Comparison of methods for evaluating the suitability of Vertisols for Gossypium hirsutum (Bt cotton) in two contrasting agro-ecological regions

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Comparison of methods for evaluating the suitability of Vertisols for *Gossypium hirsutum* (Bt cotton) in two contrasting agro-ecological regions

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Abstract

Cotton (*Gossypium sp.*) is a major crop grown under rainfed conditions in Vertisols and associated soils in semi-arid tropical (SAT) regions of Peninsular India. In recent years, cotton productivity has declined due to various biophysical factors including pest and diseases, seasonal water stress soil degradation and poor crop management practices. In this study, we compare two methods for evaluating the suitability of Vertisols for cotton in contrasting two agro-ecological regions viz., sub-humid moist (SHM) region and semi-arid (SAD) were characterized. Twelve cotton growing Vertisols (seven from SHM and five from SAD) were evaluated for their suitability for cotton cultivation using soil quality index (SQI) and modified Sys-FAO method. SQIs were calculated using the weighted additive index from transformed scores of selected indicators by principal component analysis. For Sys-FAO method both biophysical and soil characteristics were considered for suitability evaluation. We found that the soils of SHM region were moderately suitable for cotton cultivation with soil moisture as the major limiting factor, whereas the soils of SAD region are marginally suitable due to high exchangeable sodium percentage and poor hydraulic conductivity. From this, it may be concluded that the weighted SQI has better agreement with the cotton yield.

Keywords: Land suitability evaluation; soil quality index; Vertisols; principal component analysis

Introduction

Globally, Vertisols and vertic intergrades cover ca. 308 million ha (USDA-SCS 1994). These soils occur under all temperature and moisture regimes, but predominantly in tropical (ca. 60%) and sub-tropical (ca. 30%) climates (Ahmad 1996; Coulombe et al. 1996; Dudal and Eswaran 1988). In India, these soils occur ca. 76.4 m ha, covering 23% of the total land area (Mandal et al. 2014). Vertisols and associated soils in central and western parts of India are popularly known as 'Black Cotton Soils', due to their historic use for cotton production. India is the largest cotton producing country in the world, followed by China and USA (DCD 2017; ICAC 2017).

Over recent decades, the cotton productivity in the semi-arid tropical (SAT) regions of India has declined due to soil degradation caused by increasing sodicity (exchangeable sodium percent 15-40), degrading soil structure, impaired drainage and poor crop management practices (Balpande et al. 1996; Vaidya and Pal 2002; Kadu et al. 2003). These issues have been compounded by inappropriate crop management practices such as lack of moisture conservation practices and pest control strategies under rainfed agriculture (Kadu et al. 2003; Blaise and Ravindran 2003, Choudhary and Gaur 2010), and rainfall variability with mid-season dry spells during the crop growth (Tripathi et al. 1990; DCD 2017).

Sustaining cotton production is, therefore, an important challenge for contemporary farming systems. Knowledge of soils, climatic conditions, and crop requirements for particular crop is an essential pre-requisite for optimizing management practices to sustain crop production (Sys 1985; Van Ranst et al. 1996). Vertisols are vulnerable to degradation when the climatic change phenomenon (humid to semi-arid in plio-pleistoscene) made the soil bio-physical factors to less desirable conditions for agriculture (Srivastava et al. 2015; Pal et al. 2016). For example, reduction in mean annual rainfall (MAR) can lead to the formation of calcareous and alkaline soils with elevated pH and calcium carbonate contents (Pal et al. 2012). However, Bhattacharyya et al. (2016) found that the chemically degraded Vertisols can be highly receptive to management interventions, such as amelioration with gypsum and irrigation with good quality water. In the SAT regions, Vertisols vary from *Typic Haplusterts* in humid tropical, *Typic/Udic Haplusterts* in semi-arid moist, and sub-humid dry climates and *Sodic Haplusterts* and *Sodic Calciusterts* in semi-arid dry (SAD) and arid dry climates (Pal et al. 2009).

The appropriate uses of Vertisols with varying physical and chemical properties need to be evaluated to optimize sustainable land management. Many approaches have been developed to evaluate the soil site suitability, such as FAO land evaluation method (FAO 1976), Storie index (Storie 1978) and parametric approach (Sys et al. 1991). For evaluating tropical soils, Naidu et al. (2006) proposed a modified Sys methodology. Evaluating agricultural land suitability involves the consideration of edaphic, climatic, agronomic, and physiographic variables. All these factors contribute differently to the suitability evaluation and yet approaches for integrating these diverse factors for land suitability evaluation are inconsistent. In recent literature, multi-criteria decision analysis (MCDA) is considered as an effective approach to perform land suitability evaluations, since these frameworks combine information from several criteria to form a single index optimized for a specific objective (Malczewski 2006; Cinelli et al. 2014; El Baroudy 2016). Among the different MCDA approaches, soil quality index (SQI) method to evaluate land suitability is recently used in many studies due to its quantitative nature (Mukherjee and Lal 2014; Biswas et al. 2017). Considering both surface and subsurface properties, SQI helps to identify the soil properties having maximum influence on crop performance in a particular region. In this context, the present study was undertaken to compare Sys land evaluation method with SQI method in order to find most suitable method for evaluating the Vertisols for cotton suitability in two different bio-climatic regions of India. The objectives of the study were (i) to evaluate soil-site suitability of Vertisols; (ii) to compare Sys soil suitability index and SQI method for suitability evaluation and (iii) to study the relationship between soil site suitability and cotton yields.

Materials and Methods

Study sites

The two sites for the present study were (i) Dhar, Madhya Pradesh, and (ii) Thimmajipet, Telangana, which have contrasting agro-ecological conditions *viz.*, sub-humid and semi-arid climates, respectively (Figure 1). The soils of both sites were developed from basaltic parent materials (Singh and Murti 1975; Pal et al. 2012), The biophysical characteristics of the study sites are presented in Table 1.

Soil sampling

Twelve representative pedons were sampled in cotton growing soils, seven from Dhar area and five in Thimmajipet area. These soils have been under Bt cotton cultivation for more than 15 years, according to the official land records of Tehsil office, corroborated by interviews with the land owners. At each site, a soil pit was dug exposing a 150 cm deep soil profile, and was described according to the soil taxonomy (Soil Survey Staff 2014). Samples were collected from each horizon using a trowel and stored in polythene bags and transported to the laboratory. The samples were air dried and sieved through 2 mm sieve prior to further laboratory analysis.

Analysis for physical and chemical soil properties

Particle-size distribution was determined using the pipette method (Mehra and Jackson 1960). Sand (2000-50 μm) and total clay (<2 μm) fractions were separated after dispersion according to the size segregation procedure (Jackson 1979). Bulk density was measured by the core method (Blake and Hartge 1986) and the porosity of the soil was calculated assuming soil particle density of 2.65 Mg m^{-3}. Saturated hydraulic conductivity was determined by constant head method (Klute and Dirksen 1986). Soil water retention at both field capacity and the permanent wilting point was measured using a pressure plate apparatus at a suction of 0.033 and 1.5 MPa, respectively (Cassel and Nielsen 1986), and available water content (AWC) was calculated by subtracting water content at permanent wilting point from water content at field capacity. Soil pH was measured with 1:2 soil/water ratio (Jackson 1979). Electrical conductivity (EC) was determined by conductivity bridge (Richards 1954). The organic carbon content of the <2 mm particle size fraction was determined using the modified Walkley and Black method (Jackson 1973), although >2 mm particle size fractions can sometimes contain non-trivial amounts of organic carbon (Cunliffe et al. 2016). Calcium carbonate equivalent was determined by the rapid titration method described by Piper (1966). Cation exchange capacity (CEC) was determined by saturating the soil exchange complex with Na, which was subsequently displaced by NH_4^+ from 1 mol L^{-1} NH_4OAc solution, and the Na in the extract was measured by using atomic absorption spectrophotometer (Richards 1954). Exchangeable Ca and Mg for non-calcareous soil were extracted using 1 mol L^{-1} neutral NH_4OAc (Lanyon and Heald 1982) and for calcareous soils KCl-TEA was used (Soil Survey Staff 2014) and determined by Inductively Coupled Plasma Atomic Emission spectrometer (ICP-

Prodigy, Teledyne, USA). Exchangeable K and Na were determined by emission spectrometer of 1 mol L^{-1} NH_4OAc extracts (Thomas 1982). Clay CEC was calculated by using the formula (CEC/clay)×100. Base saturation was calculated as the ratio of total bases to CEC. Exchangeable sodium percentage (ESP) and exchangeable magnesium percentage (EMP) were estimated as the ratio of sodium, magnesium to the sum of the exchangeable bases, respectively. Weighted average soil properties were calculated for two depths: (i) 0-30 cm depth (surface) and ii) 0-100 cm depth (soil control section).

Soil-site suitability

The soil-site suitability for cotton cultivation is derived from a combination of soil-landscape (static) and soil (dynamic) properties. The climate and landscape properties include MAR, topography, slope, erosion and these factors directly influence the physical and chemical properties of the soil and thus influence the soil quality. For developing a soil–site suitability criteria for cotton, the procedure advocated by FAO was followed *viz.,* (i) characterization of existing soil, climatic and land use conditions, (ii) development of soil-site criteria (iii) matching the crop requirements with the existing soil and climatic conditions, and (iv) determining the soil-site suitability for cotton (FAO 1976). Soil-site suitability for cotton was evaluated based on the criteria given by Naidu et al. (2006), which is a modification of FAO method (FAO 1976), Sys (1985) and NBSS&LUP (1986). The soil suitability for cotton cultivation of the whole soil profile (0-150 cm) was classified according to criteria presented in **Error! Reference source not found.**.

Soil quality index

Soil quality index (SQI) is an effective tool to support decision-making in crop production systems. SQIs are derived from the minimum data sets which are selected according to the defined soil function and management goals. Most soil quality evaluation studies have focused on the properties of near-surface (0-30 cm) layers (Liebig et al. 2001; Cambardella et al. 2004; Karlen et al. 2008) with few exceptions where subsurface properties also considered (Merrill et al. 2012, 2013; Moncada et al. 2014; Ray et al. 2014). Vasu et al. (2016) established the importance of subsurface soil properties while evaluating crop (*Zea mays, Cajanus cajan* and *Gossypium hirsutum*) productivity and soil quality relationship by SQI. In the present study, SQI was derived based on the methodology outlined by Andrews et al. (2002), and we followed three steps for SQI evaluation: (i) selection of key indicators for a minimum dataset (MDS), (ii) scoring the indicators, and (iii) calculating the SQI for two depths: (i) 0-30 cm depth (near surface), and (ii) 0-100 cm depth (rooting zone/soil control section).

Indicators of minimum dataset (MDS)

Principal component analysis (PCA) was performed on 17 physical and chemical soil properties to identify the minimum datasets that would be used for developing soil quality indices. PCA reduces the data dimension without losing information (Armenise et al. 2013). The eigen values shows the relative contribution of a principal component (PC) to the total variance, and PCs with eigen values ≥ 1 were retained (Andrews et al. 2002). The PCs selected were subjected to varimax rotation to enhance the variability of the components. Under each PC, highly weighted variables were selected (within 10% of the highest factor loading) and further multivariate correlation co-efficient was used to check the redundancy and correlation between the variables. If the variables were highly correlated (r >70%), then parameters with the highest loading factor (as absolute value) were retained as soil quality indicators (Anderson-Teixeira et al. 2011; Chen et al. 2013).

Scoring the Identified Indicators

All the selected indicator values were transformed using linear scoring functions with respect to their contribution to soil functions. Each indicator was scored using one of the following curves: (i) “more is better” (upper asymptotic sigmoid curve) indicators of each observation divided by the highest observed value such that the highest value received a score of 1 (ii) "less is better" (lower asymptotic sigmoid curve) the lowest observed value divided by each observation, such that the lowest observed value receives a score of 1 and (iii) "midpoint optimum" (Gaussian curve bell-shaped curve) where higher is better up to an optimum threshold value (*e.g.* pH 6.5) then the score decreases again with distance from the threshold (Wymore 1993; Liebig et al. 2001).

Soil quality index calculation

The soil quality indicator scores were integrated into indexes through weighted additive index approach, from the weightage based on the PCA for both the depth *i.e.,* near-surface (0-30 cm) and the cotton rooting zone (0-100 cm). Each PC explained a certain amount (%) of the variation in the total dataset (Andrews et al. 2002). 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 for selected soil parameters from PCs. In the case of uncorrelated soil parameters within a PC, weightage factors were equal to the percentage of total variance explained by the PC standardized to unity. For correlated indicators, the percentage of the total variance explained by the PC was divided among these and then standardized to unity (Masto et al. 2008). Weighted mean of the MDSs was calculated for both the depths *i.e.,* 0-30 cm and 0-100 cm and subsequently the weighted mean of the SQI were derived for each profile. The calculated SQI values were correlated with the results of soil suitability analysis.

Results and Discussion

Soil physical and chemical characteristics

The descriptive statistics for the measured physical and chemical properties of soils from both the study areas are described in Tables 2 and 3. These data were used to develop SQI for assessing soil-site suitability. In both the study areas, coefficient of variation (CV) were high (> 35) for saturated hydraulic conductivity, $CaCO_3$, and OC. However, in Dhar soils, EC, ESP, and sand content also had high CV. These large CV values in soil properties may be due to both natural pedogenic processes and management practices (Rao and Wagenet 1985).

Among the various soil properties used for assessing the site suitability of Thimmajipet soils, ESP (13.7 – 46.7 %) appears to be more prominent factor that limit the crop production due to soil structural degradation (caused by high sodium along with the presence of magnesium) resulting in low saturated hydraulic conductivity (sHC) (0.01-0.21 cm h^{-1}). In contrast, ESP was lower (0.50 - 24%), and sHC was higher (0.01 - 1.25cm h^{-1}) in Dhar soils.

Cotton growth is generally affected by impeded drainage and these condition can be induced by high ESP and EMP (Bange et al. 2004).

Thimmajipet soils have more $CaCO_3$ content than Dhar soils (7.8% *vs.* 1.2%). This could be attributed to the pedogenic formation of $CaCO_3$ in Thimmajipet soils where PET exceeds MAR (Pal et al. 2012; Vasu et al. 2017). Higher $CaCO_3$ contents increase soil pH and reduce hydraulic conductivity, adversely affecting cotton yields (Seghal 1991; Kadu et al. 2003; Bhattacharyya et al. 2016). In Dhar soils, higher MAR (> 1100 mm) has resulted in soluble $CaCO_3$ being translocated to the lower depth of soil by percolating water, resulting in low concentration of $CaCO_3$ in the upper 100 cm of the soil. Soil pH was high (9.3 mean) in Thimmajipet soils, due to the presence of pedogenic $CaCO_3$, whereas in Dhar it ranges from neutral to alkaline (7.6-9.0). Thus, $CaCO_3$ does not constrain growth in Dhar soils, whereas in Thimmajipet soils, higher free $CaCO_3$ content in the surface horizon modifies soil properties to make them chemically degraded (Bhattacharyya et al. 2016). Mean organic carbon was lower (0.26 %) in Dhar than the Thimmajipet (0.48 %). The CEC of the soils of both the regions are high due to the presence of smectite minerals (Pal and Deshpande 1987).

Soil site suitability assessment

The soil-site suitability assessment (Naidu et al. 2006; supplementary information Table S2) showed the Dhar region soils were moderately suitable (S2) for cotton cultivation with soil moisture as the major limiting factor, whereas the Thimmajipet region soil were marginally suitable (S3) with comparatively more limitation due to soil (high ESP) and climatic parameters (lower MAR and higher PET). The differentiating characteristics identified with respect to the soil site suitability for cotton cultivation of the two regions is presented in table 4.

Soil quality assessment

Selection of minimum datasets

From PCA results, four principal components (PCs) with eigen values higher than 1 were selected for indicator selection and the four PCs explained 84% of the total variability in soil properties (supplementary information Table S4). In PC1, silt, bulk density (BD), porosity, available water content (AWC), pH, electrical conductivity (EC), exchangeable sodium per cent (ESP) and exchangeable magnesium per cent (EMP) were the highly weighed parameters. However, multivariate correlation showed significant relationship between these parameters (supplementary information Table S5) and hence BD was retained due to its highest loading factor. Apart from BD, pH and EMP were also included in MDS since these parameters significantly influence the growth of cotton in Vertisols, by affecting hydrologic properties of the soils. Clay, $CaCO_3$ and Ca/Mg ratio were chosen from PC2 and after correlation only Ca/Mg was retained as MDS (Table S4). Saturated hydraulic conductivity was selected in PC3 (Table S3), as clay CEC is a derived parameter from clay and CEC values (CEC/clay × 100). Organic carbon was selected as an indicator from PC4.

Thimmajipet receives approximately half the precipitation of Dhar. The greater aridity resulting from higher PET than MAR in Thimmajipet led to high pH, ESP and EMP, formation of pedogenic $CaCO_3$ which reduced the saturated hydraulic conductivity of the soils. The high ESP and EMP in these soils could be attributed to the presence of pedogenic carbonates (Pal et al. 2016). Impairment of hydraulic conductivity due to clay dispersion caused by high ESP and EMP was reported by Zade (2007) and Pal et al. (2016). Vasu et al. (2016) emphasized that ESP and saturated hydraulic conductivity has to be considered as effective indicators for assessing soil quality in Vertisols of SAT regions of India which are susceptible to faster degradation than their humid region counterparts (Wilding et al. 1963; Pal et al. 2016).

Thimmajipet soils, occurring in SAD region with high ESP (13.7- 46.6) and calcareousness are very hard when dry, adversely affecting crop growth. Optimizing the physical and chemical properties of the Thimmajipet soils to make them suitable for cotton cultivation would require (expensive) chemical amelioration measures (Pal et al. 2000; Bhattacharyya et al. 2016). The indicators selected for assessing SQI depend on both the requirements of particular crops, and the available data (Qi et al. 2009). Our results showed that while selecting soil quality indicators, consideration has to be given for inherent properties (little change over time) rather than the dynamic properties (changes with respect to soil management) as inherent properties have greater influence on soil functions (Juhos et al. 2016)

Soil quality index

The SQI was calculated from the MDSs indicator scores of each observation from both regions. SQI values >0.57 in the weighted additive index is considered as better (more than the mean value) (Table 6). The results showed that the weighted SQI of Thimmajipet soils were significantly higher than the average value (μ=0.57) irrespective of soil depth (Table 5). In Dhar region, the SQIs of the soils were less than the mean values except for pedon 5. The lower SQI values obtained for soils in Dhar region may be due to higher exchangeable magnesium percent (EMP) (μ=28.02) and bulk density (μ=1.6M g m^{-3}) (Table 3) and the higher SQI of Thimmajipet may be due to better aggregation and a positive Ca/Mg ratio. Overall, SQI for both surface and sub-surface soils indicates Thimmajipet is better suited for cotton agriculture than the Dhar.

The SQI of both the depths are more or less similar and the nutrient content does not exhibit much variation among sites because nutrient content is heavily influenced by management practices. Hence, the nutrient related parameters were not considered for evaluating the SQI. As per the soil suitability criteria, Dhar soils were marginally suitable and Thimmajipet soils are unsuitable for cotton cultivation. However, according to the SQI, the soils of Thimmajipet region were classified as moderate to high in quality (Table 6). Contradictorily, the results of modified Sys method classified the Dhar soils with higher suitability class (S2) than Thimmajipet soils (S3). These results endorse the views of Sojka and Upchurch, (1999) who criticized the indicator based SQI approach as statistical dependent rather than accounting for the soil processes specific to the location. Hence we correlated the SQI values with the crop yield for the respective sites, and found that SQI was a stronger predictor of cotton yield in the Dhar region (R^2=0.83) compared to the Thimmajipet region (R^2=0.49) (Figure 2). Our findings are consistent with those of Vasu et al. (2016).

It is important to note that the higher scores of SQI of Thimmajipet soils had moderate/low correlation with yield (R^2=0.49), but *vice-versa* the SQIs of Dhar soils were low (μ=0.57) but were more strongly correlated with yield (R^2=0.83) (Table 7). SQI is a strong predictor of cotton yield within regions, but is a weak predictor across regions. Our findings support the arguments that site characteristics such as rainfall, slope, soil depth, length of growing period, stoniness and drainage must be considered when assessing soil-site suitability for crops.

Conclusion

The present study compared two methods (SQI and Sys index) for evaluating the suitability of Vertisols for cotton cultivation in contrasting agro-ecological regions. Results showed that the methods differ and produced contrasting results with respect to the crop suitability. Our analysis suggested that the inherent and dynamic properties of soils of Thimmajipet were modified due to climate driven pedogenic processes which result in poor conditions for the growth and development of cotton. The soils of Dhar region have comparatively better characteristics as the sub-humid climate with higher rainfall, which supports successful cotton cultivation. However, the SQI approach rated the Dhar soils lower than the Thimmajipet soils, which indicates that excluding important site-characteristics in suitability evaluations may lead to incorrect conclusions. Hence, we re-emphasize that if MAR, slope, soil depth, length of growing period are considered for suitability evaluation, the SQI could be used a promising tool for monitoring the changes in soil quality.

Conflict of interests

The authors declare no conflicts of interest regarding the publication of this paper.

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Table 1. General description of the focal study regions.

Location	**Dhar, Madhya Pradesh**	**Thimmajipet, Telangana**
Agro-ecological sub-region[1]	5.2	7.2
Köppen climate classification	Sub-humid (moist)	Semi-arid (dry)
Length of growing period [days][1]	120-150	90-120
Mean annual rainfall (MAR) [mm][2]	1100	550
Potential evapotranspiration (PET)[2]	1500-1800	1600-1800
Mean annual temperature [°C] [2]	25	31.5
Soil type[3]	Typic Haplusterts	Typic Haplusterts Sodic Haplusterts
Soil moisture regime	Ustic	Ustic

([1] after Mandal et al. 2014; [2] after the Indian Meteorological Department; [3] USDA soil taxonomy).

Table 2. Descriptive statistics for physio-chemical soil properties of soils in Dhar, Madhya Pradesh

Parameters	Min.	Max.	Mean	Std. Dev.	C V	Skewness	Kurtosis
Sand (%)	4.1	26.6	9.3	3.8	40.7	2.74	11.50
Silt (%)	25.7	48.0	37.9	3.0	8.0	-0.98	9.89
Clay (%)	12.1	60.2	47.9	10.5	21.9	-2.19	4.99
sHC (cm h^{-1})	0.01	1.2	0.1	0.2	136.0	3.30	13.31
BD (Mg m^{-3})	1.5	1.7	1.6	0.04	2.4	-0.36	-0.11
Porosity (%)	34.7	41.2	37.3	1.5	4.1	0.36	-0.14
AWC (%)	9.1	16.5	13.4	1.7	12.7	-0.50	0.28
pH (1:2)	7.6	9.0	8.2	0.3	3.6	0.59	1.10
EC (dS m^{-1})	0.2	0.7	0.2	0.1	46.6	1.79	2.95
$CaCO_3$ (%)	0.01	21.2	1.2	4.7	391.2	4.02	15.13
OC (%)	0.06	0.6	0.2	0.1	49.4	0.57	0.33
CEC [cmol (p+) kg^{-1}]	26.1	71.3	49.7	9.2	18.6	-0.22	1.02
Clay CEC	54.7	231.7	99.4	28.6	28.8	2.98	12.65
Base saturation (%)	79.8	143.1	112.5	14.9	13.2	-0.11	-0.50
Ca/Mg	0.9	4.4	2.6	0.9	35.4	-0.16	-0.55
ESP	0.5	24.0	3.7	5.0	135.2	3.00	9.44
EMP	18.2	50.6	28.0	7.8	27.9	1.31	1.54

Table 3. Descriptive statistics for physio-chemical soil properties of soils in Thimmajipet, Telangana

Parameter	Min.	Max.	Mean	Std. Dev.	C V	Skewness	Kurtosis
Sand (%)	39.5	68.1	55.6	7.9	14.2	-0.48	-0.57
Silt (%)	1.0	18.2	9.9	3.7	37.8	-0.13	0.45
Clay (%)	19.8	52.4	34.3	8.0	23.3	0.49	0.18
sHC (cm h $^{-1}$)	0.01	0.2	0.04	0.06	161.2	2.27	4.05
BD (Mg m^{-3})	1.2	1.5	1.3	0.06	4.6	0.72	-0.22
Porosity (%)	42.6	51.7	48.4	2.4	5.0	-0.72	-0.22
AWC (%)	10.6	39.4	24.2	9.3	38.4	0.21	-1.44
pH (1:2)	8.3	9.7	9.3	0.3	4.1	-1.00	0.43
EC (dS m^{-1})	0.1	1.6	0.9	0.5	53.3	-0.18	-1.50
$CaCO_3$ (%)	3.7	23.8	7.8	3.6	46.3	3.42	15.40
OC (%)	0.08	1.6	0.4	0.3	73.9	1.92	4.63
CEC [cmol (p+) kg^{-1}]	19.5	40.2	27.6	7.4	26.8	0.53	-1.35
Clay CEC	58.7	106.2	80.5	11.5	14.3	0.51	-0.30
Base saturation (%)	74.8	115.6	95.7	10.1	10.6	-0.23	-0.54
Ca/Mg	1.3	2.2	1.8	0.2	14.0	0.09	-1.02
ESP	13.7	46.6	26.7	6.7	25.3	0.90	2.11
EMP	15.4	30.8	22.2	3.9	17.7	0.53	-0.48

Table 4. Differentiating characteristics identified with respect to the soil site suitability for cotton cultivation of the two regions.

Characteristics	Dhar (SHM)	Thimmajipet (SAD)
Mean Temperature	S1	S2
Rainfall	S2	S3
Length of growing period	S2	S3
Soil drainage	S2	S1
Water logging	S2	S1
Slope	S1	S2
ESP	S1	S3
EMP	S2	S3
	S2 w	S3 s c

w- moisture /wetness constraints: s-soil related constrains; c-climate related constraints

Table 5. Weighted soil quality indices, of individual pedons with two depths (0-30 cm and 0-100 cm) using linear scored indicators chosen by principal component analysis minimum data set (MDS) of both study regions

Pedon no.	**Dhar**		**Thimmajipet**	
	0-30 cm	0-100 cm	0-30 cm	0-100 cm
1	0.48	0.56	0.76	0.72
2	0.36	0.37	0.79	0.78
3	0.56	0.48	0.67	0.68
4	0.46	0.44	0.74	0.74
5	0.65	0.58	0.80	0.82
6	0.54	0.50		
7	0.33	0.30		

Table 6. Summary statistics for the soil quality index (SQI)

Parameters	Additive	Weighted
Mean	2.82	**0.57**
Standard Error	0.04	0.02
Median	2.79	0.58
Mode	2.64	0.37
Standard Deviation	0.34	0.17
Sample Variance	0.12	0.03
Kurtosis	-0.63	-1.26
Skewness	0.26	-0.11
Range	1.44	0.60
Minimum	2.18	0.27
Maximum	3.62	0.87
Lower limit	2.14	0.23
Upper limit	3.50	0.91

Table 7. Site suitability for cotton production

Assessment method	Dhar (SHM)	Thimmajipet (SAD)
Soil site suitability analysis	Moderately suitable (S2)	Marginally suitable (S3)
Soil quality index (weighted)	Low	Moderate to high
SQI and yield correlation	Linear model Yield = 538.05 SQI + 81.3 r^2=0.83	Linear model Yield = 754.86 SQI -263.4 r^2=0.49

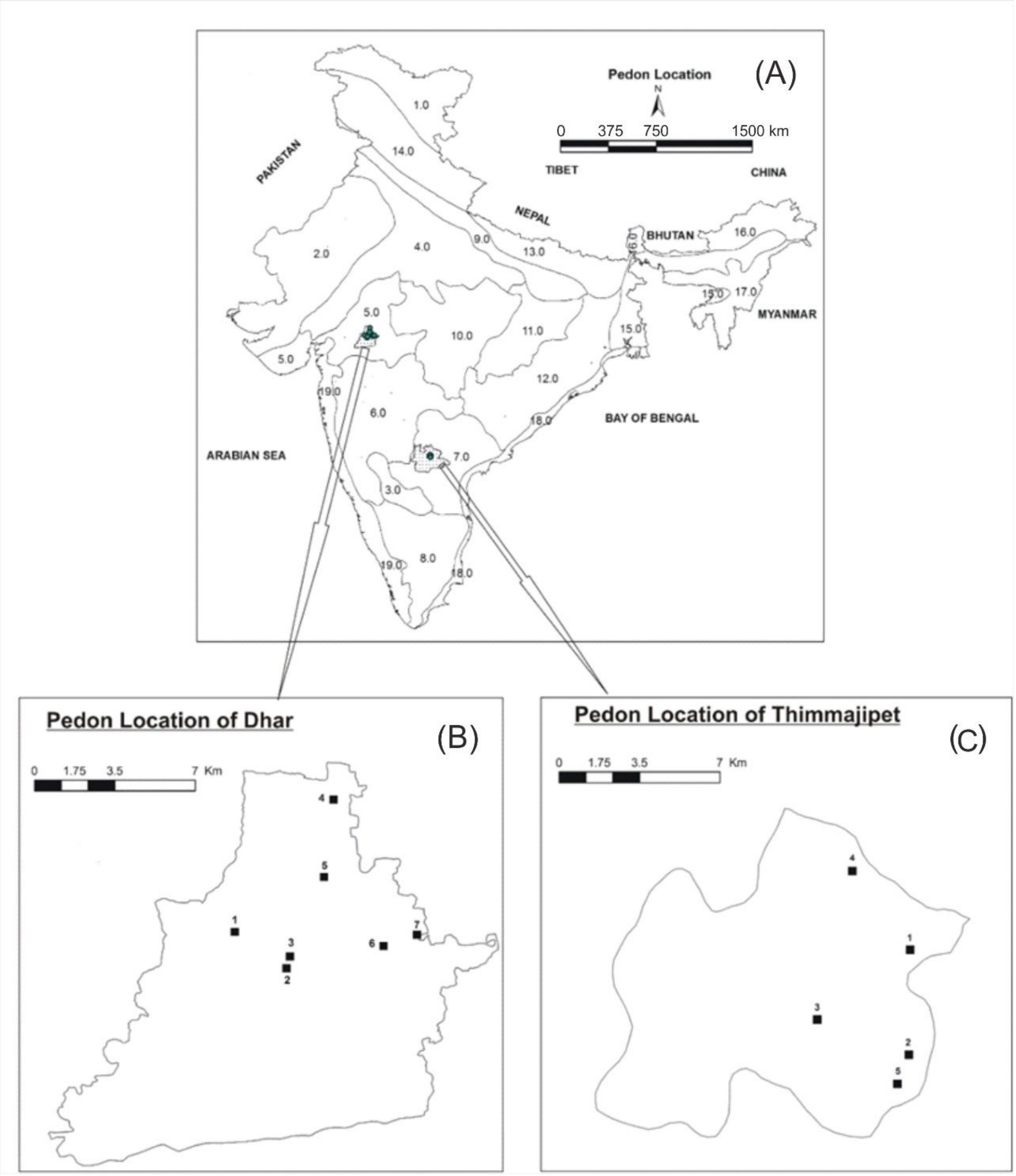

Figure 1. (A) 20 agro-ecological regions of India, The numbers denote the different agro-ecological regions (after Sehgal, 1991; Velayutham et al. 1999; Mandal et al. 2014), (B) Location of the seven sampling pedons in the Dhar region, and (C) Location of the five sampling pedons in the Thimmajipet region.

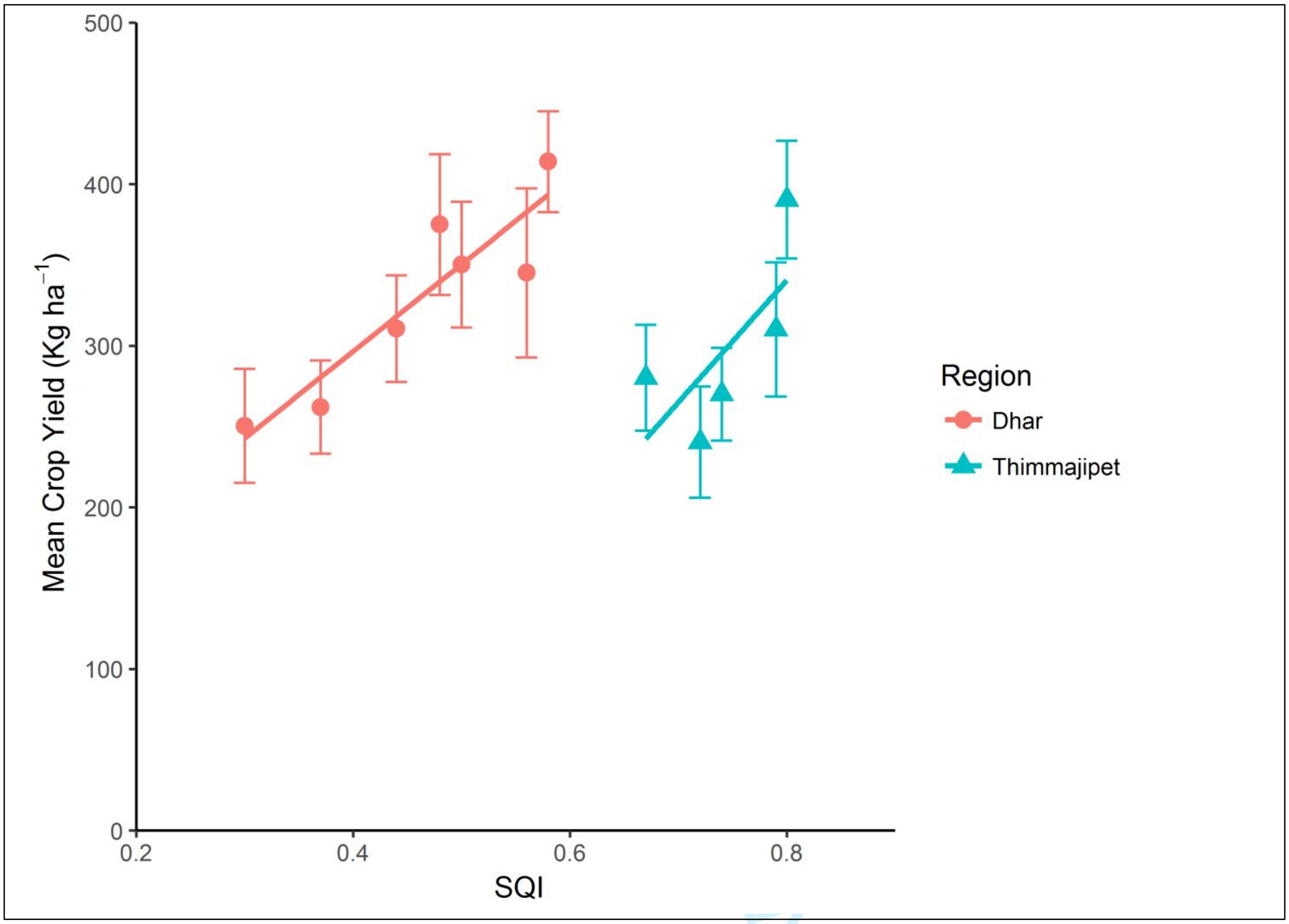

Figure 2. Relationship between weighted index-derived SQI to cotton yield for Dhar and Thimmajipet sites

Supplementary Information

Table S1. Location of field sampling sites.

Region	Pedon		Latitude and Longitude
Dhar	D-1	Sardarpur	22°40'01" N ; 74°59'10"E
	D-2	(Rajpura	22°33'59" N ; 75°07'43"E
	D-3	Marol)	22°35'56" N ; 75°08'18"E
	D-4	Kheda	23°01'59" N ; 75°15'33"E
	D-5	Dattigara	22°49'08" N ; 75°13'57"E
	D-6	Dhar-I	22°37'40" N ; 75°23'51"E
	D-7	Dhar –II	22°39'32" N ; 75°29'24"E
Thimmajipet	T-1	Spot 1	16°40'26" N ; 78°17'37"E
	T-2	Spot 2	16°37'26" N ; 78°16'37"E
	T-3	Spot 3	16°38'48" N ; 74°12'59"E
	T-4	Spot 4	16°43'12" N ; 78°14'34"E
	T-5	Spot 5	16°36'58" N ; 78°15'16"E

Table S2. Soil-site suitability criteria (crop requirements) for cotton (Naidu et al. 2006)

Soil-site characteristics		Rating				
		Unit	**Highly suitable S1**	**Moderately suitable S2**	**Marginally suitable S3**	**Not suitable N**
Climatic regime	Mean temperature in growing season	^{o}C	20-30	31.-35	<19 >35	
	Total rainfall	mm	700-1000	500-700 1000-1250	<500 >1250	
Land quality			**Land characteristics**			
Moisture availability	Length of growing period	Days	180-240	120-180	<120	
	AWC	mm/m	200-250	125-200	50-125	<50
Oxygen availability to roots	Soil drainage	Class	Well to moderately well	Imperfectly drained	Somewhat excessive	Stagnant/ excessive
	Waterlogging in growing season	Days	1-2	2-3	3-5	>5
Nutrient availability	Texture	Class	sic, c	sicl, cl	si, sil, scscl	sl, cm, s, ls
	pH	1:2.5	6.5 – 7.5	7.6 – 8.0	8.1 – 9.0	<6.5 or >9.0
	CEC	cmol(p+)kg^{-1}	>55	50-55	30-50	<30
	OC	%	>1.0	0.75-1.0	0.50-0.75	<0.50
Rooting conditions	Effective soil depth	Cm	100-150	60-100	30-60	<30
	Stoniness	%	<15	15-25	25-50	15-35
	Coarse fragments	Vol %	<5	5-10	10-15	15-35
Soil toxicity	Salinity (EC) Saturation extract	dS/m	2-4	4-8	8-12	>12
	Sodicity (ESP)	%	5-10	10-20	20-30	>30
	EMP	%	>5	5-10	10-25	>25
Erosion hazard	Slope	%	1-2	2-3	3-5	>5

Naidu, L.G.K., Ramamurthy, V., Challa, O., Hegde, R., Krishnan, P., 2006. Manual Soil-Site Suitability Criteria for Major Crops (No. NBSS Publication No. 129). NBSS&LUPP, Nagpur, India.

Table S3. Classifications of soil suitability for cotton production

	Suitability	Limitations
S1	Highly suitable	(with only slight limitations)
S2	Moderately suitable	(moderate limitations)
S3	Marginally suitable	(severe limitations)
N	Unsuitable	(major limitations)

Table S4. Results of principal component analysis (PCA) of soil quality indicators.

	Principal component			
Parameters	PC 1	PC2	PC3	PC4
Total eigen value	9.062	2.159	1.807	1.259
% total variance	53.304	12.698	10.628	7.408
% cumulative variance	53.304	66.003	76.631	84.039
Weightage	0.634	0.151	0.126	0.088
Rotated component matrix				
Sand (%)	0.676	0.597	-0.218	-0.282
Silt (%)	-0.779	-0.479	0.177	0.213
Clay (%)	-0.196	-0.864	-0.135	0.175
sHC (cm hr^{-1})	-0.183	-0.035	**0.907**	-0.061
BD (Mg m^{-3})	**-0.844**	-0.400	0.195	0.117
Porosity (%)	0.844	0.399	-0.196	-0.117
AWC (%)	0.807	0.200	-0.230	0.380
pH	**0.700**	0.540	-0.338	0.086
EC (dS m^{-1})	0.743	0.235	-0.247	0.090
$CaCO_3$ (%)	0.419	0.733	0.261	-0.038
OC (%)	0.100	0.145	-0.107	**-0.869**
CEC [cmol (p+) kg^{-1}]	-0.349	-0.729	0.374	0.269
Clay CEC	-0.114	-0.075	0.910	0.180
Base saturation (%)	-0.669	-0.021	-0.205	0.275
Ca/Mg	-0.023	**-0.764**	0.399	-0.170
ESP	0.742	0.555	-0.259	0.025
EMP	**-0.764**	0.375	-0.171	0.284

sHC = saturated hydraulic conductivity

Table S5. Correlation coefficient between highly weighted variables under different PCs.

PC 1 variables	silt	BD	porosity	AWC	pH	EC	ESP	EMP
Silt	1.000							
BD	0.672**	1.000						
porosity	-0.671**	-1.000**	1.000					
AWC	-0.606**	-0.632**	0.633**	1.000				
pH	-0.756**	-0.658**	0.658**	0.643**	1.000			
EC	-0.590**	-0.574**	0.574**	0.558**	0.657**	1.000		
ESP	-0.711**	-0.730**	0.731**	0.642**	0.867**	0.759**	1.000	
EMP	0.392**	0.465**	-0.464**	-0.381**	-0.280*	-0.243	-0.307*	1.000

PC 2 Variables	clay	CaCO3	Ca/Mg
Clay	1		
CaCO3	-0.726**	1	
Ca/Mg	0.464**	-0.360**	1

PC 3 Variables	sHC	Clay CEC
sHC	1	
Clay CEC	.798**	1