21 for clay content and 0.65 for both BD and Zn.

The mean SQI of different soil types with 95 % confidence interval is shown in the (Fig. 4). The SQI was highest for P_5 followed by P_1, P_4, P_3 and P_2. The ANOVA showed that the SQI among different soils were significantly different. The Tukey's post-hoc test (Fig. 5) shows that, except the combination of soils P_2 and P_3, all soils combinations were significantly different from each other.

Five PCs with eigen values greater than one was identified by PCA results (Table 4), and each PC's soil variables with a high loading factor were taken into consideration for MDS. In PC_1, PC_2, PC_4 and PC_5, the factor loadings for chemical attributes were high and might be referred to as chemical components. Physical components in PC_3 had high factor loadings. The soil parameters selected from PC_1 were pH, OC, BD, clay, available nitrogen

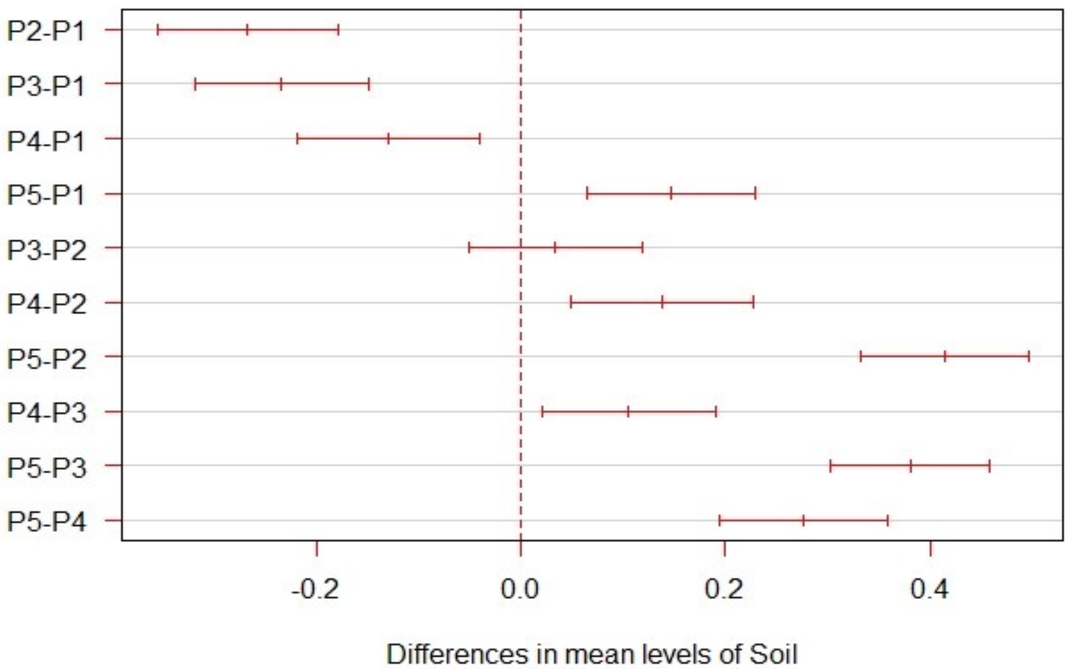

Fig. 5. Tukey post-hoc test of different soil types.

and available iron (Table 7). Only OC, the factor loading with the highest value was kept in the MDS, despite the substantial correlations between these parameters (Table 7). One significant indication of soil quality is thought to be organic carbon (43). Through nutrient supply, moisture retention and soil physical property stability, it plays a significant function in the rainfed production system in semi-arid parts of India (44). Organic carbon has also been identified as a major factor of soil quality by many researchers (22, 45-47). Although Soil depth, despite having the lowest factor loading, has been regarded as a secondary consideration in terms of soil quality as an expert opinion within the Minimum Data Set framework (48). It provides the soil ability to support crop growth (49). Many researchers have considered soil depth in the MDS (6, 50-53). Further, the deep soils will conserve more moisture in the profile in rainfed conditions (54).

Available phosphorous, zinc, manganese and copper were elected from PC_2 and subsequent to correlation analysis, only zinc was incorporated in the MDS (Table 8). The soil parameter selected from PC_3, were saturated hydraulic conductivity sHC, available potassium, silt and sand. However, multivariate correlation between these parameters indicated high correlation and only sand which has the highest factor loading was retained in the MDS (Table 9). Moreover CEC, COLE and AWC were selected from PC_4 with higher factor loading/eigen vectors. The parameters that were chosen were not mutually exclusive. CEC was correlated with COLE and AWC, hence, CEC was selected in the MDS owing to highest loading factor in the PC_4 (Table 10). Similarly, EC was selected from PC_5. Available Zn was identified as an important soil quality parameter (55). Soil nutrient supply capability is influenced by Cation Exchange capability (CEC), which is dependent on soil pH, organic matter content and the amount and kind of clay present (56). Along with the physical properties, only the sand content was included in the MDS.

Table 7. Correlation coefficient (Pearson) for highly loaded parameters in PC_1.

PC_1 Correlations						
	pH	**OC**	**BD**	**CLAY %**	**N**	**Fe**
pH	1					
OC	-.491**	1			.	
BD	.235	-.507**	1			
CLAY %	.572**	-.607**	.511**	1	-	
N	-.400**	.699**	-.532**	-.494**	1	
Fe	-.519**	.937**	-.520**	-.635**	.798**	1

**. Correlation is significant at the 0.01 level (2-tailed).

Table 8. Correlation coefficient (Pearson) for selected MDS parameters from PCA results.

PC_2 Correlations				
	P	**Zn**	**Mn**	**Cu**
P	1			
Zn	-.366	1		
Mn	-.261	.779**	1	
Cu	-.448*	.804**	.923**	1

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 9. Correlation coefficient (Pearson) for selected MDS parameters from PCA results.

PC_3 Correlations				
	HC	K	Silt	Sand
sHC	1			
K	-.440*	1		
Silt	-.261	.014	1	
Sand	.539**	-.462*	-.638**	1

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 10. Correlation coefficient (Pearson) for highly loaded parameters in PC_4.

PC_4 Correlations			
	CEC	COLE	AWC
CEC	1		
COLE	.527**	1	
AWC	.443*	.489**	1

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

The resulting SQI were then normalized in relation to the highest possible SQI, which is the total of the highest PCA weighting factors for every key indicator. Weights were defined from the variance explained by each PC during PCA (Table 11). The results indicated that soil quality index varied from 0.16 in soils of Pedon 13 to 0.72 in soils of Pedon 21.

Reclassification of Soil Quality Index

The soil quality index obtained has been reclassified in to low, medium and high based on a moving average graph and the inflection points as breakpoints for the classes. The soil quality class of each soil series and the extent of area are given in (Table 12) and the spatial distribution is depicted in (Fig. 6).

The soil quality indices of the region differ from low (0.16) to high (0.72). The great difference in soil quality is due to soil heterogeneity and soil deprivation. The soil quality in soils of Diwartola was found high with an area of 242.7 ha (13.5 %), followed by the soils of Bareli-1 and Bareli-3 were found to be medium in soil quality with total geographical area of 462.8 ha (25.7 %), whereas, Diwara and Bareli-2 were found to be low in soil quality with an area of 966.1 ha (53.8 %). The soils of Bareli-1 series are marginally suitable for cultivation, because, these soils are shallow, medium in organic matter content and also average in productivity, whereas, the soils of Bareli-2 series are not suitable for cultivation, because, these soils have a medium level of organic matter, are very shallow and are not particularly productive since they cannot

Table 11. SQI computed using the weighing factor from the eigen values of PCA.

	PC_1	PC_2	PC_3	PC_4	PC_5	SQI (sum of PC_1 to PC_5)	RSQI
	OC	Zn	Sand	CEC	EC		
Weightages	0.288	0.243	0.199	0.177	0.093		
Pedon-1	0.029	0.060	0.002	0.117	0.091	0.30	41.3
Pedon-2	0.082	0.034	0.198	0.054	0.087	0.46	62.8
Pedon-3	0.070	0.008	0.198	0.231	0.092	0.60	82.8
Pedon-4	0.017	0.001	0.199	0.057	0.003	0.28	38.1
Pedon-5	0.225	0.132	0.004	0.160	0.003	0.52	72.4
Pedon-6	0.013	0.177	0.005	0.007	0.075	0.28	38.3
Pedon-7	0.001	0.003	0.199	0.137	0.059	0.40	55.0
Pedon-8	0.288	0.137	0.002	0.015	0.002	0.44	61.2
Pedon-9	0.009	0.044	0.022	0.181	0.082	0.34	46.6
Pedon-10	0.001	0.176	0.067	0.061	0.093	0.40	54.9
Pedon-11	0.001	0.001	0.199	0.211	0.066	0.48	65.9
Pedon-12	0.287	0.167	0.002	0.022	0.089	0.57	78.1
Pedon-13	0.009	0.046	0.003	0.072	0.033	0.16	22.5
Pedon-14	0.001	0.035	0.028	0.100	0.084	0.25	34.3
Pedon-15	0.172	0.128	0.001	0.043	0.010	0.35	48.9
Pedon-16	0.285	0.006	0.045	0.052	0.072	0.46	63.4
Pedon-17	0.234	0.007	0.199	0.114	0.087	0.64	88.4
Pedon-18	0.002	0.001	0.199	0.206	0.083	0.49	67.7
Pedon-19	0.001	0.175	0.199	0.204	0.075	0.65	90.1
Pedon-20	0.003	0.030	0.196	0.185	0.001	0.41	57.2
Pedon-21	0.211	0.044	0.198	0.184	0.087	**0.72**	**100.0**
Pedon-22	0.234	0.168	0.014	0.094	0.006	0.52	71.1
Pedon-23	0.219	0.002	0.025	0.077	0.090	0.41	57.1
Pedon-24	0.050	0.004	0.027	0.146	0.068	0.29	40.4
Pedon-25	0.288	0.168	0.023	0.218	0.002	0.70	96.5
Pedon-26	0.287	0.177	0.199	0.012	0.016	0.69	95.3
Pedon-27	0.139	0.067	0.003	0.194	0.089	0.49	67.9
Pedon-28	0.002	0.071	0.156	0.148	0.005	0.38	51.8

Table 12. Soil quality of different soil series and their extent of area.

Sl. No.	Soil series	SQI	Soil Quality Class	Area	
				ha	% of TGA
1	Diwartola	0.72	High	242.7	13.5
2	Diwara	0.41	Low	239.5	13.3
3	Bareli-2	0.40	Low	726.6	40.5
4.	Bareli-1, Bareli-3	0.65 and 0.69	Medium	462.8	25.7

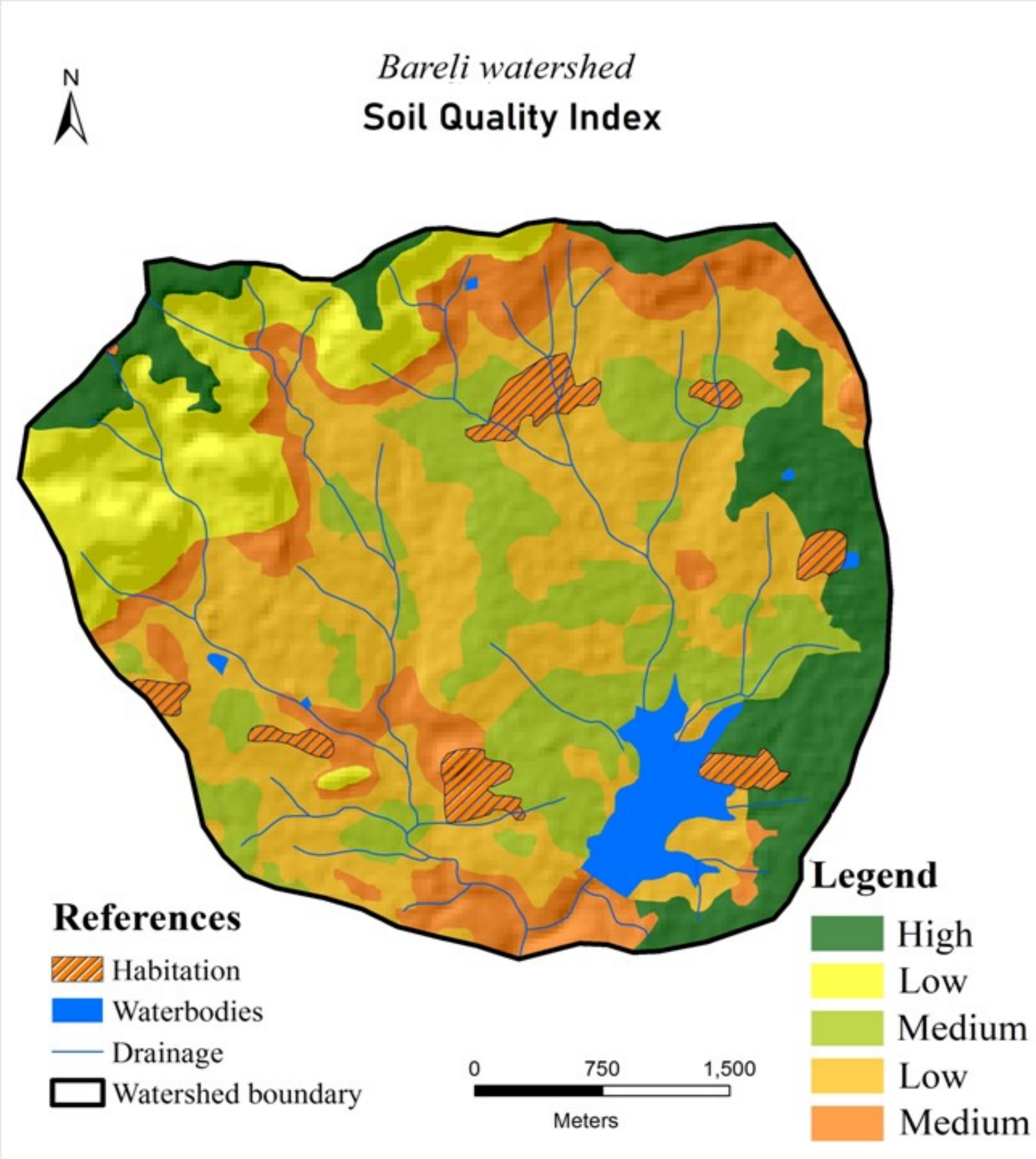

Fig. 6. Spatial distribution of soil quality index in Bareli watershed

support the best possible plant growth due to depth the problem however, the soils of Bareli-3 series are shallow, medium in organic matter content and also average in productivity due to limitation of depth and slope.

The results demonstrate that incorporating both dynamic and inherent properties is essential for establishing the connection between specified soil functions and soil characteristics. This approach effectively integrates data on the surface and subsurface soil for evaluating the quality of the soil (57). Reported PCA methods for indicator selection in the soils of the Indo-Gangetic Plains. However, the current study reveals that the indicators selected by PCA methods varied, resulting in significantly different Soil Quality Indices (SQI). Furthermore, the impact of climate change on both short-term and long-term soil processes must be considered when devising management strategies to prevent soil resource degradation and ensure sustainable agricultural productivity.

Land resource management

The plateau, which makes up 13.5 % of the watershed, has very shallow to shallow soils (Diwartola) that are used for single and double-crop farming, primarily sorghum cultivation. Diwartola soils have very high levels of available K, very high levels of available P and high levels of available N. The soils have moderate erosion and a high level of soil quality. Agri-horticulture with aonla, guava, custard apple and drum stick may be used with integrated nutrient management under appropriate soil and water conservation measures like contour bunding, gully plugging and water harvesting structures to increase the productivity in cultivated land units under single crop.

Pediments cover 66.3 % of the watershed, having very shallow to moderately deep soils (Bareli-1, Bareli-2 and Bareli-3), primarily supporting a single crop system (49.59 %) with sorghum as the major kharif crop and double crop (2.2 %) with wheat and gram during rabi season the mapping units of moderately to fairly well-cultivated lands with significant limitations due to soil depth, texture and surface stoniness. The soils in Bareli-2 are low in available nitrogen, very high in available phosphorus and medium to moderately high in available potassium with moderate-severe erosion and low in soil quality due to limitation of very shallow depth. In contrast, the soils in Bareli-1 and Bareli-3 are high in available nitrogen, very high in available phosphorus and very high in available potassium. Overall, the soil quality is medium; the soils are average in soil productivity and moderate to very severe eroded without any soil and water conservation measures. To address these issues, proper field bunding, gully plugging and contour bunding are necessary to conserve soil and water. Additionally, implementing agri-horticulture interventions, such as planting aonla, guava, custard apple and drumstick, along with silvipasture systems incorporating multi-purpose trees and integrated nutrient management, is recommended to enhance productivity in these land units.

The hills, ridges and isolated mounds account for 6.6 % of the total geographical area (TGA). The soils in these regions, known as Diwara, are found on moderately sloping (5-10 %) to moderately steep (15-25 %) lands and are typically shallow and moderately eroded. low in soil quality with poor productivity these lands are predominantly under forest cover and classified as wasteland. To enhance the productivity of such areas, afforestation with appropriate tree species is recommended. Additionally, implementing continuous contour trenches can help mitigate runoff, reduce soil erosion and improve soil moisture retention, fostering better land management.

The escarpment soils (Diwara) constituting 6.7 % of the watershed are very shallow, low in soil quality with poor productivity. The land units are poor in soil fertility with high, moderately high and medium to moderately high in available N, P and K respectively. The area is suggested for afforestation of moderately dense degraded forest in order to maintain ecological balance in the area.

Conclusion

The soil quality was evaluated in the Bareli watershed of Seoni district, Madhya Pradesh and mapped using a Soil Quality Index (SQI). The process involved establishing crucial management goals, selecting indicators as a minimum data set (MDS), assigning weights and scoring the selected indicators through integrated principal component analysis and GIS. Indicators for assessment included soil depth, sand, silt, clay, bulk density, hydraulic conductivity, available water capacity, coefficient of linear extensibility. pH, electrical conductivity, organic carbon and cation exchange capacity) and available N, P, K, Fe, Mn, Cu and Zn. Five soil series namely Diwartola, Diwara, Bareli-1, Bareli-2 and Bareli-3 were identified and mapped into 24 mapping units at a 1:10000 scale. The assessment revealed that Diwartola soils are of high quality, Bareli-1 and Bareli-3 soils are of medium quality whereas Diwara and Bareli-2, soils are of low quality. Suitable agro-interventions, including agri-horticulture, agroforestry, silvipasture, intensive cultivation and various soil and water conservation measures, were recommended for different mapping units.

Acknowledgements

The authors express their sincere gratitude to the ICAR–National Bureau of Soil Survey and Land Use Planning, Nagpur, Maharashtra, for providing the necessary sampling and laboratory facilities for the analysis of soil samples. We also extend our thanks to Bihar Agricultural University, Sabour, for granting the BAU Communication number.

Authors' contributions

SN, MSSN and NS conceived and planned the experiments, collected soil profile samples and analyzed the samples. PT and RS prepared the data and performed statistical analysis. NK and RS estimated soil quality using PCA. SNI, MSSB, BL and SPD wrote the manuscript. JP drafted the manuscript. AKP and KB contributed to the final version of the manuscript. KGU revised the manuscript.

Compliance with ethical standards

Conflict of interest: Authors declare that they don't have any conflict of interest.

Ethical issues: None.

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