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Soil quality index (SQI) as a tool to evaluate crop productivity in semi-arid Deccan plateau, India

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ABSTRACT

Assessment of soil quality index (SQI) using only the surface soil properties provides an incomplete information as the crop productivity is influenced by both surface and subsurface properties, with the latter being inherently linked to pedogenic processes. Two different SQIs were estimated for soil surface (0–15 cm) and control section (0–100 cm) using soil profile data of six identified soil series in part of semi-arid tropical (SAT) Deccan plateau and correlated with crop yield. Principal component analysis (PCA) and expert opinion (EO) methods were used for selecting minimum soil data set (MDS). Additive and weighted index methods were compared for SQI estimation. SQI obtained showed variation as PCA and EO methods produced different results. In general, weighted index SQIs were better correlated with crop yield than the additive index SQIs for both PCA and EO methods. EO derived weighted index SQI were comparable for both surface and control section except for few cases and consistent in their correlation with the crop yield, indicating its better performance as compared to PCA. Reason is that the PCA is a data dimension reduction technique whereas EO method is primarily conceived by the experts on cause-effect relationship of soil properties (such as hydraulic conductivity, $CaCO_3$ and exchangeable sodium percentage) that are influenced by regressive pedogenic processes in SAT environments. Results showed that consideration of both surface and control section soil properties helps in establishing a good relationship between soil functions and management goal. In addition, it also satisfies the need to integrate both surface and subsurface soil information for soil quality assessment.

1. Introduction

The concept of soil quality was introduced for proper stratification and allotment of agricultural inputs (Warkentin and Fletcher, 1977). Karlen et al. (1997) defined soil quality as 'the capacity of specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation'. A quantitative formula and conceptual framework were proposed to evaluate soil quality and it was recommended that the soil quality should be evaluated based on soil functions (Doran et al., 1996; Karlen et al., 1997). Subsequently, soil quality gained importance as a tool to assess various agricultural and horticultural production systems around the world (Bouma and Droogers, 1998; Andrews et al., 2002; Armenise et al., 2013; Mukherjee and Lal, 2014).

Soil quality can be conceptualised in two aspects *viz*., inherent and dynamic soil quality (Seybold et al., 1999). The inherent soil quality shows little change over time whereas dynamic soil quality changes with respect to soil management (Larsen and Pierce, 1994). The changes in soil properties may occur within hours to a period of decades with respect to response level of soil properties (Carter, 1996). However, the limits to which dynamic soil properties can change are dictated by inherent properties (Norfleet et al., 2003). The inherent soil properties are influenced by pedogenic processes and the changes are more pronounced in tropical climate due to physical and chemical weathering enhanced by high temperature and precipitation.

In general, soil quality assessment is carried out by selecting a set of soil properties which are considered as indicators of soil quality. Soil functions are sensitive to soil quality indicators (Aparicio and Costa, 2007), hence the indicators should be easy to measure (Dumanski and Pieri, 2000). The selection of minimum soil data set (MDS) is based on methods such as principal component analysis (PCA) (Andrews and Carroll, 2001), expert opinion (EO) (Andrews et al., 2002) and factor analysis (Shukla et al., 2006). PCA reduces the dimension of large volume of data and facilitate the indicator selection by categorically grouping the soil properties into principal components (PC). Expert opinion, primarily based on available literature, field experience and knowledge

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of soil scientists, emphasises on the cause-effect relationship of soil properties influenced by pedogenic processes (Pal et al., 2012, 2013).

Many of the earlier soil quality evaluations were done using the surface (dynamic) soil properties (Andrews et al., 2002; Armenise et al., 2013) and studies using soil profile data (dynamic and inherent) are limited (Ray et al., 2014; Moncada et al., 2014). Surface soil properties may be easy to measure and evaluate but they provide incomplete information since soil functions are driven by pedogenic processes in the soil control section. Soil quality evaluation using both surface and subsurface properties will help to identify the soil properties having maximum influence on soil functions. Hence, it is only appropriate to use soil profile characteristics governed by soil genesis and represented by taxonomy for soil quality assessment (Merril et al., 2012, 2013).

Semi-arid tropical (SAT) region accounts for 11.6 million km^2 over the world (Srinivasarao et al., 2008). Sustaining agricultural productivity in SAT region would remain a great challenge due to the vulnerability of the soils to the effects of climate change. In Indian subcontinent, 50% of the total geographical area is characterised by arid and semi-arid climate. Deccan plateau covers about 0.42 million km^2 in central and south India and is a major food grain producing region. The soils of Deccan plateau are diverse in nature and they are prone to both natural and anthropogenic degradation (Pal et al., 2000). SAT Vertisols in this region with pH ≥ 8.0 and substantial $CaCO_3$ content indicate variations in mean annual rainfall (MAR) and most of them were classified as *Typic/Udic Haplusterts* in semi-arid (moist) climate, and *Sodic Haplusterts* and *Sodic Calciusterts* (exchangeable sodium percentage, ESP ≥ 15) in semi-arid (dry) and arid (dry) climates, respectively (Pal et al., 2009). They occur in close association with red ferruginous soils (*Typic Haplustalfs* and *Typic Rhodustalfs*) (Bhattacharyya et al., 1993). These soils are poor in organic carbon due to SAT climate (Venkanna et al., 2014) and are also poor in nitrogen, low in phosphorus fixation capacity (Shailaja and Sahrawat, 1994) responds little to fertilizer P application and poor in productivity (Pal et al., 2012). They have low saturated hydraulic conductivity (sHC) due to subsoil sodicity.

Moreover, they are naturally degraded and hence their functions *viz*., hydraulic conductivity, drainage and nutrient supply were impaired. The natural degradation of these soils could be attributed to regressive pedogenesis (Pal et al., 2013). Soil development by progressive pathway include conditions, processes and factors that promote horizonation, assimilative upbuilding and/or subsurface deepening whereas the regressive pathway includes factors that promotes haploidization (simplified profiles), surface removal, alteration of physico-chemical stability, formation of non-conducive soil environment for the survival, growth and reproduction of living organisms and plants in soil (Johnson and Watson-Stegner, 1987; Johnson et al., 1990). It indicates that soil development is not unidirectional (Phillips, 1993). The degree of modifications of soil properties due to pedogenic processes (progressive/regressive) varies with climate. Therefore, assessment of soil quality in SAT soils requires an account of pedogenesis, and both the surface and subsurface soil characteristics should be given due importance for evaluating soil quality.

Evaluation of soil and site characteristics for their suitability for agricultural land use in general and for the cultivated crops, in particular, is being carried out by several methods developed over a period of time. Among them, FAO land evaluation (FAO, 1976); Storie index (Storie, 1978) and parametric approach (Sys et al., 1991) are most commonly used. However, these methods were not favoured for their qualitative nature and attempts have been made to evaluate the soils through

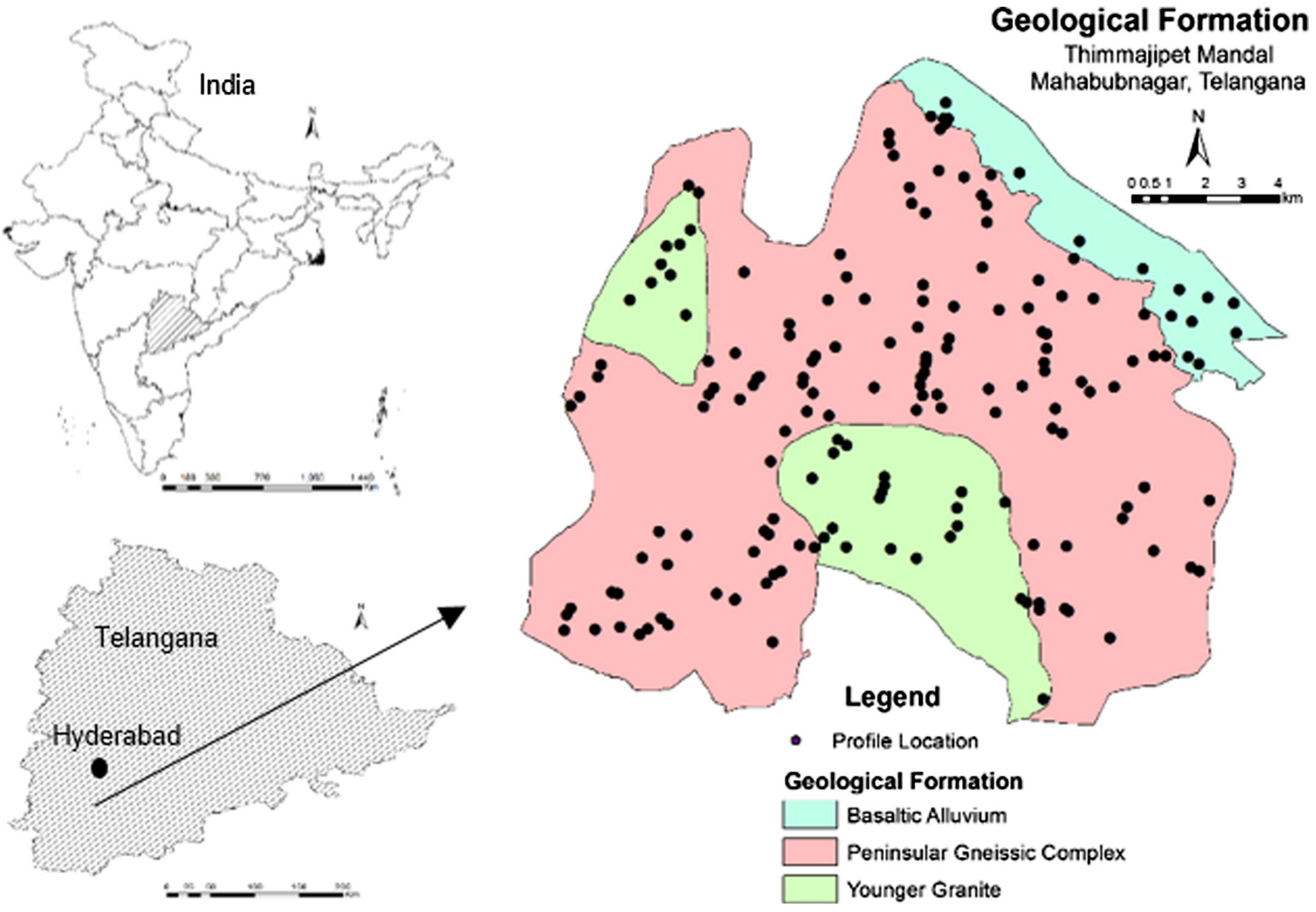

Fig. 1. Geological formations in the study area and location of soil profiles.

quantitative index for agricultural land use (El Baroudy, 2016) while it was also emphasised to apply soil science knowledge in the broader context of land evaluation (Bouma et al., 2012). Recent literature on soil quality assessment advocates on developing and defining quantitative index for the same (Mandal et al., 2001; Merril et al., 2013; Askari and Holden, 2015; de Paul Obade and Lal, 2016). Therefore, soil quality index (SQI) assumes greater significance.

In order to develop an acceptable and pragmatic SQI protocol for the vast and adverse SAT soils, several studies need to be conducted; the present study is an endeavour in that direction. It was conducted in part of the SAT Deccan plateau region with objectives i) to select minimum soil data sets (MDS) by comparing Principal Component Analysis (PCA) and Expert Opinion (EO) using soil profile data, ii) to calculate SQI by additive and weighted index methods, and iii) to correlate the SQI with crop yield.

2. Materials and methods

2.1. Description of the study area

The study area (Thimmajipet Mandal), located about 100 km from Hyderabad is a part of Mahabubnagar district, Telangana and covers an area of 200.90 km^2. It lies between 16°55′N latitude and 78°20′E longitude and characterised by *ustic* soil moisture and *hyperthermic* soil temperature regimes (Soil Survey Staff, 2003). The climate is semi-arid (dry) with 450–550 mm of MAR. Soils were formed on three types of geological formations (Fig. 1). Rainfed agriculture is predominant and about 10% of the cultivated areas are irrigated with bore-well water. Major crops grown during *monsoon* season (June–September) are cotton (*Gossypium hirsutum*), maize (*Zea mays*) and pigeon pea (*Cajanus cajan*). In winter or post-monsoon season (October–January) groundnut (*Arachis hypogaea*) occupies the major areas. The length of the growing period (LGP) is 90–120 days.

2.2. Soil sampling and analysis

Soil profiles in the cultivated fields were studied in catenary sequence for their morphological characteristics (Fig. 1). A total of 182 soil profiles were studied in 15,230 ha area. Horizon-wise soil samples (127) from 27 soil profiles representing six identified soil series were collected. The morphological properties of one representative pedon from each soil series are presented in Table 1.

The samples were air-dried, ground, sieved (<2 mm) and analysed for soil physical and chemical properties. Particle size analysis was carried out using hydrometer method (Gee and Bauder, 1986); bulk density (BD) by core method (Blake and Hartge, 1986); gravimetric water content at −33 kPa and −1500 kPa by pressure plate apparatus (Klute, 1986). Available water content (AWC) was calculated as difference between water content at −33 kPa and −1500 kPa. Volumetric water content was determined by multiplying the gravimetric water content with bulk density. Total porosity was calculated from bulk density and assumed particle density of 2.65 Mg m^{-3}. Percent water filled pore space (%WFPS) was calculated by formula proposed by Weinhold et al. (2008). Saturated hydraulic conductivity (sHC) was estimated by constant head method (Klute and Dirksen, 1986).

Coefficient of Linear Extensibility (COLE) is an indicator of swelling and shrinkage potential of soils. It was determined by the procedure outlined by Schafer and Singer (1976). To determine COLE value, approximately 100 g of each soil sample (two replicates) were taken in a plastic cup and saturation paste were prepared by adding deionised water. The soil paste were added to Teflon coated iron containers 15 × 2 × 1 cm in dimension. The pores created while adding the paste

Table 1
Morphological properties and taxonomy of representative pedon of soil series used in the study.

Series	Depth (cm)	Horizon	Colour	Texture	Structure	Effervescence
Gummagonda – *Loamy – skeletal, mixed, hyperthermic, Lithic Ustorthents*						
	0–17	Ap	Brown (7.5YR4/3)	Gravelly sandy clay loam	Subangular blocky	Nil
Pullagiri – *Loamy, mixed, hyperthermic, Typic Haplustepts*						
	0–18	Ap	Dark brown (7.5YR3/2)	Gravelly sandy clay loam	Subangular blocky	Slight
	18–52	B	Dark brown (7.5YR3/3)	Gravelly sandy clay loam	Subangular blocky	Slight
Chegunta – *Fine loamy, mixed, hyperthermic, Typic Rhodustalfs*						
	0–13	Ap	Dark brown (7.5 YR3/2)	Sandy clay loam	Subangular blocky	Nil
	13–37	Bt1	Reddish brown (5YR4/3)	Sandy clay	Subangular blocky	Slight
	37–70	Bt2	Dark red (2.5YR3/6)	Sandy clay	Subangular blocky	Slight
	70–89	Bt3	Dark red (2.5YR3/6)	Sandy clay	Subangular blocky	Slight
	89–120	Bt4	Dark red (2.5YR3/6)	Sandy clay	Subangular blocky	Slight
Nerelapally – *Fine-loamy, mixed, hyperthermic, Vertic Haplustepts*						
	0–18	Ap	Dark gray (10YR4/1)	Sandy clay loam	Subangular blocky	Strong
	18–38	Bw1	Dark gray (10YR4/1)	Sandy clay loam	Subangular blocky	Strong
	38–69	Bw2	Dark gray (10YR4/1)	Sandy clay loam	Subangular blocky	Violent
	69–94	Bw3	Dark gray (10YR4/1)	Sandy clay loam	Subangular blocky	Violent
	94–122	Bw4	Dark grayish brown (10YR4/2)	Sandy clay loam	Subangular blocky	Violent
	122–151	Bw5	Brown (10YR5/3)	Sandy clay loam	Subangular blocky	Violent
Avancha – *Fine, smectitic, hyperthermic, Sodic Haplusterts*						
	0–20	Ap	Dark gray (10YR4/1)	Clay	Subangular blocky	Violent
	20–43	Bw1	Very dark grayish brown (10YR3/2)	Clay	Subangular blocky	Violent
	43–68	Bw2	Very dark gray (10YR3/1)	Clay	Subangular blocky	Violent
	68–94	Bss1	Very dark gray (10YR3/1)	Clay	Angular blocky	Violent
	94–131	Bss2	Very dark gray (10YR3/1)	Clay	Angular blocky	Violent
	131–155	Bss3	Dark gray (10YR4/1)	Clay	Angular blocky	Violent
Koduparthy – *Fine – Loamy, mixed, hyperthermic, Typic Ustifluvents*						
	0–9	Ap	Brown (10YR4/3)	Sandy clay loam	Subangular blocky	Strong
	9–19	2A1	Dark yellowish brown (10YR4/4)	Sandy clay loam	Subangular blocky	Strong
	19–33	2A2	Dark yellowish brown (10YR4/4)	Sandy loam	Subangular blocky	Strong
	33–72	3A1	Grayish brown (10YR5/2)	Sandy loam	Subangular blocky	Strong
	72–88	3A2	Brown (10YR5/3)	Loamy sand	Single grain	Strong
	88–118	3A3	Brown (10YR5/3)	Loamy sand	Single grain	Strong
	118–160+	B	Dark gray (10YR4/1)	Sandy clay loam	Subangular blocky	violent

to the container were removed by tapping. The containers were dried at 105 °C and then the COLE was determined from the following formula.

$$\text{COLE} = (l_m - l_d)/l_d$$

where l_m is the moist length of soil paste and l_d is the dry length of soil paste.

Soil pH and electrical conductivity (EC) were measured with 1:2 soil:water ratio (Whitney, 1998). Organic carbon (OC) was determined by the method of Walkley and Black (1934). $CaCO_3$ equivalent (%) was determined by the method described by Piper (1966). Cation exchange capacity (CEC) and exchangeable cations were estimated by 1 *N* ammonium acetate (pH 7.0) method (Schollenberger and Simon, 1945; Sumner and Miller, 1996). Base saturation (BS) was estimated as the ratio of total bases to CEC. Exchangeable sodium percentage (ESP), exchangeable magnesium percentage (EMP) and exchangeable calcium percentage (ECP) were estimated as the ratio of sodium, magnesium and calcium to CEC, respectively. Sodium adsorption ratio (SAR) was calculated as the square root of the ratio of sodium (Na) to half of calcium (Ca) and Magnesium (Mg). Descriptive statistics for 24 soil variables are given in Table 2. Crop yield data for an eight-year period (2008–2015) was obtained from Department of Agriculture, Government of Telangana, Hyderabad. Soil series wise average yield data for cotton, maize and pigeon pea were computed and correlated with SQI.

2.3. Soil quality evaluation

To calculate SQI, four steps were followed namely a) defining management goal, b) selection of indicators as MDS, c) scoring the selected indicators, and d) calculating SQI. Karlen et al. (1997) defined five major soil functions, which are: sustaining biological diversity, regulating and partitioning water and solute flow, buffering and detoxifying organic and inorganic materials, storing and cycling nutrients and providing support of socioeconomic structures. However, it is well recognised that in semi-arid regions, crop productivity is stagnated due to low level of management, predominantly rainfed conditions and poor resource availability (Wani et al., 2009; Sahrawat et al., 2010). In the present study, productivity function is given prime importance among the soil functions though crop cultivation amidst adverse SAT regions is influenced by both edaphic and non-edaphic factors.

2.3.1. Indicator selection

The selection of indicators was done using two methods *viz*., principal component analysis (PCA) and expert opinion (EO) methods.

2.3.1.1. Principal component analysis. PCA was performed using SPSS (version 20.0) for 24 soil physical, chemical properties and derived indices. The objective of PCA was to reduce the dimension of data while minimising the loss of information (Armenise et al., 2013). Principal components (PC) with high eigenvalues were considered best representatives explaining the variability (Andrews et al., 2002). PCs with eigenvalues ≥1 (Kaiser, 1960) were selected since PC with eigenvalue <1 accounts for less variation than generated by a single variable. The retained PCs were subjected to varimax rotation to maximise the correlation between PC and the soil properties by distributing the variance (Waswa et al., 2013). Under each PC, highly weighted variables were selected as soil quality indicators. Multivariate correlation coefficients were used to check for redundancy and correlation between the variables. If the variables are well-correlated ($r > 0.70$), then variable with highest factor loading (absolute value) was retained as indicator among the well-correlated variables (Andrews and Carroll, 2001).

2.3.1.2. Expert opinion. PCA, though widely accepted, is a method of data reduction which simplifies the procedure of indicator selection. However, the authors of the present study were of the opinion that it is necessary to consider the study area characteristics such as climate, rainfall

Table 2
Descriptive statistics of soil properties used for soil quality assessment.

Variable	Min	Max	Mean	Std. dev	CV	Skewness
% sand (2–0.05 mm)	39.50	88.60	61.59	11.50	0.19	0.32
% silt (0.05–0.002 mm)	1.00	18.20	9.05	4.18	0.46	−0.13
% clay (<0.002 mm)	4.60	52.40	29.36	10.97	0.37	−0.37
BD (Mg m^{-3})	1.24	1.99	1.48	0.19	0.13	0.92
Porosity (%)	24.91	53.21	44.03	7.16	0.16	−0.91
sHC (cm h^{-1})	0.00	15.85	1.73	3.60	2.08	2.73
AWC (%)	0.51	39.43	15.06	10.20	0.68	0.81
%WFPS	1.42	78.56	32.48	19.50	0.60	0.72
pH (1:2)	5.75	9.76	8.32	1.17	0.14	−0.77
EC (1:2) (dS m^{-1})	0.00	1.66	0.49	0.56	1.15	0.90
$CaCO_3$ (%)	2.43	23.89	5.91	2.88	0.49	3.35
OC (%)	0.08	1.66	0.48	0.27	0.57	1.69
Exch. Ca	0.30	15.70	6.59	4.88	0.74	0.18
Exch. Mg	0.20	8.90	3.49	2.94	0.84	0.42
Exch. Na	0.10	18.20	3.90	4.54	1.16	1.20
Exch. K	0.20	3.67	1.44	0.80	0.55	0.91
Sum of exch. cations	1.20	40.00	15.42	12.33	0.80	0.45
CEC [cmol (p^+) kg^{-1}]	2.59	40.20	17.89	11.64	0.65	0.49
Base saturation (%)	27.66	120.93	76.14	26.04	0.34	−0.30
Ca/Mg	1.33	4.30	2.15	0.60	0.28	1.54
ESP	0.61	46.66	16.25	12.27	0.76	0.24
EMP	4.00	31.44	16.33	7.55	0.46	0.12
ECP	8.42	57.40	33.07	12.99	0.39	−0.29
SAR	0.07	18.75	4.10	4.89	1.19	1.25

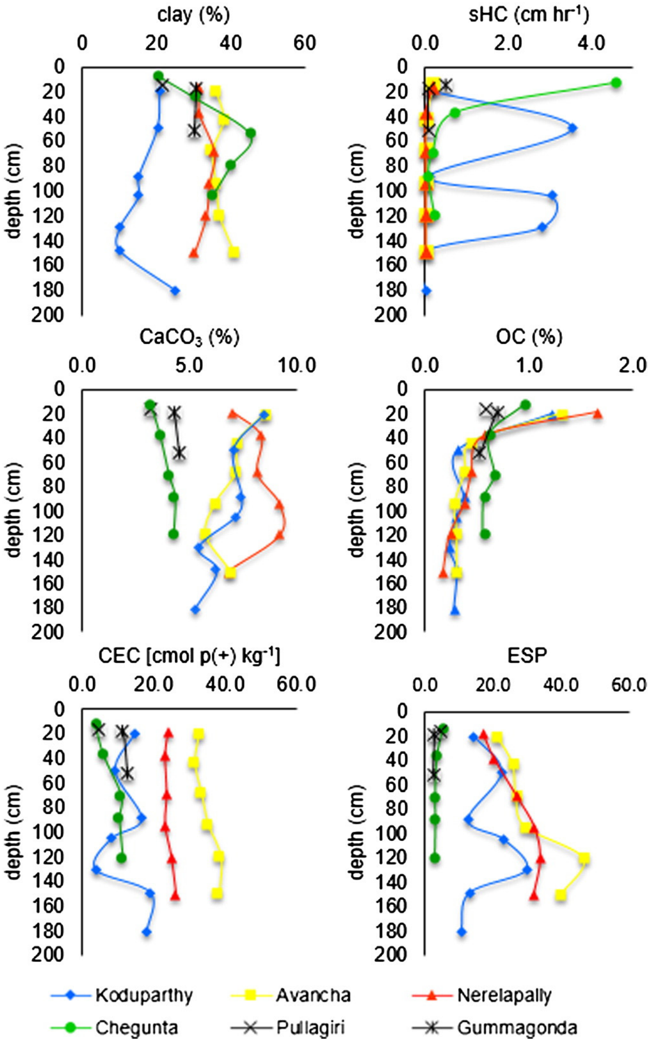

Fig. 2. Depth-wise distribution of soil properties used as minimum soil dataset.

Table 3
Principal components, eigenvalues and component matrix variables.

Principal components	PC 1	PC 2	PC 3	PC 4	PC 5
Eigenvalue	14.908	3.205	2.078	1.257	1.083
% variance	57.33	12.32	7.99	4.83	4.16
% cumulative variance	57.33	69.66	77.65	82.48	86.65
Weightage factor	0.66	0.14	0.09	0.06	0.05
Factor loadings (Rotated component matrix)					
Sand	−0.181	**−0.901**	−0.159	0.074	−0.221
Silt	0.097	0.065	0.171	−0.049	**0.926**
Clay	0.153	**0.919**	0.102	−0.059	−0.122
BD	−0.188	**−0.899**	−0.264	−0.024	−0.141
Porosity	0.186	**0.898**	0.267	0.028	0.142
sHC	−0.063	**−0.668**	−0.422	0.086	0.335
AWC	**0.647**	0.544	0.205	0.355	−0.173
%WFPS	**0.638**	0.477	0.204	0.356	−0.258
pH	**0.776**	−0.131	0.316	0.294	0.213
EC	**0.841**	0.414	0.027	−0.010	0.002
$CaCO_3$	0.293	0.031	**0.597**	0.302	0.211
OC	−0.099	0.039	0.071	**−0.842**	0.032
Ca	**0.660**	0.560	0.448	−0.098	0.078
Mg	**0.734**	0.479	0.403	−0.140	0.041
Na	**0.871**	0.383	0.146	0.098	0.062
K	0.268	0.229	0.529	−0.311	0.260
Sum of cations	**0.774**	0.492	0.362	−0.056	0.080
CEC	**0.762**	0.586	0.182	−0.096	0.069
BS	0.419	0.241	**0.821**	0.018	0.102
Ca/Mg	**−0.706**	0.228	−0.177	0.160	−0.004
ESP	**0.844**	0.035	0.335	0.237	0.144
EMP	0.390	0.354	**0.768**	−0.140	−0.039
ECP	0.015	0.520	**0.789**	−0.040	−0.033
SAR	**0.877**	0.381	0.132	0.079	0.051

Bold face factor loadings were considered highly weighted and underlined were retained in MDS.

and associated pedogenic processes modifying the soil properties which determine the crop productivity before choosing variable(s) as indicators. Moreover, it is important that the selected indicator(s) should truly represent the complexity and function of the soil (Moncada et al., 2014). The semi-arid climate coupled with low MAR plays major role in modification of soil properties in the study area. Therefore, soil quality indicators were selected based on available data and literature pertaining to the soils of the study area.

2.3.2. Scoring of indicators

Selected indicators in MDS were scored into dimension less values ranging from 0 to 1 using linear scoring method (Liebig et al., 2001). Indicators were ranked in ascending or descending order depending on whether a higher value was considered "good" or "bad" in terms of soil function. For 'higher is better' indicators, each value of indicator was divided by the highest value such that the highest value received a score of 1. For 'less is better' indicators, the lowest value was divided by each data value such that the lowest value received a score of 1. For indicators like clay and pH, "optimum" threshold value is considered. They were scored as 'higher is better' upto a threshold value (*e.g.* pH 7.5) then scored as 'lower is better' above the threshold (Andrews et al., 2002).

2.3.3. SQI calculation

We used horizon-wise data of soil profiles to calculate SQI. Soil properties at surface (0–15 cm) level are more dynamic and they are indicative of dynamic soil quality whereas properties at control section (0–100 cm) represent inherent soil quality. SQI for both depths were calculated.

2.3.3.1. Additive index. The additive index was calculated by adding the transformed scores (for both PCA and EO selected indicators) from each soil horizon. Weighted mean for 0–15 and 0–100 cm depth were calculated to arrive at a single index value for each soil profile. The mean SQI for each soil series was then calculated from weighted mean SQI of soil profiles from respective soil series.

2.3.3.2. Weighted index. The transformed indicator data was given weightage based on the results of PCA. Each PC explained a certain amount (%) of the variation in the total dataset. The total percentage of variance from each PC was divided by percentage of cumulative variance to derive the weightage factor (Ray et al., 2014). The derived weightage factor was used with selected variables (indicators) from respective PCs. The weighted variables were then summed up to derive index value for all soil horizons. The weight assignment for the indicators selected by EO method was based on the relative importance of each selected indicator in determining the soil function. Weightage factor was assigned such that the total of all factors comes to unity. Then the SQI for each soil series was calculated as described in the additive index method.

3. Results

3.1. Physical and chemical properties

Six soil series *viz*., Gummagonda (*Loamy-skeletal, mixed, hyperthermic, Lithic Ustorthents*); Pullagiri (*Loamy, mixed, hyperthermic*, *Typic Haplustepts*); Chegunta (*Fine-loamy, mixed, hyperthermic, Typic Rhodustalfs*); Nerelapally (*Fine-loamy, mixed, hyperthermic*, *Vertic Haplustepts*); Avancha (*Fine, smectitic, hyperthermic, Sodic Haplusterts*) and Koduparthy (*Fine-loamy, mixed, hyperthermic*, *Typic Ustifluvents*) were identified based on soil correlation and classified as per US Soil Taxonomy (Soil Survey Staff, 2014). Coefficient of variation (CV) was used to interpret soil variability (Wilding, 1985). The most variable properties (CV > 0.35) are silt, clay, sHC, AWC, %WFPS, EC, $CaCO_3$, OC, exchangeable cations, CEC, ESP, EMP, ECP and SAR. The moderately variable properties (CV 0.15–0.35) are sand, porosity, BS and

Table 4
Correlation coefficient (Pearson) for highly loaded parameters in PC 1.

Parameter	AWC	WFPS	pH	EC	Ca	Mg	Na	Sum of bases	CEC	Ca/Mg	ESP	SAR
AWC	1											
WFPS	0.989^{a}	1										
pH	0.545^{a}	0.527^{a}	1									
EC	0.781^{a}	0.748^{a}	0.620^{a}	1								
Ca	0.757^{a}	0.705^{a}	0.575^{a}	0.803^{a}	1							
Mg	0.738^{a}	0.693^{a}	0.599^{a}	0.814^{a}	0.977^{a}	1						
Na	0.821^{a}	0.784^{a}	0.677^{a}	0.881^{a}	0.850^{a}	0.861^{a}	1					
Sum of bases	0.797^{a}	0.749^{a}	0.637^{a}	0.857^{a}	0.978^{a}	0.976^{a}	0.935^{a}	1				
CEC	0.793^{a}	0.742^{a}	0.545^{a}	0.871^{a}	0.942^{a}	0.946^{a}	0.913^{a}	0.967^{a}	1			
Ca/Mg	−0.273^{b}	−0.268^{b}	−0.575^{a}	−0.414^{a}	−0.413^{a}	−0.522^{a}	−0.452^{a}	−0.471^{a}	−0.452^{a}	1		
ESP	0.680^{a}	0.654^{a}	0.829^{a}	0.730^{a}	0.706^{a}	0.716^{a}	0.876^{a}	0.799^{a}	0.707^{a}	−0.518^{a}	1	
SAR	0.814^{a}	0.777^{a}	0.667^{a}	0.880^{a}	0.846^{a}	0.869^{a}	0.997^{a}	0.935^{a}	0.915^{a}	−0.467^{a}	0.864^{a}	1

[a] Correlation is significant at the 0.01 level.

[b] Correlation is significant at the 0.05 level.

exchangeable Ca/Mg. The properties with least variation (CV < 0.15) are BD and pH (Table 2). The large variation in most of the soil properties may be attributed to a combination of intrinsic (weathering, erosion, deposition and soil forming processes) and extrinsic (management practices) factors (Rao and Wagenet, 1985).

Soil depth varied from 16 cm (*Ustorthents*) to 190 cm (*Ustifluvents*) in the study area. Soil texture varied from loamy sand to clay at surface and soil control section. Depth-wise distribution of soil properties for a representative pedon each from six soil series is given in Fig. 2. The soils of Koduparthy series were formed by fluvial processes in earlier humid climate (Dutta et al., 2001). As a result, depth distribution of properties were irregular (Fig. 2) and sandy layers in subsurface enhances leaching losses of nutrients in these soils. Percentage clay varied from 20.2 (Chegunta) to 36.6 (Avancha) at surface and from 4.6 (Koduparthy) to 52.4 (Avancha) at control section. The sHC varied from 0 to 15.85 cm h^{-1} (Table 2) and soils of Avancha (subsurface soils), Pullagiri, Nerelapally and Avancha (control section) are poor in sHC (Fig. 2). $CaCO_3$ content ranged from 2.43% at surface to as high as 23.9% in the control section, and generally showed increasing trend with depth except in Gummagonda soils and irregular in soils of Koduparthy. The high pH (>8.5) observed in soils of Avancha and Nerelapally is due to the presence of pedogenic $CaCO_3$.

The mean OC content at surface layer and control section were observed to be 0.65 and 0.45% (data not presented), respectively, though higher OC was observed in surface horizons (Fig. 2). CEC varied from 3.9 to 32.7 cmol (p^+) kg^{-1} in surface, and from 2.59 to 40.20 cmol (p^+) kg^{-1} in the control section. The soils of Nerelapally and Avancha have high CEC due to dominant smectite minerals (Pal and Deshpande, 1987), whereas soils of Koduparthy have low CEC which is irregularly distributed with depth. However, all these soils are alkaline in reaction and their ESP ranged from 16.9 to 46.7 (Fig. 2), which impairs crop productivity.

3.2. Principal component analysis

The results obtained from PCA indicated five PCs with eigenvalues >1 (Table 3) and soil variables from each PC were considered for MDS. The soil parameters selected from PC 1 were AWC, %WFPS, pH, EC, exchangeable Ca, Mg, Na, sum of exchangeable cations, CEC, exchangeable Ca/Mg, ESP and SAR. However, multivariate correlation between these parameters indicated high correlation (Table 4) and only SAR which has the highest factor loading was retained in the MDS. Sand, clay, BD, porosity and sHC were chosen from PC 2 and after correlation results (Table 5) only clay was included in MDS. From PC 3, $CaCO_3$, base saturation, ECP and EMP were selected and only base saturation was considered as indicator based on correlation (Table 6). Organic carbon and silt were selected as indicators from PC 4 and PC 5, respectively since they were the only highly weighed parameters. The selected parameters were not independent of each other. Base saturation was correlated with SAR, silt and clay (Table 7), and SAR was correlated with clay. Base saturation is a derived parameter which is dependent on CEC of the soil (Hazelton and Murphy, 2007).

Table 6
Correlation coefficient (Pearson) for highly loaded parameters in PC 3.

Parameter	$CaCO_3$	BS	ECP	EMP
$CaCO_3$	1			
BS	0.527[a]	1		
ECP	0.506[a]	0.716[a]	1	
EMP	0.455[a]	0.865[a]	0.512[a]	1

[a] Correlation is significant at the 0.01 level.

3.3. Expert opinion

Minimum soil data set properties were selected based on the available soil data according to consensus of the authors, available literature on SAT soils and management concerns in the Deccan plateau region. The soil properties selected as indicators were clay, sHC, $CaCO_3$, OC, CEC and ESP. Clay influences the soil management and productivity. The soils with adequate amount of clay (15–20%) and larger amount of silt are the most productive whereas soils with >35% clay pose problems for their management especially in semi-arid regions due to limited soil moisture.

The soils of Deccan plateau vary in their amount and type of clay. The red ferruginous soils have kaolin interstratified with hydroxyl-interlayered vermiculite as dominant clay mineral (Pal et al., 2014) and they are alkaline in reaction due to the presence of pedogenic $CaCO_3$ (Chandran et al., 2013). The Vertisols have smectite as their dominant clay mineral (Pal et al., 2012). The clay fraction in these soils influence their carbon sequestration potential, adsorption and desorption of nutrients and hydraulic properties (Chaudhari, 2001).

Hydraulic conductivity is an important physical property of SAT soils since it controls the depth distribution of soil moisture and also influences the water availability to crops. The SAT Vertisols of the Deccan plateau has problem of salinity, waterlogging and they also have high sodium in the exchange complex. The sHC is impaired by even an ESP of ≥5 in these soils (Balpande et al., 1996). Results from this study indicated poor sHC (<1 cm h^{-1}) for soils of Pullagiri, Avancha, Nerelapally (both surface and subsurface horizons) and soils of Chegunta (subsurface horizons). The drainage of these soils were impaired due to poor sHC and led to poor crop productivity (Kadu et al., 2003).

The soils of Thimmajipet contain substantial amount of $CaCO_3$ and are pedogenic in nature. It increased with depth except in soils of Gummagonda. Apart from lithogenic (non-pedogenic, NPC) carbonates, which are part of smectitic parent material (Pal et al., 2012), occurrence of pedogenic $CaCO_3$ (PC) in semi-arid soils of India is common (Pal et al., 2000; Srivastava et al., 2002). The formation of PC is attributed to the lowering of pCO_2 due to water loss by high evapotranspiration, which leads to the precipitation of $CaCO_3$. The Ca^{2+} ions required for the precipitation have emanated from dissolution of NPCs present in the subsurface layers (Balpande et al., 1996; Srivastava et al., 2002). It leads to depletion of Ca^{2+} ions in the soil solution and NPC and it decreases the Ca/Mg ratio. This results in an increase in EMP and ESP and development of subsoil sodicity. The hydraulic properties are impaired by subsoil sodicity and yield of cotton reduced to the magnitude of 50% in central India (Kadu et al., 2003). Thus, PC limits crop productivity and

Table 5
Correlation coefficient (Pearson) for highly loaded parameters in PC 2.

Parameter	Sand	Clay	BD	Porosity	sHC
Sand	1				
Clay	−0.932[a]	1			
BD	0.878[a]	−0.836[a]	1		
Porosity	−0.877[a]	0.836[a]	−1.000[a]	1	
sHC	0.591[a]	−0.660[a]	0.647[a]	−0.644[a]	1

[a] Correlation is significant at the 0.01 level.

Table 7
Correlation coefficient (Pearson) for selected MDS parameters from PCA results.

Parameters	Silt	Clay	BS	SAR	OC
Silt	1				
Clay	−0.061	1			
BS	0.282[a]	0.354[a]	1		
SAR	0.176	0.471[a]	0.611[a]	1	
OC	0.015	−0.034	−0.104	−0.178	1

[a] Correlation is significant at the 0.01 level.

Table 8
Correlation coefficient (Pearson) for selected MDS parameters from Expert opinion method.

Parameter	Clay	sHC	$CaCO_3$	OC	CEC	ESP
Clay	1					
sHC	−0.661[a]	1				
$CaCO_3$	0.114	−0.227[b]	1			
OC	−0.034	−0.133	−0.116	1		
CEC	0.660[a]	−0.521[a]	0.332[a]	−0.066	1	
ESP	0.148	−0.180	0.509[a]	−0.289[a]	0.706[a]	1

[a] Correlation is significant at the 0.01 level.
[b] Correlation is significant at the 0.05 level.

their formation and increase in ESP are concurrent processes in SAT soils.

Organic carbon is considered as an important soil quality indicator (Lal, 2002). It plays major role in the rainfed production systems of semi-arid regions of India through nutrient supply, moisture retention and stability of soil physical properties (Bhattacharyya et al., 2007). Earlier investigations in the study area documented low OC level (Srinivasarao, 1987) and it remained low (≤0.5%) over the years. The mean OC content is low (0.48%) as observed in the present study (Table 2), and it was felt that poor accumulation of OC might have played important role in influencing the current soil quality status. Therefore, OC was selected as one of the soil quality indicator. Cation exchange capacity influences nutrient supplying capacity of soils as it depends on quantity and type of clay, soil pH and organic matter. Among the selected parameters, sHC had significant negative correlation with clay, $CaCO_3$ and CEC. $CaCO_3$ was positively correlated with ESP and CEC (Table 8). The selected parameters were given weightage in order to calculate weighted SQI. The weightage factor given were 0.3 (clay and $CaCO_3$) and 0.1 (sHC, OC, CEC and ESP). The weightage factors were assigned based on their relative magnitude of influence on crop productivity based on the data used in the present study, the consensus of the authors and the above discussed literature on SAT soils.

3.4. Soil quality index

Soil quality index (SQI) was calculated for selected soil series for the soil depth 0 to 15 cm (surface soils) and for 0 to 100 cm (soil control section) except Gummagonda (only 0–15 cm) and Pullagiri (0–15, 0–50 cm) due to limiting depth (Table 9). An SQI value of >2.0 and 0.4 were considered good from additive and weighted index, respectively, based on the range of SQIs in all the horizons of studied soil pedons. In PCA method, in both surface soils and soil control section, additive index resulted in better SQI for soils of Chegunta, Nerelapally, Avancha and Koduparthy (except in soil control section for Koduparthy) whereas weighted index produced better SQI for Chegunta and Pullagiri soils.

In EO method, in both surface soils and soil control section, additive index resulted in better SQI for soils of Pullagiri, Chegunta and Avancha and only in surface soils for soils of Nerelapally (Table 9). The weighted index produced better SQI for soils of Pullagiri and Chegunta in both surface soils and soil control section whereas only in surface soils for soils of Nerelapally. Results indicate that, under both PCA and EO method, with respect to defined SQI, additive index SQIs were comparable except in soils of Pullagiri (both surface and control section), Nerelapally (control section) and Koduparthy (surface). Similarly, weighted index SQIs were also comparable except in surface soils of Nerelapally.

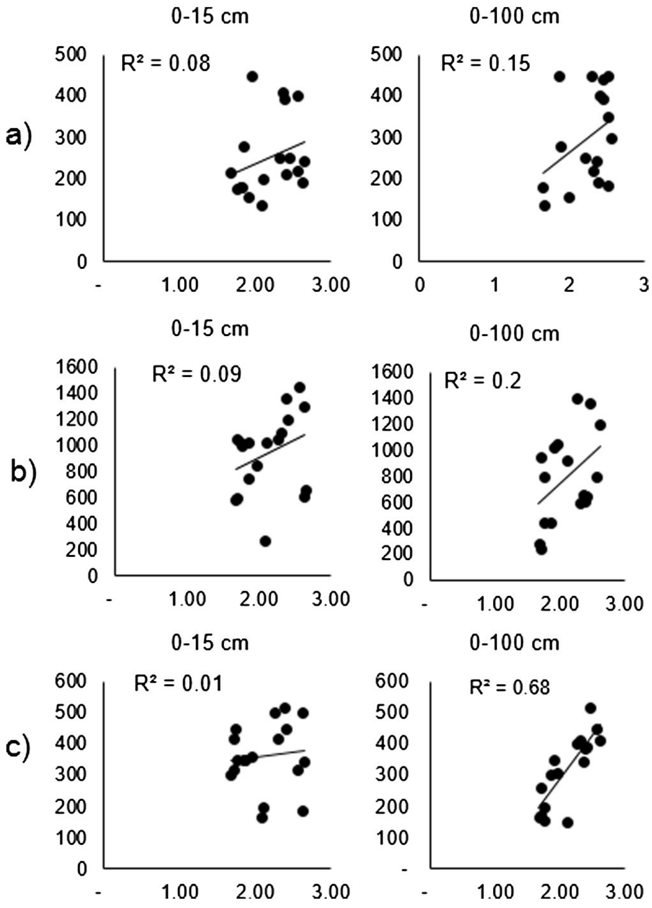

Fig. 3. Correlation of PCA additive index derived SQI with yield of cotton (a); maize (b); and pigeon pea (c). X axis = SQI; Y axis = yield (kg ha^{-1}).

3.5. SQI and crop yield correlation

The estimated SQI values were correlated with recorded yield of cotton, maize and pigeon pea. To assess the relationship of SQI with crop yield, $R^2 > 0.47$ ($n = 18$) was defined as significant. In PCA method, additive index of both surface and control section had poor correlation with yield of crops (Fig. 3) except with pigeon pea yield ($R^2 = 0.68$). However, weighted index had significant correlation (Fig. 4) with maize (both surface and control section); cotton and pigeon pea (control section). In EO method, both additive and weighted index had significant correlation with yield of crops for both surface and control section (Figs. 5 and 6).

The correlation of additive and weighted index with crop yield were not comparable for both surface soils and control section except pigeon pea (control section) in PCA method whereas they were comparable in EO method. However, in EO method, control section SQI by both additive and weighted index had higher R^2 values than surface SQI (except

Table 9
Soil quality index (SQI) values for six identified soil series by different methods.

SQI method	Gummagonda		Pullagiri		Chegunta		Nerelapally		Avancha		Koduparthy	
Depth (cm)	0–15	0–100	0–15	0–50	0–15	0–100	0–15	0–100	0–15	0–100	0–15	0–100
PCA additive index	1.67	–	1.84	1.89	2.37	2.45	2.64	2.36	2.61	2.39	2.07	1.67
PCA weighted index	0.39	–	0.50	0.64	0.58	0.78	0.28	0.38	0.30	0.28	0.27	0.22
EO additive index	1.81	–	2.34	2.19	2.59	2.55	2.10	1.79	2.35	2.33	1.77	1.62
EO weighted index	0.32	–	0.42	0.40	0.54	0.45	0.44	0.35	0.38	0.35	0.27	0.28

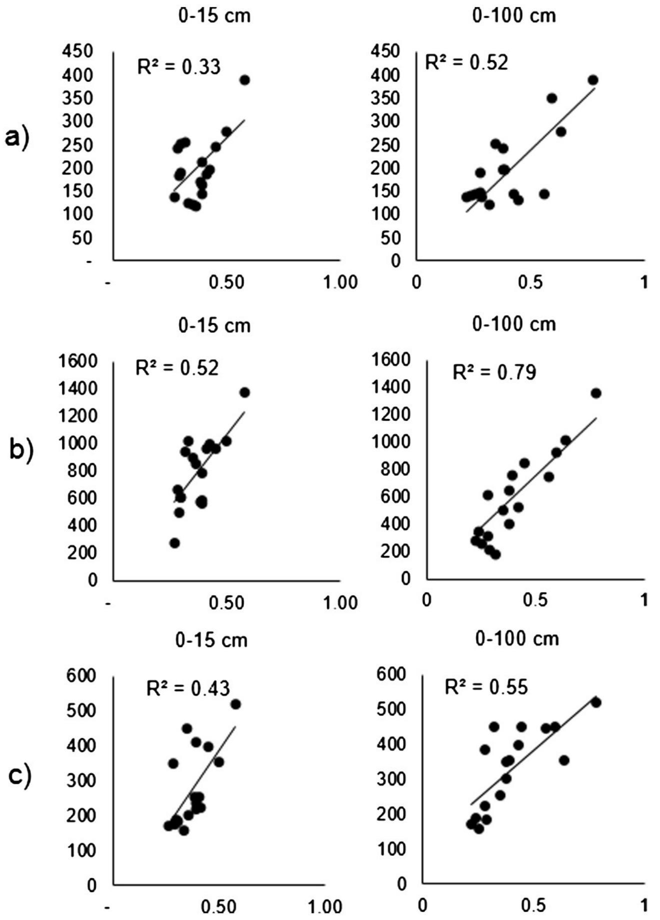

Fig. 4. Correlation of PCA weighted index derived SQI with yield of cotton (a); maize (b); and pigeon pea (c). X axis = SQI; Y axis = yield (kg ha^{-1}).

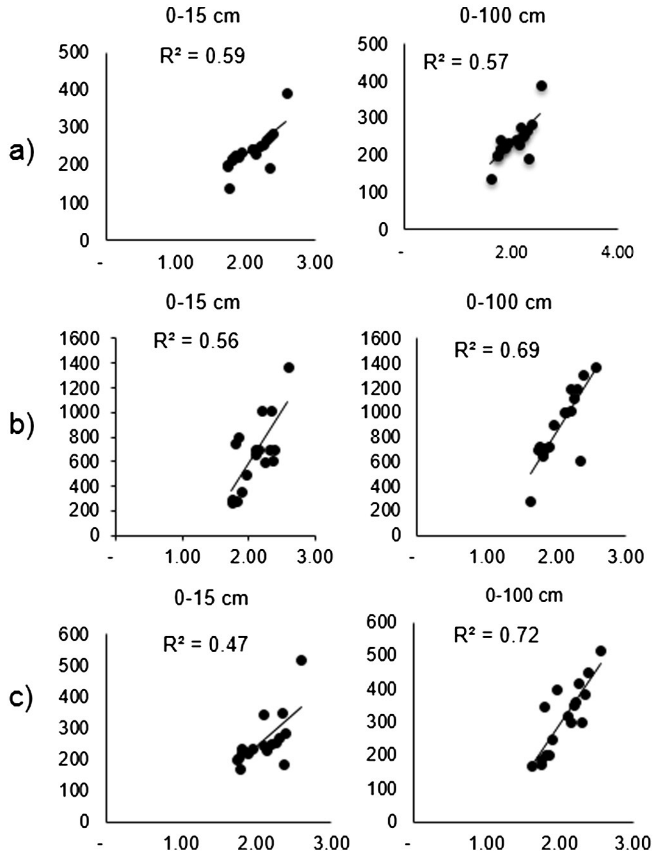

Fig. 5. Correlation of EO additive index derived SQI with yield of cotton (a); maize (b); and pigeon pea (c). X axis = SQI; Y axis = yield (kg ha^{-1}).

for cotton in additive index) indicating their better relationship with yield.

4. Discussion

SQI is a product of few selected soil indicator properties and it warrants selection of most appropriate properties, which have dominant influence on soil functions. PCA and EO methods used in this study differed in selection of indicators except that clay and OC were selected by both the methods. In PCA, factor loadings were high for chemical properties in PC 1 and PC 3 and they can be termed as *chemical components*. The factor loadings were high for physical properties in PC 2 and it can be termed as *physical component*. It can be argued that using complete data set or selection of more indicators may best represent soil quality but when there is high correlation between selected indicators it results in duplication of data (Qi et al., 2009). Clay and silt, though dependent, were included as indicators from PCA method in this study since they were not correlated (Table 7).

Generally, soil quality in the study area varied from low to high. The large variation in soil quality is due to soil heterogeneity and soil degradation caused by subsoil sodicity. As estimated, soils of Chegunta series are of better quality followed by Pullagiri soils. SQI for Koduparthy series is very low and soils of Gummagonda, Nerelapally and Avancha are also poor in quality (Table 9). Soils of Gummagonda series are not suitable for deep rooted crops like cotton and pigeon pea and their yield were low because soils are very shallow, poor in organic matter content (Fig. 2) and water holding capacity. Soils of Koduparthy are also low in productivity since they do not possess the capacity to support optimum plant growth due to leaching of nutrients in the sandy layers (>80% sand) along with percolating water, and lack of root anchorage due to dispersed/sandy/or single grain structure (Table 1). The soils of Nerelapally and Avancha are sodic with pH > 8.5 and the problem of sodicity impairs crop productivity. Presence of $CaCO_3$ leads to the formation of sodium carbonate in the subsurface layers (discussed in section 3.3.) and increases the pH (Nayak et al., 2004) which causes micronutrient deficiency.

The relationship between sHC and clay ($r = -0.67$), ESP ($r = -0.72$), exchangeable Ca/Mg ratio ($r = 0.48$) and EMP ($r = -0.66$) clearly indicated that high Na and Mg impaired the hydraulic properties of soils. The sHC of Nerelapally and Avancha soils were nil in both surface and subsurface layers. This reduces water and air permeability, increases resistance to root penetration and limits the crop performance. Since the MAR is low coupled with very hot summer, the soils remain with very less moisture content in subsurface layers. The yield of crops primarily depends on the available moisture content in rainfed farming situations. However, the quantum of moisture stored in the soil profile and its release is influenced by nature and amount of clay and exchangeable Na and Mg in the exchange complex (Pal et al., 2012). The negative correlation for the available water content with yield of cotton ($r = -0.301$) and pigeon pea ($r = -0.455$) in Avancha soils showed that the moisture available during the crop growth period is very less which led to reduction in yield.

Hewitt (2004) ascertained that soil productivity is influenced by subsurface (control section) characteristics. Our results showed that consideration of both dynamic and inherent properties will help to establish relationship between soil properties and defined soil function and answers the question of integrating surface and subsurface soil information for soil quality assessment. Ray et al. (2014) obtained similar results from PCA as well as EO methods for indicator selection for soils of Indo-Gangetic Plains. But the present study indicates that the indicators selected by the two methods were different and resulted in significantly

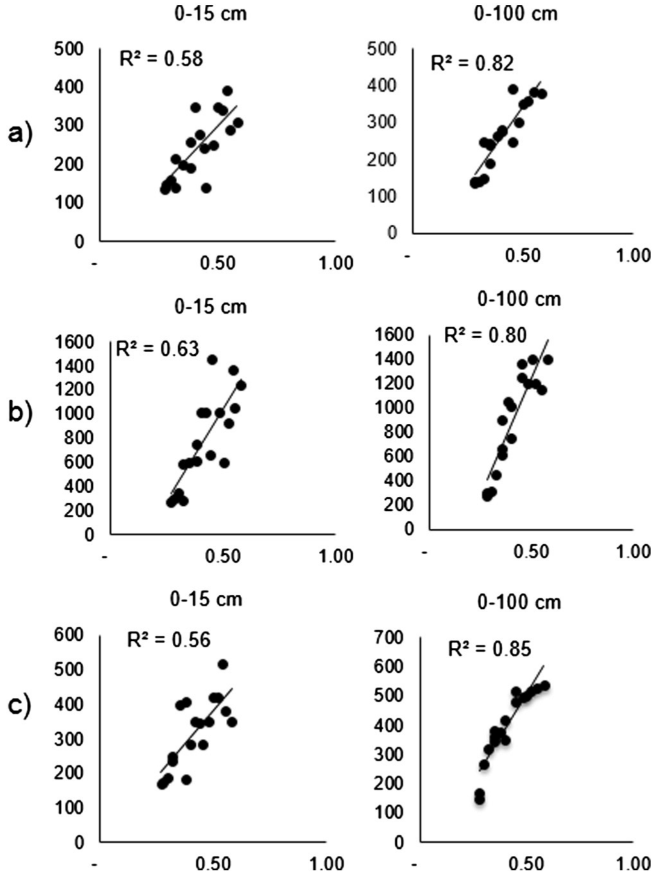

Fig. 6. Correlation of EO weighted index derived SQI with yield of cotton (a); maize (b); and pigeon pea (c). X axis = SQI; Y axis = yield (kg ha^{-1}).

different SQI. The EO method is comparatively better option for soil quality assessment in the SAT region since indicators were selected with due consideration of regressive pedogenic processes and their influence on soil properties. This fact is supported by correlation of SQI with crop yield. It demonstrated that SQIs for soil control section has comparatively better relationship with crop productivity than SQIs for surface soil properties for deep rooted crops. Among the SQI by two indexing methods, weighted index has better correlation with crop yield. The low correlation levels of additive index may be due to selected indictors, which may differ in their ability to influence crop yield. The highly correlated EO weighted index derived SQIs may be used to predict yield levels in SAT soils. In addition, the present study helped to identify sHC, $CaCO_3$ and ESP as potential indicators of soil degradation and they need periodical assessment and monitoring to arrest this menace.

Moreover, the effect of climate change on short-term and long-term soil processes needs to be accounted for developing management strategies to protect soil resources from degradation *viz-á-viz* sustain agricultural productivity. Simulation models have been used to quantify and predict the impact of concurrent changes in climatic parameters on growth and development and yield of crops over the world (Ainsworth et al., 2002; Adam et al., 2011; White et al., 2011) and in India (Hebbar et al., 2013; Venugopalan et al., 2014). Models such as *InfoCrop, CERES-Wheat* are commonly used in India, however, most of them are driven by biophysical parameters, rainfall variability, water balance and economic implications (Asseng et al., 2015; Dasgupta et al., 2013) and little attention has been given to soil (Bhattacharyya et al., 2007) especially in India with large diversity of soils. As SQI accommodates many soil properties as indicators of soil quality, their integration in the simulation models for predicting the effect of climate change on soil functions as well as crop yield will strengthen the knowledge and accuracy of models which will pave way for developing suitable management practices.

5. Conclusions

Soil quality assessment in the SAT Deccan plateau region by PCA and EO methods produced different results. PCA explained the variation in soil properties and their interaction categorically as principal components. On the other hand the EO method, which considered soil characteristics influenced by pedogenesis, identified indicators of soil degradation and outweighed the results obtained by the PCA. Among the indexing methods, weighted index by both PCA and EO was highly correlated with crop yields. But the SQIs estimated by EO weighted index showed a better correlation. We conclude that inclusion of subsurface soil properties along with dynamic surface properties to evaluate SQI by weighted index method helps to establish a good relationship between SQI and defined soil function.

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