Soil and land quality indicators of the Indo-Gangetic Plains of India

S. K. Ray[1,*], T. Bhattacharyya[1], K. R. Reddy[2], D. K. Pal[3], P. Chandran[1], P. Tiwary[1], D. K. Mandal[1], C. Mandal[1], J. Prasad[1], D. Sarkar[1], M. V. Venugopalan[4], K. Velmourougane[4], G. S. Sidhu[5], K. M. Nair[6], A. K. Sahoo[7], T. H. Das[7], R. S. Singh[8], R. Srivastava[1], T. K. Sen[1], S. Chatterji[1], N. G. Patil[1], G. P. Obireddy[1], S. K. Mahapatra[5], K. S. Anil Kumar[6], K. Das[7], S. K. Reza[9], D. Dutta[9], S. Srinivas[6], K. Karthikeyan[1], A. Srivastava[10], M. Raychaudhuri[11], D. K. Kundu[11], V. T. Dongare[1], D. Balbuddhe[1], N. G. Bansod[1], K. Wadhai[1], M. Lokhande[1], A. Kolhe[1], H. Kuchankar[1], S. L. Durge[1], G. K. Kamble[1], M. S. Gaikwad[1], A. M. Nimkar[1], S. V. Bobade[1], S. G. Anantwar[1], S. Patil[1], V. T. Sahu[1], S. Sheikh[1], D. Dasgupta[1], B. A. Telpande[1], A. M. Nimje[1], C. Likhar[1], S. Thakre[1], K. G. Mandal[10], G. Kar[10], K. M. Gaikwad[1], H. Bhondwe[1], S. S. Dohtre[1], S. Gharami[1], S. G. Khapekar[1], A. Koyal[4], Sujatha[4], B. M. N. Reddy[4], P. Sreekumar[4], D. P. Dutta[7], L. Gogoi[7], V. N. Parhad[1], A. S. Halder[5], R. Basu[5], R. Singh[6], B. L. Jat[6], D. L. Oad[6], N. R. Ola[6], A. Hukare[1], J. Khuspure[1], B. P. Sunitha[4], B. Mohanty[3], D. Hazarika[7], S. Majumdar[5], R. S. Garhwal[6], A. Sahu[8], S. Mahapatra[11], S. Puspamitra[11], A. Kumar[9] and N. Gautam[1]

[1]Regional Centre, National Bureau of Soil Survey and Land Use Planning, Nagpur 440 033, India
[2]Institute of Food and Agricultural Sciences, Soil and Water Science Department, University of Florida, Gainesville, Florida, USA
[3]International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, India
[4]Central Institute for Cotton Research, Nagpur 440 010, India
[5]Regional Centre, National Bureau of Soil Survey and Land Use Planning, New Delhi 110 012, India
[6]Regional Centre, National Bureau of Soil Survey and Land Use Planning, Bangalore 560 024, India
[7]Regional Centre, National Bureau of Soil Survey and Land Use Planning, Kolkata 700 091, India
[8]Regional Centre, National Bureau of Soil Survey and Land Use Planning, Udaipur 313 001, India
[9]Regional Centre, National Bureau of Soil Survey and Land Use Planning, Jorhat 785 004, India
[10]National Bureau of Agriculturally Important Microorganisms, Mau 275 101, India
[11]Directorate of Water Management, Bhubaneswar 751 023, India

Sustaining soil and land quality under intensive land use and fast economic development is a major challenge for improving crop productivity in the developing world. Assessment of soil and land quality indicators is necessary to evaluate the degradation status and changing trends of different land use and management interventions. During the last four decades, the Indo-Gangetic Plains (IGP) which covers an area of about 52.01 m ha has been the major food producing region of the country. However at present, the yield of crops in IGP has stagnated; one of the major reasons being deterioration of soil and land quality. The present article deals with the estimation of soil and land quality indicators of IGP, so that, proper soil and land management measures can be taken up to restore and improve the soil health. Use of principal component analysis is detailed to derive the minimum dataset or indicators for soil quality. The article also describes spatial distribution of soil and land quality with respect to major crops of IGP.

Keywords: Land quality index, principal component analysis, soil quality and health.

Introduction

SOIL is an important non-renewable natural resource upon which depends the survival of mankind, flora and fauna. Hence research is being conducted all over the world to find the best possible measures to preserve the soils, and with improved management practices use them to enhance agricultural productivity by maintaining environmental quality. Though it is well known that there are numerous alternative uses of soil as a living resource, the meaning of the terms 'soil health' and 'soil quality' depends on the defined purpose, such as for agricultural use[1,2]. Soil quality is defined as the capacity of a soil to function, within ecosystem and land, to sustain biological activity, maintain environmental quality, and promote plant, animal and human health[2–4]. Subsequently the two terms are used interchangeably[5], although it is important to distinguish that soil quality is related to soil function[6,7], whereas soil health presents the soil as a finite, non-renewable and dynamic living resource[8].

Maintaining soil quality under intensive land use and fast economic development is a major challenge for sustainable resources use in the developing world[4]. A basic assessment of soil health and soil quality is necessary to

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*For correspondence. (e-mail: skraysrs@yahoo.com)

evaluate the degradation status and changing trends following different land use and smallholder management interventions[9]. This is the reason why Africa has not yet been able to produce enough food to keep pace with demand, and per capita food production is declining[10,11] largely due to loss of soil health and soil quality.

High rates of soil erosion, loss of organic matter, reduction in fertility and productivity, chemical and heavy metals contamination, and degradation of air and water quality have sparked interest in the concept of soil quality and its assessment[2,5]. Although soil quality has a variety of (sometimes conflicting) definitions in the current literature, it is most often defined as 'the capacity of the soil to function'[12]. The Soil Science Society of America[13] defined soil quality as the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water quality, and support human health and habitation. The National Research Council[14] (USA) defined soil quality as the capacity of the soil to promote the growth of plants, protect watersheds by regulating the infiltration and partitioning of precipitation, and prevent water and air pollution by buffering potential pollutants such as agricultural chemicals, organic wastes and industrial chemicals. It is known that there is no single parameter that can quantify soil quality[15], but certain soil properties when considered in combination can be reasonably good indicators of soil quality[16,17]. As soil quality is difficult to quantify directly[18], a minimum dataset (MDS) of soil properties or indicators has been proposed as a means to infer the ability of a soil to perform these basic functions. For good quality indicators, the selected soil properties should be sensitive, easy to measure, verifiable and well-related to land management and the effect of environmental transformation[19,20]. If we are to follow such an approach, we will need a MDS of measurable soil quality indicators (SQI)[3] that can be used to provide quantitative information on the capacity of a soil to function in a desired manner. Soil quality indicators must be clearly correlated with quantifiable soil functions, must respond in a measurable way to external change (natural or anthropogenic), must be adaptable for use by individuals with a range of backgrounds and skills, must be found in existing databases that are accessible and of value to soil quality assessment, and must be easily integrated into larger, ecosystem-scale, models, including socio-economic models.

Researchers all over the world have been trying to analyse the parameters linked to agricultural productivity. Although analysts have long recognized that land quality plays an important role in agricultural productivity, land quality has been difficult to quantify and include in productivity models due to data limitations. Unlike SQI, computing a land quality index (LQI) becomes ideally unattainable because the land quality indicators cannot be accurately quantified in an open system as in soil/land. It is possible to attain closeness through simulation of natural conditions of all the functional factors of land quality. Conceptually, when one or more of these functional parameters are subjected to infinitesimal change, it is likely to bring sharp change in the overall land quality indicator value. Controlled conditions under long-term management experiments can attain closeness with reality. Determining the LQI is more challenging because of the contribution of several factors which are responsible towards its development. The changes in biophysical and other factors govern the yield of crops and determine the vegetative status and demography of a particular landscape. Hence our aim here was to understand and assimilate the factors (SQI, climate quality index (CQI)) responsible for the decreasing yields in the Indo-Gangetic Plains (IGP) and validate whether these parameters selected are truly limiting factors for the yield of crops. Cultivated land quality[21] has been assessed and it is related to the productive potential of the land. In India, a crop-specific (sorghum) LQI has also been developed[22] from SQI. Accuracy of the indicator determines the assessment of SQI and LQI. The indicators used also depend upon other local and regional factors, landform types, risk of erosion, anthropogenic activities and natural conditions, selected socio-economic indicators, crop type and vegetation apart from biophysical factors.

The IGP is one of the most extensive fluvial plains of the world (Figure 1). The course of River Ganga and deposition of alluvium have been governed by the various tectonic events in its past history, which are active even today[23–26]. The soils of the IGP developed from the alluvium of the rivers Ganga, Yamuna, Indus, Ramganga, Ghagra, Rapti, Gandak, Bhagirathi, Silai, Damodar, Ajay and Kosi. The IGP covers the Indian states of Rajasthan, Punjab, Haryana, Uttar Pradesh, Bihar, West Bengal and Tripura. It occupies an area of about 52.01 m ha and represents 10 agro-ecological regions (AERs) and 29 agoecological sub-regions (AESRs) of the country[27–31]. The soils belong to Entisol, Inceptisol, Alfisol, Aridisol, Mollisol and Vertisol orders of soil taxonomy[32]. There is a need to analyse the past trends to understand the role of biophysical factors, socio-economic perceptions and other factors leading to emergence of characteristics of the present agricultural systems, i.e. decline/stagnation in yield and deterioration in soil health. Of these factors, the most fundamental one with enormous value and importance to influence the other dynamic factors is the biophysical factor, i.e. the quality of soil substrate on which life of man and the quality of the environment sustain[33].

In IGP, changes in levels of carbon in the soils between 1980 and 2005 were monitored to determine the link between soil organic carbon (SOC) and decline in productivity over the years[34]. However, datasets for the period between 1980 and 2005 indicated an overall increase in SOC, which is a positive indicator of soil quality and increase in soil productivity. However, there was also a concomitant increase in soil inorganic

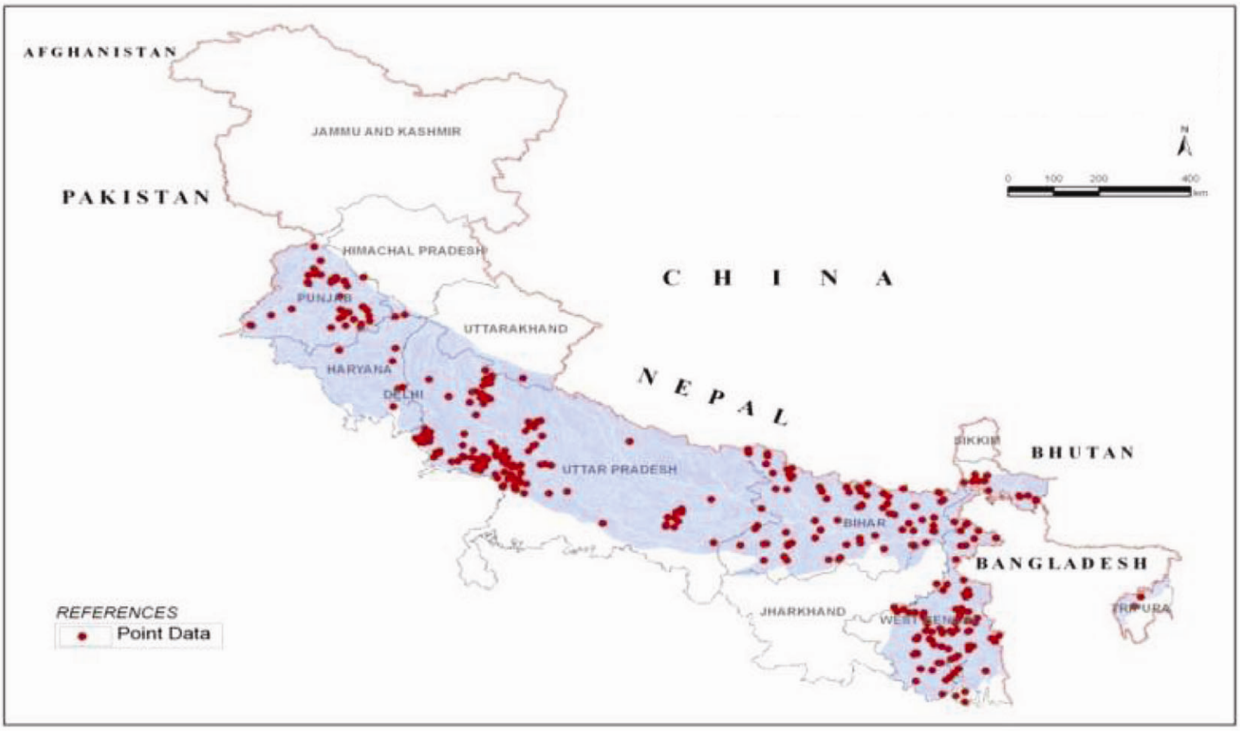


Figure 1. Location of various soils series in the Indo-Gangetic Plains (IGP), India.

carbon (SIC), which indicates negative effect on soil productivity and is a major cause for chemical degradation of soils.

During the last four decades or more, the IGP has been the major food producing region of the country. The main crops of the region are rice and wheat, apart from pulses, oilseeds, cash crops and horticultural crops. The higher yields could be achieved on loamy and fertile soils with the use of high-yielding varieties, higher irrigated areas, fertilizers and improved soil management practices, apart from socio-economic and external factors[35]. However, at present, the yield of crops has stagnated due to the high degree of physical and chemical degradation of land, nutrient deficiencies and imbalances, depleting ground water level, and pollution of soil and groundwater by nitrogen, phosphorus and heavy metals[36]. These changes in biophysical properties over time might have resulted in decreasing yield of crops. Moreover, the use of heavy machinery agricultural implements has resulted in hard pan formation[37], which had manifestations in soil properties in terms of increase in bulk density (BD), decrease in saturated hydraulic conductivity (sHC), resulting in decrease/stagnation of crop yields, especially of wheat in the upper IGP. It is envisaged that deterioration of soil and land quality is one of the major reasons for the decline in yield. Therefore, our objective is to determine the soil and land qualities of the IGP region, so that proper land management measures can be taken up to restore or improve the soil health conditions for sustainability of the region.

Materials and methods

Study area

The IGP is a vast area encompassing nine states in different AESRs of the country (Figure 1). It covers 10 AERs and 29 AESRs of the country[28]. The climate of IGP varies widely from arid to humid. The rainfall, temperature and potential evapotranspiration (PET) thus vary widely. It also consists of various bioclimatic zones. The cropping pattern belongs generally to rice–wheat system. Barring the area in the extreme west (Rajasthan), rice (*Oriza sativa* L.) is grown throughout the IGP. However, in the extreme east wheat (*Triticuma estivum* L.) is not a preferred crop due to shorter winters. Other crops grown include sugarcane (*Saccharum officinarum* L.), cotton (*Gossypium hirsutum* L.), mustard (*Brassica juncea* L.), safflower (*Carthamus tinctorius* L.), pearl millet (*Pennisetum glaucum* L.), potato (*Solanum tuberosum* L.) and groundnut (*Arachis hypogea* L.).

Materials

Two types of datasets have been used in this work; one was the benchmark spot data collected from 30 hotspot profile soil samples during 2005 (refs 33, 38) covering the whole IGP, except Tripura (Table 1). The other dataset is the baseline data comprising information about 417

Table 1. Representative soils in IGP in a climosequence and their classification

AER/Bio-climate	Soil series	District/State	Classification		MAR (mm)
			WRBSR[40]	Soil Survey Staff[41]	
2, Western Plains, hot-arid/hot arid	MASITAWALI	Hanumangarh, Rajasthan	Hapli-Aridic Arenosols	Torrifluventic Haplustepts	221
2, Western Plains, hot-arid/hot arid	NIHALKHERA	Firozpur, Punjab	Hapli-Calcaric Luvisols	Aridic Haplustalfs	268
2, Western Plains, hot-arid/hot arid	JASSI PAWALI	Bhatinda, Punjab	Hapli-Calcaric Luvisols	Aridic Haplustalfs	368
2, Western Plains, hot-arid/hot arid	JODHPUR RAMANA	Bhatinda, Punjab	Hapli-Aridic Luvisols	Aridic Haplustalfs	368
4, Northern Plains, hot semi-arid/semi-arid dry	HIRAPUR	Aligarh, Uttar Pradesh	Vertic Solonetz (Siltic)	Vertic Natrustalfs	627
9, Northern Plains, hot sub-humid (dry)/semi-arid dry	BHANRA	Patiala, Punjab	Hapli-Protic Arenosols	Typic Ustipsamments	674
4, Northern Plains, hot semi-arid/semi-arid dry	GHABDAN	Sangrur, Punjab	Gleyic-Solonetz (Siltic)	Haplargidic Natrustalfs	674
4, Northern Plains, hot semi-arid/semi-arid dry	PHAGUWALA	Sangrur, Punjab	Haplic Calcisols	Oxyaquic Haplustalfs	674
9, Northern Plains, hot sub-humid (dry)/semi-arid dry	DHADDE	Kapurthala, Punjab	Verti-Oxyaquic Luvisols	Oxyaquic Vertic Haplustalfs	680
4, Northern Plains, hot semi-arid/semi-arid dry	FATEHPUR	Ludhiana, Punjab	Hapli-Eutric Luvisols	Inceptic Haplustalfs	680
9, Northern Plains, hot sub-humid (dry)/semi-arid dry	JAGJITPUR	Kapurthala, Punjab	Verti-Oxyaquic Luvisols	Oxyaquic Vertic Haplustalfs	680
4, Northern Plains, hot semi-arid/semi-arid dry	SAKIT	Etah, Uttar Pradesh	Vertic Solonetz (Siltic)	Oxyaquic Haplustalfs	681
4, Northern Plains, hot semi-arid/semi-arid dry	ZARIFA VIRAN	Karnal, Haryana.	Haplic Solonetz (Siltic)	Typic Natrustalfs	720
9, Northern Plains, hot sub-humid (dry)/semi-arid moist and sub-humid dry	BERPURA	Ambala, Haryana	Haploluvi-Eutric Cambisols	Oxyaquic Haplustalfs	905
9, Northern Plains, hot sub-humid (dry)/semi-arid moist and sub-humid dry	SIMRI	Bareilly, Uttar Pradesh	Vertic Solonetz (Siltic)	Typic Haplustalfs	1052
13, Easter Plains, hot sub-humid (moist)/sub-humid dry	BELSAR	Bhagalpur, Bihar	Verti-Gleyic Luvisols (Hyposodic)	Aeric Endoaqualfs	1086
13, Easter Plains, hot sub-humid (moist)/sub-humid dry	EKCHARI	Bhagalpur, Bihar	Verti-Gleyic Luvisols (Hyposodic)	Vertic Endoaqualfs	1086
9, Northern Plains, hot sub-humid (dry)/sub-humid moist	SARTHUA	Bhojpur, Bihar	Vertic-Gleyic Sodic Luvisols	Vertic Endoaqualfs	1102
13, Easter Plains, hot sub-humid (moist)/sub-humid moist	NANPUR	Vaishali, Bihar	Gleyi-Calcaric Cambisols (Sodic)	Fluventic Endoaquepts	1110
13, Easter Plains, hot sub-humid (moist)/sub-humid moist	GAUPUR	Samastipur, Bihar	Hapli-Calcaric Luvisols (Siltic)	Typic Endoaqualfs	1252
14, Western Himalaya, warm, moist semiarid to dry sub humid/sub-humid moist	HALDI	Udhamsinghnagar, Uttaranchal	Umbri-Eutric Fluvisols	Typic Haplustalfs	1252
15, Bengal Plains, hot sub-humid to humid/sub-humid moist	HANGRAM	Barddhaman, West Bengal	Verti-Gleyic Luvisols (Siltic)	Vertic Endoaqualfs	1404
15, Bengal Plains, hot sub-humid to humid/sub-humid moist	KONARPARA	Barddhaman, West Bengal	Verti-Gleyic Luvisols (Siltic)	Vertic Endoaqualfs	1404
15, Bengal Plains, hot sub-humid to humid/sub-humid moist	MADHPUR	Barddhaman, West Bengal	Verti-Gleyic Chromic Luvisols (Clayic)	Chromic Vertic Endoaqualfs	1404

(*Contd*)

Table 1. (*Contd*)

AER/Bio-climate	Soil series	District/State	Classification WRBSR[40]	 Soil Survey Staff[41]	MAR (mm)
15, Bengal Plains, hot sub-humid to humid/sub-humid moist	SASANGA	Barddhaman, West Bengal	Verti-Gleyic Chromic Luvisols (Clayic)	Chromic Vertic Endoaqualfs	1404
15, Bengal Plains, hot sub-humid to humid/sub-humid moist	CHUNCHURA	Hugli, West Bengal	Gleyi-Haplic Vertisols (Siltic)	Typic Endoaquerts	1583
15, Bengal Plains, hot sub-humid to humid/sub-humid moist	MOHANPUR	Nadia, West Bengal	Verti-Endogleyic-Luvisols (Siltic)	Vertic Endoaqualfs	1583
18, Eastern coastal plains, hot sub-humid to semi-arid/humid	SAGAR	24-Parganas, West Bengal	Verti-Endogleyic-Sodic Cambisols (Siltic)	Vertic Endoaquepts	1908
15, Bengal Plains, hot sub-humid to humid/per-humid	SEORAGURI	Coochbehar, West Bengal	Hapli-Endogleyic-Luvisols (Siltic)	Typic Endoaqualfs	3292
16, Eastern Himalayas, warm per-humid/per-humid	SINGVITA	Darjiling, West Bengal	Endogleyic-Luvisols (Dystric)	Umbric Endoaqualfs	3390

AER, Agro ecological region; MAR, Mean annual rainfall.

soil series (including many benchmark soils) encompassing the whole of IGP from Rajasthan to Tripura[39].

Methods

The datasets (both hotspots and extended) for the whole of IGP were divided into two groups based on physiographic delineation, climate, vegetation, parent material and soil to facilitate the calculation procedure:

(1) Upper IGP consisting of Rajasthan, Punjab, Haryana, Uttarakhand and Uttar Pradesh.
(2) Lower IGP consisting of Bihar, West Bengal and Tripura.

Calculation of soil quality index

To evaluate SQI, four main steps were followed, namely to (a) define the goals; (b) find out the MDS or the independent soil parameters by principle component analysis (PCA) or through expert opinion (EO) which gave an optimal representation of the soils of the IGP; (c) give certain score to the MDS using appropriate methods, and (d) deduce an overall score or SQI from the above functions. Our aim is to calculate a composite SQI from quantifiable data for the Upper and Lower IGPs.

SQI was calculated following standard methodologies[2,5,12], as described by Andrews *et al.*[17]. The methodologies were modified wherever applicable for Indian soil conditions. However, for the calculation of SQI, the methodology used by Andrews *et al.*[17] was used. To arrive at the MDS, two methodologies were followed: (1) using PCA, and (2) seeking expert opinion.

Principal component analysis

This technique is employed to identify the minimum soil parameters which can give interpretable information to explain the physical and chemical parameters of a particular group of soils having multiple parameters to handle. The PCA technique[2,17] has been employed here using SPSS (version 20.0). Derivation of the MDS was done using multivariate data reduction technique with the help of standardized PCA. Principal components (PCs) for a dataset are defined as a linear combination of the variables that account for maximum variance within the set by describing vectors of closest fit to (x) observations in (y) dimensional space, subject to being orthogonal to one another[17,42]. The methodology adopted here to select a subset from a large dataset is similar to that described by Dunteman[42] and Andrews *et al.*[17]. It was assumed here that PCs with eigen values ≥ 1 were examined[43]. Moreover, PCs that explained ≥5% of the variability in the soil data were included[44]. An example of applying PC analysis, on the data from the upper IGP (hotspots) for 0–15 cm soil depth (Table 2) showed that six PCs explained >5% of the total variance. Only highly weighted variables were retained from each PC. When more than one factor was retained under a single PC, multivariate correlation coefficients were employed to determine if the variables could be considered redundant and therefore eliminated from the MDS[45]. If the highly weighted factors were not correlated, then each was considered important and thus retained in the MDS. Among well-correlated variables, one with the highest factor loading (absolute value) was chosen for the MDS. Another methodology adopted for deriving the MDS from the available data was based on EO, which involved consensus from the experts'

Table 2. Principal components (PCs) of soil quality parameters, eigenvalues and component matrix variables for Upper IGP (hotspots) surface soils (0–15 cm depth)

Parameters	PC 1	PC 2	PC 3	PC 4	PC5	PC6
Total eigenvalue	8.431	6.171	5.276	4.217	4.072	2.491
% Total variance	22.786	16.677	14.259	11.397	11.006	6.731
% Cumulative variance	22.786	39.463	53.722	65.120	76.126	82.857
Weightage	0.275	0.201	0.172	0.138	0.133	0.081
Rotated component matrix						
Sand (2–0.05 mm)	**–0.886**	–0.278	–0.182	–0.130	0.015	0.014
Silt (0.05–0.002 mm)	**0.841**	0.223	0.233	0.168	–0.070	–0.145
Clay (<0.002 mm)	**0.699**	0.373	–0.085	–0.068	0.199	0.485
Fine clay (%)	0.459	0.435	–0.252	–0.118	0.406	0.473
Fine clay/ total clay (%)	–0.155	0.314	–0.388	–0.113	**0.644**	0.226
BD (Mg/m^3; oven dry)	0.391	–0.327	**0.729**	–0.009	0.206	0.010
COLE (room temperature)	**0.848**	0.126	–0.003	–0.121	0.139	–0.142
sHC* (cm/h)	**–0.597**	–0.344	0.171	0.148	0.503	0.232
WDC	0.301	0.082	0.034	**–0.770**	–0.253	0.005
pH water (1 : 2)	0.094	0.283	–0.067	0.519	**0.698**	0.040
$CaCO_3$	–0.216	0.053	–0.028	0.051	**0.774**	0.315
OC	0.352	–0.349	**0.528**	0.105	–0.377	0.227
Ex.Ca	**0.897**	–0.364	–0.041	–0.050	–0.049	0.067
Ex.Mg	0.382	–0.260	**0.837**	–0.073	0.056	0.157
Ex.Na	0.132	**0.916**	–0.038	0.157	0.075	–0.088
Ex.K	0.009	0.087	0.200	–0.050	–0.034	**0.847**
Sum of Ex. cations	**0.845**	0.053	0.426	–0.008	0.033	0.143
CEC	0.314	0.179	0.104	–0.166	–0.222	–0.022
Clay CEC (cmol(p+)kg^{-1})	**0.596**	0.059	–0.260	0.134	–0.315	0.152
BS	–0.063	–0.259	**–0.918**	–0.015	0.031	0.054
Ex.Ca/Mg	–0.064	–0.263	**–0.907**	0.003	0.025	0.082
ECP	–0.087	–0.274	**0.920**	–0.044	0.096	0.114
EMP	0.047	**0.903**	–0.040	0.182	0.049	–0.091
ESP	0.445	–0.430	–0.054	–0.151	0.206	**0.511**
CO_3^{2-} clay	**0.942**	–0.122	0.217	–0.035	0.024	–0.004
Sat %	**0.942**	–0.122	0.217	–0.035	0.024	–0.004
ECe	–0.440	–0.170	–0.185	–0.050	**–0.634**	0.378
Ca_s	–0.111	–0.133	–0.296	–0.003	**–0.863**	0.157
Mg_s	0.136	0.437	0.033	**0.861**	0.066	–0.124
Na_s	–0.462	–0.238	–0.501	0.064	0.076	0.534
K_s	0.151	0.523	–0.100	**0.730**	0.185	–0.131
Sum_{cs}	0.046	**0.594**	–0.291	0.590	–0.305	0.090
HCO_{3s}	–0.134	0.056	0.071	**0.779**	–0.421	0.134
Cl_s^-	0.131	0.505	0.033	**0.818**	0.130	–0.140
SO_s^{2-}	–0.276	0.432	0.172	0.289	0.239	0.293
Sum_{as}	0.135	**0.861**	–0.048	0.173	0.131	0.110
SAR	–0.002	**0.855**	0.044	0.260	0.261	0.114

*Bold face factor loadings are considered highly weighted.

BD, Bulk density; COLE, Coefficient of linear extensibility; sHC, Saturated hydraulic conductivity; WDC, Water dispersible clay; Ex.Ca, Ex.Mg, Ex.Na, Ex.K, Exchangeable calcium, magnesium, sodium and potassium; CEC, Cation exchange capacity; Clay CEC, Cation exchange capacity of clay; BS, Base saturation percentage; Ex.Ca/Mg, Exchangeable calcium to magnesium ratio; ECP, Exchangeable calcium percentage; EMP, Exchangeable magnesium percentage; ESP, Exchangeable sodium percentage; CO_3^{2-}, clay–carbonate clay; sat %, Saturation percentage; ECe, Electrical conductivity at saturation; Ca_s, Soluble calcium; Mg_s, Soluble magnesium; Na_s, Soluble sodium; K_s, Soluble potassium; Sum_s, Sum of soluble cations; HCO_{3s}, Soluble bicarbonate; Cl_s^-, Soluble chloride; SO_s^{2-}, Soluble sulphate; Sum_s, Sum of soluble anions; SAR, Sodium absorption ratio.

recommendations in the literature[26,33,46] and form common management concerns of the IGP soils.

Methodology for SQI calculation

To arrive at the MDS, the results of PCA were used. From the variance data (Table 2), the percentage of total variance for each PC was divided by percentage of cumulative variance to get the weightage value (Wi) for each PC. All the independent parameters (after Pearson's correlation) were considered as the MDS. The dataset was converted into unit less values, which can be added and converted into a composite score. Data of these parameters were given scores (0 to 1) against each parameter. This is obtained by dividing a certain parameter value by the highest value for that particular parameter if 'more is better'[47] for that particular parameter, e.g. for cation exchange capacity (CEC), higher the value, better it is as a soil quality parameter and also for the overall sustenance of the soil. Similarly, for BD 'less is better'. This indicates that lower the value of BD, better it is for the health of a soil. Accordingly, each value was divided by a higher value to get a value ≤1 (which is denoted by Si). The product of Si*Wi against each PC was calculated. The cumulative sum of the product of 'Si*Wi' (SQI = Si*Wi) of each row (i.e. for each corresponding parameter) would give the SQI for a particular soil. The higher the total value better is the soil quality for a particular soil. To compare SQI of one soil with another in a particular region, an index called relative soil quality index (RSQI) is obtained as

$$\text{RSQI} = (\text{SQI of the reference soil/SQI which has the highest value in the region}) * 100.$$

Spatial distribution

GIS and SOTER[48] were used to show the SQI and RSQI dataset in a spatial domain for IGP. The data were related with the soil polygons of the IGP at 1 : 1 m scale. SQI and RSQI thematic maps were prepared. By converting the point data to the polygon data, SOTER data and maps were used to represent uniformly SOTER id units (soil units) representing a single soil series. This helped prepare uniform SQI and RSQI maps.

Calculation of land quality index

The scheme followed for computing LQI is shown in Figure 2. The methodology for arriving at the LQI is first to calculate the CQI using the following equation

$$\text{CQI} = \text{ET}_\text{C} \times T_\text{Q} \times N_\text{s},$$

where $\text{ET}_\text{C} = \text{ET}_\text{O}/\text{rainfall}$, ET_O is the evapotranspiration for a particular crop during its growth period; $T_\text{Q} = \Delta T/T$ (temperature quotient), ΔT = maximum temperature – minimum temperature for each month, T is the average temperature of each month during the cropping season; $N_\text{s} = n/N_0$, n is the number of bright sunshine hours for a particular crop during its growth period, N_0 is the total sunshine hours.

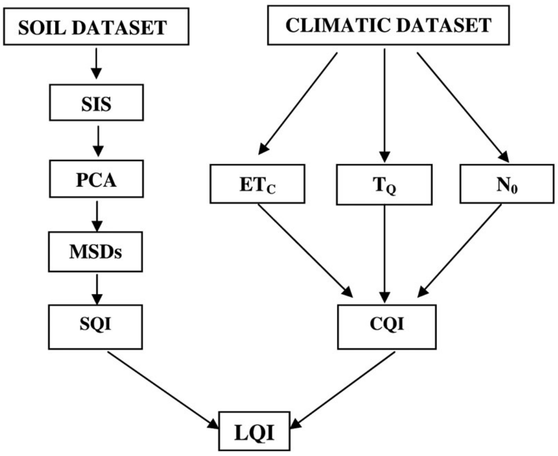


Figure 2. Schematic diagram showing derivation of land quality index for the IGP, India. SIS, Soil information system; PCA, Principal component analysis; MSDs, Minimum datasets; SQI, Soil quality index; ET_C, Rainfall factor; T_Q, Temperature factor; N_0, Sunshine factor CQI, Climate quality index; LQI, Land quality index.

Each climatic factor was assigned a quotient depending upon whether a particular parameter is beneficial or not for a particular crop in IGP. The ET-rainfall factor (ET_i) was obtained by considering ET-rainfall as more is better, i.e. more the ET value for a particular crop per unit rainfall, better it is for sustenance of the crop. Similarly, for the temperature factor ($T_{\text{Q}i}$), it was considered more is better for rice and less is better for wheat. For the sunshine factor (N_{0i}), more is better was considered. For each of these factors, weightage factor was also determined using the scale of relative importance to show the analytical hierarchy process (AHP) from 1 to 9; 1 indicating equal importance to factors and 9 indicating absolute importance of a particular factor. The weightage factors are derived from the solution of the matrix formed from the assigned AHP values. The weightage factors were calculated for a group of soils occurring in a particular AESR as the climatic factors were almost similar within an AESR. An example of the matrix for AESR 4.3, is as follows

$$\begin{bmatrix} 9 & 3 & 4 \\ 1/3 & 1 & 3 \\ 1/4 & 1/3 & 1 \end{bmatrix}$$

$$v_1 = \sqrt[3]{X_1 * X_2 * X_3}\,,\; v_2 = \sqrt[3]{Y_1 * Y_2 * Y_3}\,,$$
$$v_3 = \sqrt[3]{Z_1 * Z_2 * Z_3}.$$

Weightage factors for the rainfall, temperature and sunshine components of CQI were calculated by the following equations

$$R_\text{F} = v_1/(v_1 + v_2 + v_3),\; T_\text{F} = v_2/(v_1 + v_2 + v_3),$$
$$S_\text{F} = v_3/(v_1 + v_2 + v_3).$$

The product of the weightage factor and climate factor (e.g. ET_i) for a particular parameter gave each of the individual climatic parameter values; CQI was calculated by the summation of each of the climatic parameters. LQI was calculated as the product of CQI and the SQI as follows (Figure 2)

$$\text{LQI} = \text{SQI} * \text{CQI}.$$

Results

Arraying of available datasets and their description

The IGP datasets (both hotspots as well as extended) were first arranged and divided into upper and lower IGP. Later the data were screened and checked for the availability of all types of data. The soils with incomplete data were discarded. The datasets were screened, arranged and tabulated. The weighted means for each parameter for the surface (0–15) and subsurface (0–100 cm) soils were calculated. The weighted mean dataset and analytical data of soil series for extended data are detailed elsewhere[39]. Some datasets in the extended data such as sHC, BD and moisture retention, wherever scanty, have been derived using pedotransfer functions[49].

The soils of the upper IGP vary from sandy loam to silty loam to clay loam, while those of the lower IGP range from sandy clay loam to silty clay to clay, with few exceptions. Clay illuviation is an important soil-forming process in both the upper and lower IGP[33,50]. The movement of clay has an important pedological significance as clay bears a good relationship with other soil properties (discussed later). Some of the upper and lower IGP soils exhibit considerable amount of shrink–swell activity and have higher coefficient of linear extensibility (COLE) value[33]. The intensity of occurrence of higher COLE value is more frequent in the soils of the lower than the upper IGP[33,51]. BD varies from very low to very high (1.1 to 2.0 Mg m^{-3}). Higher BD values may be due to soil compaction arising from puddling of the soils and other management activities, including use of heavy agricultural implements. A decrease in yield of crops has been observed with increase in BD[28]. The soils of Rajasthan, parts of Punjab, Haryana and Uttar Pradesh are impoverished in organic carbon (OC), but are usually highly calcareous in nature[52,53]. The sHC values of these soils are at times very low wherever there are problems of sodicity, especially in several parts of Uttar Pradesh. However, in many other places such as Rajasthan and southwestern parts of Punjab, the sHC values are higher because of sandy soils and lesser problems of sodicity. The soils of the lower IGP have higher organic carbon compared to the upper IGP. These are also near neutral to slightly alkaline, less calcareous than the soils of the upper IGP. Despite this, the sHC values of the lower IGP soils (<10 mm h^{-1}) are low and drainage is a major problem[33,46]. There is also a decrease in the water dispersible clay (WDC) with depth for some of these soils. Such type of behaviour of these soils is unusual because of relatively low exchangeable sodium percentage (ESP). One reason might be high exchangeable magnesium percentage (EMP), which decreases the sHC as magnesium disperses the clay. In this connection the Ca/Mg ratio is more relevant to interpret the soil quality relative to crop growth.

Derivation of MDS by PCA

The datasets for both hotspots as well as extended data were bifurcated into upper and lower IGP and PCA was carried out on each set of data. The PCA data for upper IGP (hotspots, 0–15 cm depth) showed that all the eigenvalues were >1 and it explained more than 82% of the cumulative variance in the data. Representative screen plot showing the variation of eigenvalues with soil components is shown in Figure 3. The MDS were chosen based on the highly weighed factor loading of the variables. This was done by considering the absolute value of the factor loadings. In total six PCs were extracted for the upper IGP hotspot dataset of 0–15 cm depth soil. The parameters in each PC were considered based on higher values of the factor loading. All the six PCs have eigenvalues > 1 (Table 2).

The soil parameters obtained from PCA under PC1 were sand, silt, clay, COLE, sHC, exchangeable calcium (Ex.Ca), sum of exchangeable cations, clay cation exchange capacity (CEC), clay carbonate and percentage of saturation. Among these parameters the highly weighted are sand, silt, COLE, Ex.Ca, sum of exchangeable bases, clay carbonate and percentage of saturation. However, sHC is such a parameter in the semi-arid tropics of India which governs the movement of water in the soil system and also the availability of water and nutrients to plants[33,54]. Other parameters are highly correlated to each other and so sHC was retained for the MDS in PC1. In PC2, the soil parameters obtained were exchangeable sodium (Ex.Na), EMP, sum of soluble cations, sum of soluble anions and sodium absorption ratio (SAR). Except sum of soluble cations, all other parameters were highly weighted. EMP was retained for the MDS in PC2 owing to having high weightage value on the one hand and good correlation among other parameters in the PC on the other[17,45].

In PC3, the soil parameters obtained were BD, exchangeable Mg, base saturation (BS), exchangeable Ca/Mg ratio and exchangeable calcium percentage (ECP) with

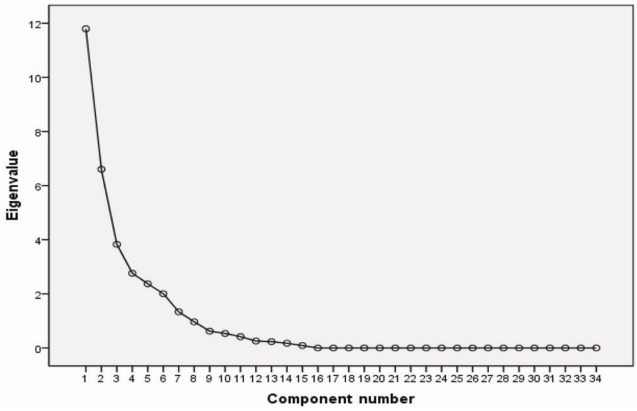


Figure 3. Representative scree plot showing variation of eigenvalues with soil components for hotspots.

high weightages and OC with relatively lower weightage. Exchangeable Mg, BS, exchangeable Ca/Mg ratio, ECP and BD are highly correlated with each other. BD is also correlated with OC, but owing to higher weightage factor of BD, it is retained for the MDS. In case of PC4, the soil parameters were WDC, soluble Mg, K, HCO_3^- and Cl^-. Among these parameters, except HCO_3^-, the others are correlated with each other as well as with MDS from other PCs. Hence HCO_3^- is retained for the MDS in PC4. In PC5, the soil parameters are fine clay to total clay ratio, pH, $CaCO_3$, electrical conductivity at saturation (ECe) and soluble Ca. Highly weighted parameters are soluble Ca and $CaCO_3$. The former parameter is correlated with other MDS and also not easily determinable; hence $CaCO_3$ has been considered for the MDS in PC5. In PC6, the soil parameters obtained are exchangeable K with higher weightage and ESP with lower weightage. Exchangeable K is correlated with other parameters in PC4 and as ESP is a more representable parameter for the IGP region, it is retained for the MDS in PC6. Finally for the upper IGP (hotspots) in the 0–15 cm depth, the MDS are sHC, EMP, BD, HCO_3^-, $CaCO_3$ and ESP. These parameters are independent of each other as shown by the correlation coefficient[17] values < 0.6 in Table 3. These MDS are time-specific and management-oriented. The MDS should be compared with various timescale data vis-à-vis changes in management practices[16,55]. This is not uncommon in the IGP where soil properties change due to use of amendment and other management practices. The final MDS obtained were subjected to calculations to get the soil factor, weightage factor and SQI as enumerated in the 'Materials and methods' section. The SQI for the upper IGP (hotspots) in the 0–15 cm depth and RSQI were calculated to compare datasets within the upper IGP (Table 4). The data showed that Jassi-Pauwali (Aridic Haplustalfs) soil in Bhatinda district, Punjab was of better quality (SQI – 0.66, RSQI – 100) than other soils in the upper IGP. Close to Jassi-Pauwali soils are the Fatehpur soils (IncepticHalustalfs) from Ludhiana district, Punjab (SQI – 0.57, RSQI – 87). Fatehpur soils also have good hydraulic properties and do not have problems of sodicity[33]. The Hirapur soils (Vertic Natrustalfs) in Aligarh district, Uttar Pradesh, owing to having poor structure developed from high ESP and poor hydraulic properties, were rated as the low quality soil (SQI – 0.22, RSQI – 33) in the set of data considered for the upper IGP.

Table 3. Correlation matrix showing MDS for the upper IGP (hotspot) in the 0–15 cm depth

	BD	HC	$CaCO_3$	EMP	ESP	HCO_3
BD	1	0.123	0.5	0.32	0.193	0.083
HC	0.123	1	0.596	0.307	0.093	0.002
$CaCO_3$	0.49	0.596	1	0.084	0.106	0.181
EMP	0.32	0.307	0.084	1	0.346	0.115
ESP	0.193	0.093	0.106	0.106	1	0.248
HCO_3	0.083	0.02	0.181	0.181	0.258	1

HC, Hydraulic conductivity; EMP, Exchangeable magnesium percentage; ESP, Exchangeable sodium percentage.

The SQI estimated with the help of EO for the upper IGP (hotspots) in the 0–15 cm depth involved sHC, clay, EMP, ESP, OC and BS with decreasing weightage from sHC to BS (Table 5). The higher values of SQI by EO method were found for Fatehpur soils (SQI – 0.50, RSQI – 100) followed by Phaguwala (Oxyaquic Haplustalfs) (SQI – 0.44, RSQI – 89) and Jassi-Pauwali (SQI – 0.42, RSQI – 84) soils, all of which are located in Punjab. Low values of SQI were obtained for soils of Simri (Typic Haplustalfs) in Barailydistrict, Uttar Pradesh (SQI – 0.20, RSQI – 100) and Zarifa Viran (Typic Natrustalfs) soils (SQI – 0.21, RSQI – 0.41) in Karnal district, Haryana. SQI for both PCA and EO-drawn data indicated that the results of both the methods are comparable.

In the lower IGP (hotspots) in 0–15 cm depth, five PCs having eigenvalue > 1 were extracted, similar to the upper IGP hotspots. The soil parameters for the MDS were BD, ESP, hydraulic conductivity (HC), fine clay total clay ratio (FC/TC) and OC (Table 6). The highest SQI obtained was for Konarpara (Vertic Endoaqualfs) in Barddhaman district, West Bengal (SQI – 0.70, RSQI – 100). The other soils which have comparable SQI are Nanpur (Fluventic Endoaquepts) in Vaishali district, Bihar (SQI – 0.69, RSQI – 99) and Singhvita (Umbric Endoaqualfs) soils in Darjeeling district, West Bengal (SQI – 0.64, RSQI – 91). The lowest value of SQI was for Ekchari soils (Vertic Endoaqualfs) of Bihar (SQI – 0.41, RSQI – 59). Similarly, the soil parameters for the MDS for the Lower IGP (hotspots) in the 0–15 cm depth chosen by EO are sHC, clay, EMP, ESP and BD (Table 7). According to EO, the highest SQI was obtained for Nanpur soils (Fluventic Endoaquepts) in Vaishali district of Bihar (SQI – 0.67, RSQI – 100). Notably for the calculated (PCA-drawn) data similar results were obtained (RSQI – 99). The second highest SQI was for the soil from Barddhaman district, West Bengal (Hanrgram, Vertic Endoaqualfs, RSQI – 85). The soil with least SQI was Belsar, an Aeric Endoaqualfs (SQI – 0.29, RSQI – 43), which is also from Bhagalpur district, Bihar. On considering 0–100 depth of soil for the upper IGP hotspots, the MDS obtained were ESP, HC, FC/TC, Ex.Ca/Mg and WDC.

The subsurface dataset is known to add significance to the natural system like soil. This is because some basic soil forming processes such as availability of water and nutrients, formation of pedogenic $CaCO_3$ and concomitant development of sodicity, etc. are dependent upon subsoil information[50,52]. The subsurface soils of the upper IGP (hotspots) are better explained by Jodhpur-Ramana soils (Aridic Haplustalfs) in Bhatinda district, Punjab, which had the highest SQI (SQI – 0.75) followed by Fatehpur soils (Inceptic Haplustalfs) with SQI of 0.72 (RSQI – 97). Higher values of SQI for Fatehpur soils were also obtained in the upper IGP 0–15 cm depth data

Table 4. Soil quality indices (SQI) of various soil series for Upper IGP (hotspots) surface soils (0–15 cm depth) drawn from calculated data

	PC1	PC2	PC3	PC4	PC5	PC6		
Soil series	sHC	EMP	BD	HCO_3^-	$CaCO_3$	ESP		
Weightage	0.275	0.201	0.172	0.137	0.133	0.081	SQI	RSQI
Masitawali	0.17	0.05	0.16	0.00	0.02	0.01	0.41	62
Nihalkhera	0.09	0.20	0.15	0.01	0.02	0.01	0.48	73
Jassi-Pauwali	0.26	0.20	0.17	0.01	0.02	0.01	0.66	100
Jodhpur-Ramana	0.12	0.10	0.15	0.01	0.03	0.01	0.41	63
Hirapur	0.00	0.00	0.15	0.02	0.02	0.02	0.22	33
Bhanra	0.07	0.06	0.15	0.03	0.06	0.01	0.39	59
Ghabdan	0.14	0.02	0.15	0.00	0.02	0.01	0.35	53
Phaguwala	0.28	0.02	0.16	0.01	0.02	0.01	0.50	75
Dhadde	0.02	0.10	0.17	0.14	0.04	0.00	0.47	70
Fatehpur	0.09	0.10	0.16	0.06	0.09	0.08	0.57	87
Jagjitpur	0.05	0.05	0.17	0.01	0.03	0.01	0.32	48
Sakit	0.02	0.03	0.16	0.01	0.05	0.01	0.28	42
Zarifa-Viran	0.02	0.02	0.16	0.04	0.03	0.01	0.28	42
Berpura	0.01	0.01	0.16	0.00	0.06	0.02	0.27	40
Simri, Taitpur	0.03	0.02	0.15	0.00	0.13	0.01	0.34	51
Haldi	0.02	0.07	0.17	0.01	0.07	0.01	0.34	52

RSQI, Relative soil quality indices.

Table 5. Soil quality indices of various soil series for Upper IGP (hotspots) surface soils (0–15 cm depth) drawn from expert opinion data

	PC1	PC2	PC3	PC4	PC5	PC6		
Soil series	HC	Clay	EMP	ESP	OC	BS		
Weightage	0.275	0.201	0.172	0.138	0.133	0.081	SQI	RSQI
Masitawali	0.17	0.08	0.02	0.02	0.11	0.013	0.41	82
Nihalkhera	0.09	0.08	0.02	0.02	0.05	0.050	0.31	61
Jassi-Pauwali	0.26	0.06	0.02	0.02	0.06	0.004	0.42	84
Jodhpur-Ramana	0.12	0.06	0.01	0.01	0.05	0.081	0.34	69
Hirapur	0.00	0.11	0.04	0.04	0.05	0.014	0.25	50
Bhanra	0.07	0.05	0.02	0.01	0.10	0.012	0.26	52
Ghabdan	0.14	0.08	0.02	0.01	0.07	0.010	0.34	67
Phaguwala	0.28	0.05	0.01	0.01	0.08	0.007	0.44	89
Dhadde	0.02	0.13	0.01	0.01	0.11	0.022	0.29	57
Fatehpur	0.09	0.03	0.17	0.14	0.05	0.023	0.50	100
Jagjitpur	0.05	0.06	0.02	0.02	0.09	0.015	0.25	51
Sakit	0.02	0.12	0.02	0.02	0.07	0.016	0.26	52
Zarifa-Viran	0.02	0.08	0.02	0.01	0.07	0.010	0.21	41
Berpura	0.01	0.07	0.04	0.03	0.09	0.021	0.26	53
Simri, Taitpur	0.03	0.04	0.02	0.02	0.08	0.012	0.20	40
Haldi	0.02	0.08	0.02	0.02	0.13	0.007	0.27	54

OC, Organic carbon.

both by PCA-drawn data (RSQI – 87) as well as by EO drawn data (RSQI – 100). The EO drawn MDS for the upper IGP (hotspots) in the 0–100 cm depth shows similarity with that obtained by calculated method, as Jodhpur-Ramana secured a high SQI value (RSQI – 98). However, the highest SQI was recorded for Nihalkhera soils (Aridic Haplustalfs) in Ferozpur district, Punjab (SQI – 0.60, RSQI – 100), which is a sandy loam soil with no problems of sodicity. Berpura (Oxyaquic Haplustalfs) (RSQI – 48), Zarifa Viran (RSQI – 52) and Simri (RSQI – 52) rank among soil with the lowest SQI. All the three soils had problems of sodicity and poor internal drainage[33]. In case of the lower IGP (hotspots) for the subsurface (0–100 cm depth) soils, the calculated (by PCA) method showed highest SQI value (Table 6) for Mohanpur soils (Vertic Endoaqualfs) (SQI – 0.79, RSQI – 100). The lowest value of SQI under this group was Gaupur (Typic Endoaqualfs) (SQI – 0.48, RSQI – 61). The least value of RSQI is 61 which indicated that the relative quality of the subsurface soils of the lower IGP was better than in the upper IGP. The same set of data by EO method gave highest SQI for Nanpur soils (same as obtained for the surface soils with SQI = 0.59 and RSQI = 100). The least value was for Belsar (SQI – 0.29, RSQI – 48), which also matched with the surface soil observations (Table 7).

The combined dataset of the upper and lower IGP was obtained by normalizing each set of data pertaining to the upper and lower IGP. The SQI and RSQI values when plotted against various soil series (hotspots) for the 0–15 cm depth (calculated data) indicated higher SQI and RSQI values for Nanpur in Bihar and Konarpara (Vertic Endoaqualfs) in West Bengal (Figure 4) and lower values for Hirapur and Sakit in Uttar Pradesh, as stated earlier. Similarly, for the same set of data with EO, Nanpur represented higher SQI and RSQI values and Zarifa Viran (Haryana), Simri and Sakit (Uttar Pradesh) represented lower values of SQI and RSQI. In the subsurface dataset (0–100 cm depth), the calculated data (PCA) showed a shift in the higher SQI and RSQI values towards Mohanpur and Chunchura in West Bengal. However, the lower values of SQI and RSQI did not show much change from Hirapurand Simri in Uttar Pradesh to Berpura and Zarifa Viran in Haryana. In the subsurface, the EO-drawn data showed consistency with Nanpur (Bihar) having the highest SQI and RSQI Berpura (Haryana) and Simri (Uttar Pradesh) among the lowest SQI and RSQI values.

Table 6. Soil quality indices of various soil series for Lower IGP (hotspots) subsurface soils (0–100 cm depth) drawn from calculated data

	PC1	PC2	PC3	PC4		
Soil series	BD	CEC	OC	FC/TC		
Weightage	0.391	0.303	0.160	0.141	SQI	RSQI
Belsar	0.29	0.09	0.01	0.13	0.52	66
Ekchari	0.27	0.13	0.01	0.12	0.53	68
Sarthua	0.27	0.14	0.01	0.11	0.54	68
Nanpur	0.32	0.08	0.00	0.12	0.52	66
Gaupur	0.30	0.08	0.01	0.09	0.48	61
Hanrgram	0.28	0.20	0.01	0.12	0.61	77
Konarpara	0.27	0.15	0.02	0.13	0.56	71
Madhpur	0.25	0.17	0.02	0.13	0.58	73
Sasanga	0.27	0.20	0.04	0.13	0.64	81
Chunchura	0.30	0.30	0.02	0.10	0.72	91
Mohanpur	0.30	0.27	0.10	0.12	0.79	100
Sagar	0.40	0.19	0.01	0.11	0.71	90
Seoraguri	0.35	0.08	0.16	0.12	0.71	90
Singhvita	0.33	0.09	0.02	0.14	0.58	73

FC/TC, Fine clay total clay ratio.

Table 7. Soil quality indices of various soil series for Lower IGP (hotspots) subsurface soils (0–100 cm depth) drawn from expert opinion data

	PC1	PC2	PC3	PC4		
Soil series	HC	Clay	EMP	ESP		
Weightage	0.391	0.303	0.160	0.141	SQI	RSQI
Belsar	0.04	0.21	0.02	0.01	0.29	48
Ekchari	0.05	0.26	0.03	0.03	0.37	63
Sarthua	0.04	0.30	0.03	0.00	0.37	63
Nanpur	0.40	0.17	0.02	0.01	0.59	100
Gaupur	0.18	0.20	0.02	0.03	0.43	73
Hanrgram	0.07	0.29	0.02	0.04	0.42	72
Konarpara	0.06	0.23	0.02	0.04	0.34	58
Madhpur	0.15	0.28	0.02	0.06	0.51	86
Sasanga	0.09	0.30	0.02	0.04	0.45	77
Chunchura	0.05	0.25	0.01	0.04	0.34	58
Mohanpur	0.10	0.27	0.02	0.07	0.46	78
Sagar	0.03	0.29	0.02	0.00	0.35	59
Seoraguri	0.07	0.16	0.08	0.13	0.43	73
Singhvita	0.07	0.19	0.16	0.15	0.56	95

The extended dataset of soil information of the IGP comprised of about 417 soil series. The dataset was screened before performing PCA and was ultimately reduced to information on 187 soil series. The MDS obtained for the calculated dataset (PCA-drawn) in the 0–15 cm depth are clay, OC, sHC, ESP, BD and Ca/Mg ratio, with decreasing weightage of each MDS in the same order. The higher values of SQI and RSQI were obtained for soils of Belar (SQI – 1.05, RSQI – 100) in Hooghly district, West Bengal, and Sidhpur in East Champaran district, Bihar. The areas comprising Nadia, Barddhaman, Arambagh and East Champaran are known to be one of the most fertile soils of the IGP. For the same dataset, the MDS by EO are sHC, clay, EMP, ESP, OC and BS. Interestingly, higher SQI and RSQI were also obtained for soils of Belar (SQI – 1.01, RSQI – 100) in Hooghly district, West Bengal and Sajwar (SQI – 0.91, RSQI – 90) in Darbhanga district, Bihar. Lower SQI values were obtained by both the PCA and EO methods for soils of Biraundhi (Bhirandhi, Uttar Pradesh) and Nagaria (Shahjahanpur, Uttar Pradesh; both having SQI – 0.08, RSQI – 8) and Khoh soils (SQI – 0.09, RSQI – 9) from Gurgaon district, Haryana.

Spatial distribution of SQI

The SQI values of the IGP for the 0–15 cm depth are depicted in maps prepared using GIS software (Figures 5 and 6). For brevity, only SQI maps of surface soils are presented here. The SQI map for the 0–15 cm depth obtained from PCA method showed that about 12% area of IGP has low category of SQI (<0.35) (Figure 5), which signified natural and/or human-induced degradation and development of salt-affected soils in terms of low sHC, high ESP, low water-holding capacity, low organic carbon, waterlogging and decreasing productivity[25,31,33–56]. Most of these areas are in Punjab, Haryana and parts Uttar Pradesh. The medium category of SQI (0.35–0.55), which is the bulk of the area covered in the IGP

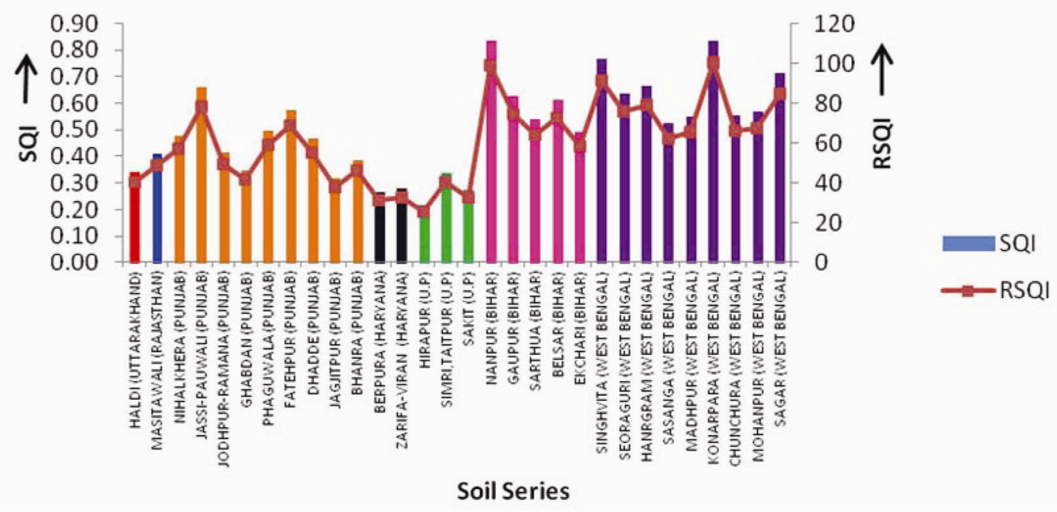
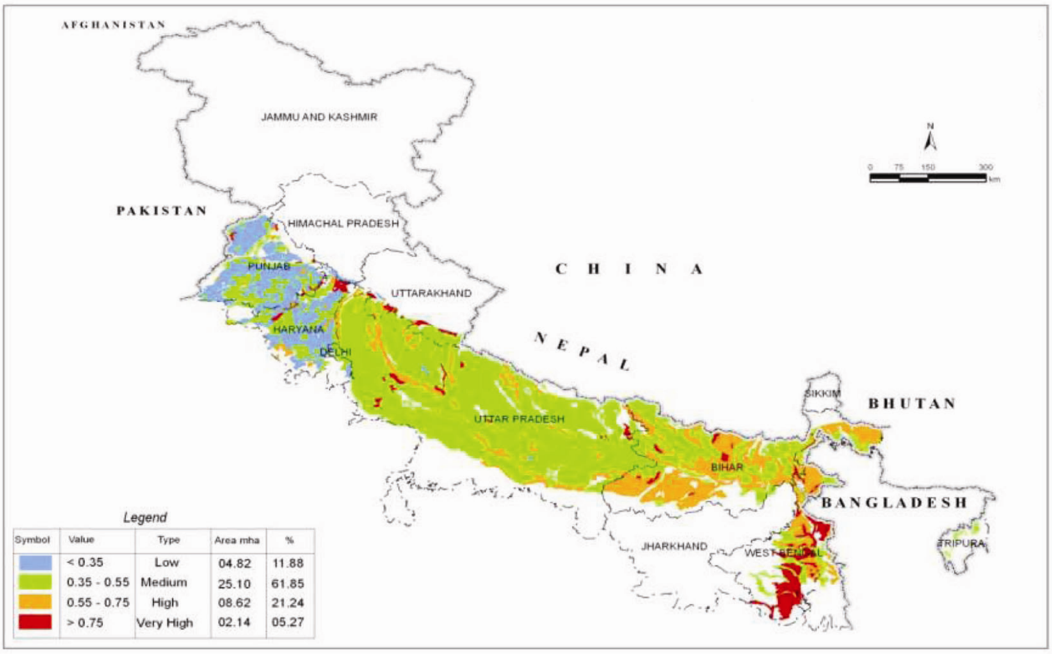


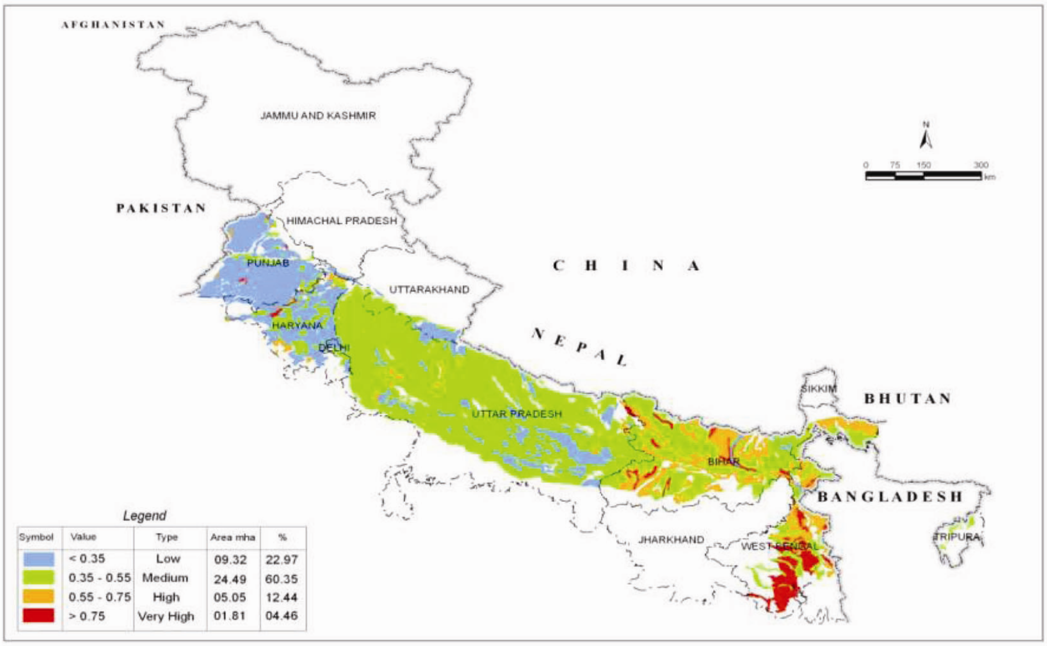
Figure 4. Variation of soil quality index (SQI) and relative SQI (RSQI; calculated) in 0–15 cm depth in different soil series (hotspots) of the IGP.



Symbol	Value	Type	Area mha	%
🟦	< 0.35	Low	04.82	11.88
🟩	0.35 - 0.55	Medium	25.10	61.85
🟧	0.55 - 0.75	High	08.62	21.24
🟥	> 0.75	Very High	02.14	05.27

Figure 5. Variation of SQI (calculated method, PCA) for 0–15 cm depth of soil in IGP.

comprised of about 62%, including parts of Punjab and Haryana, major parts of Uttar Pradesh, considerable areas in Bihar, some parts of West Bengal and most of the IGP part of Tripura. The high category of SQI (0.55–0.75) comprised of a sizable 21% of the IGP covering small parts of Punjab, Haryana and Uttar Pradesh and major parts of Bihar and West Bengal. The very high category of SQI (>0.75) comprised of a meagre 5% covering small patches in all the states, except Tripura and relatively considerable areas in Bihar and West Bengal, indicating lesser problems of degradation of soil. The various categories of SQI such as low, medium, high and very high are in the order of decreasing limitations in soil properties respectively, which also affects the proper use and management of these soils. The SQI for the 0–15 cm depth by EO indicated relatively higher spatial coverage in low category (23%) compared to that obtained by PCA technique (12%). The increase in the low category of SQI by EO method has resulted in the decrease in high category as the medium and very high categories remained almost similar by both the methods (Figures 5 and 6). When we consider the 0–100 cm depth of soil by PCA method, the figures decreased slightly in the low, medium and high categories compared to the corresponding map for the 0–15 cm depth (Figure 5). This decrease in all the first three categories probably leads to the increase in the



Symbol	Value	Type	Area mha	%
🟦	< 0.35	Low	09.32	22.97
🟩	0.35 - 0.55	Medium	24.49	60.35
🟧	0.55 - 0.75	High	05.05	12.44
🟥	> 0.75	Very High	01.81	04.46

Figure 6. Variation of SQI (by expert opinion) for 0–15 cm depth of soil in IGP.

very high category (about 12%) incorporating newer areas mainly in Bihar and West Bengal.

However, using the EO method in the 0–100 cm depth, bulk of the areas is the covered by the high category of RSQI (instead of medium category observed in the 0–15 cm depth; as an example only RSQI maps are included here) covering most of the areas of Haryana, Uttar Pradesh, Bihar and West Bengal.

Correlation of SQI with yield

Correlation studies of SQI with yields of rice–wheat system show moderate relationship considering that there are various other parameters for the yield factor. The relationship between SQI and wheat yield for surface soils of the IGP (extended data) showed a modest value of correlation ($R^2 = 0.556$). The correlation between SQI and yield of rice yielded R^2 value of 0.557.

Pedological significance of SQI

The soils under arid and semi-arid climates are impoverished in organic carbon and phosphorus, but rich in potassium. Thus, solution K obtained as one of the MDS in the upper IGP appeared to be most likely because the upper IGPV is known to be rich in Micaceous K. The adverse arid climatic conditions induce the formation of pedogenic $CaCO_3$ and as a result, sodicity develops in the subsurface of soils[50,52]. The rate of formation of $CaCO_3$ is proceeding at a very fast rate and any attempt to increase and stabilize yields by extension of irrigation will thus be hazardous[52,56]. Unlike pedogenic $CaCO_3$ of arid climate, the geogenic $CaCO_3$ in soils of sub-humid and humid climates can act as a useful source of calcium in the soil solution. To assess the pedological significance, the effect of soil subsurface phenomenon should also be taken into consideration to accommodate the physiological conditions of the plant systems which take nutrients and water from the subsurface. Moreover, water reserve at the subsurface of a soil is made available to the surface soil by capillary action phenomenon at the time of need. In view of this, SQI fractions of the surface and the subsurface were considered to calculate an overall SQI which represented fractions of surface and subsurface values of the SQI. Trial and error method by taking % contribution of SQI for each layer was considered for the calculation. A good measure of the SQI value was obtained by a combination of 70% fraction of SQI value of surface and 30% fraction of SQI value of the subsurface, which gave a composite SQI value. Correlation between this composite SQI value and yield of wheat in the IGP resulted in a modest R^2 value of 0.620.

Land quality index

LQI for the IGP was calculated based on two important crops of the region, namely rice and wheat. The principle of matrix was used to assign weightages for each of the climatic parameters as described in the ‘Materials and methods’ section. LQI was derived[21,22] as the product of CQI and SQI. LQI deduced based on SQI for the 0–15 cm depth showed higher values for Belar soil-series

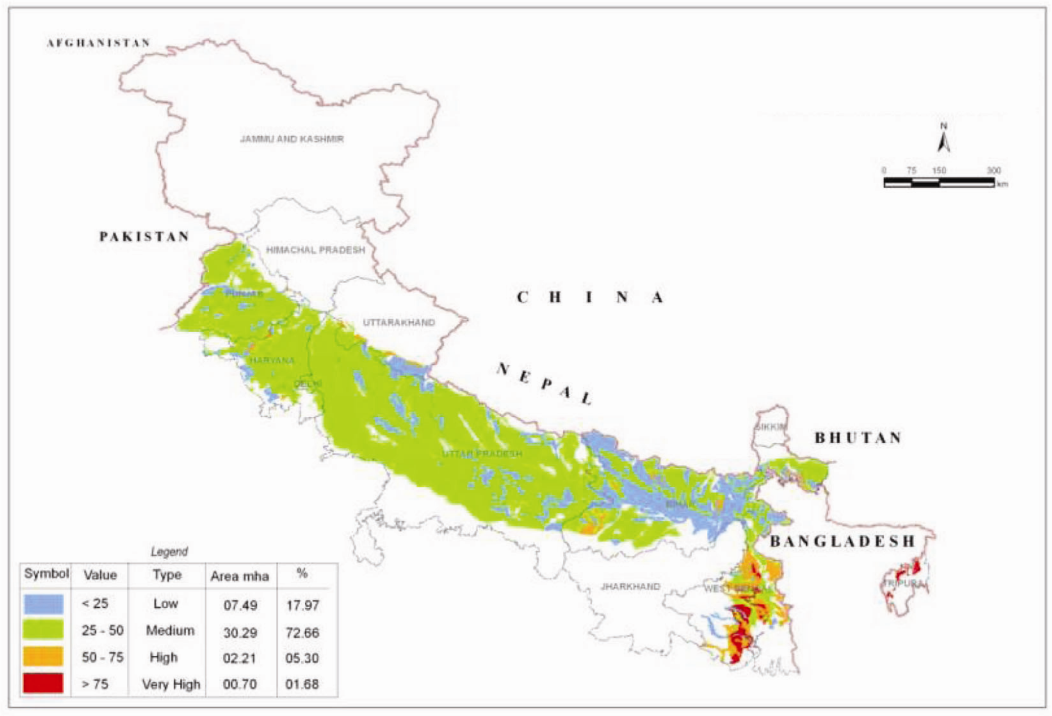


Figure 7. Distribution of relative land quality indices for rice in IGP.

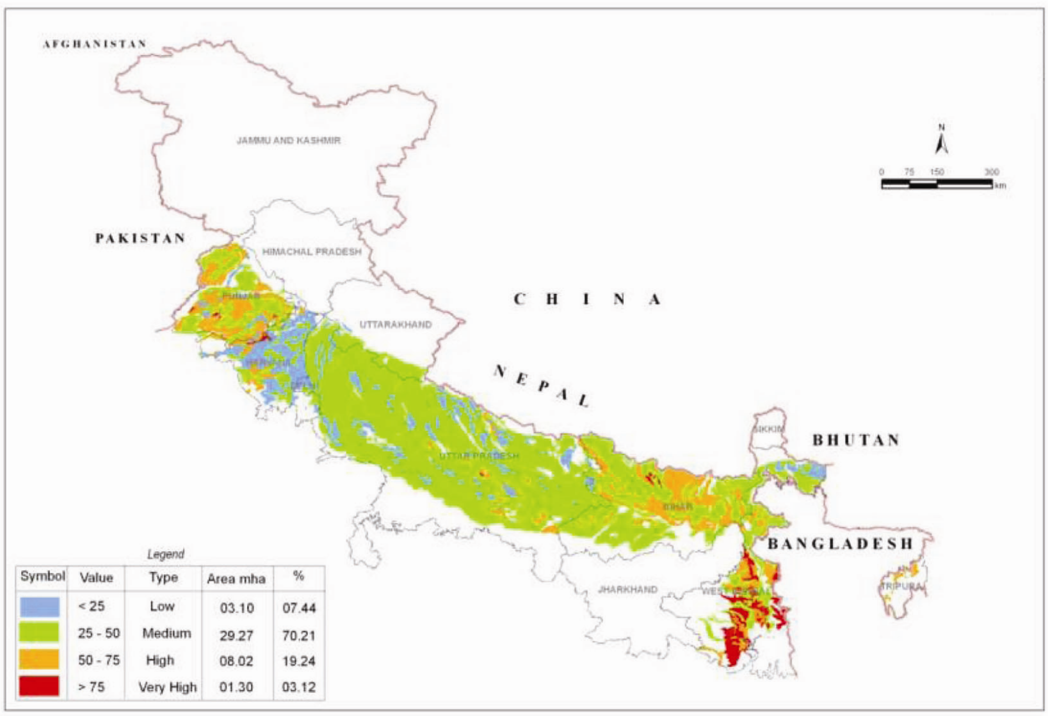


Figure 8. Distribution of relative land quality indices for wheat in IGP.

landscape (RSQI – 100) in Hooghly district and Rajdarpur soil series landscape (RLQI – 80) in Berhampur district of West Bengal. Lower values of LQI were obtained for Patar Siwan land (RLQI – 16) in Bihar and Biraundhi (RLQI – 16) in Etawah district, Uttar Pradesh. When we consider the 0–100 cm depth of soil information for calculation of SQI, higher LQI values were obtained for Multi in Nadia district (RLQI – 100) and Belar area (RLQI – 94) in Hooghly district, West Bengal. The lower values of LQI were obtained for Govindpur area

(RLQI – 14) in Sirswangaur district, Uttar Pradesh and Fatehpur area (RLQI – 15) in Ludhiana district, Punjab. LQI for wheat when calculated considering SQI for the 0–15 cm depth, the higher values were similar to those obtained for rice namely, Belar (RLQI – 100) and Rajdharpur (RLQI – 80) in West Bengal. The lower values of LQI were for Jagaus area (RLQI – 13) in Nakhoonka district, Uttar Pradesh and Khoh area (RLQI – 14) in Gurgaon district, Haryana. LQI for wheat considering SQI for 0–100 cm depth, the higher values were obtained for the same areas as obtained for the rice, namely Multi (RLQI – 100) and Belar (RLQI – 95) in West Bengal. Lower values were obtained for Govindpur (RLQI – 12) in Sirswangaur district and Thakurdwara (RLQI – 16) in Nakhoonka district, Uttar Pradesh.

Spatial distribution of LQI

In the IGP spatial distribution of LQI values was done to denote various classes of LQI (Figures 7 and 8). The LQI values were converted to their respective relative land quality index (RLQI) values and the various groups or classes, namely low (RLQI < 25), medium (RLQI 25–50), high (RLQI 50–75) and very high (RLQI >75). The RLQI for rice crop showed that about 18% area of the IGP came under low RLQI category. The highest area was covered by the medium category (about 73%); the area covered by high (5.3%) and very high (about 2%) categories was not of significance. RLQI for wheat crop showed that the area under low category is only about 7%, whereas the areas under medium and high categories are 70% and 19% respectively. The land quality of the IGP with respect to wheat showed comparatively higher area under medium, high and very high categories (about 93%) compared to the area with respect to rice (about 82%).

Discussion

The upper IGP hotpots consisted of 16 and the lower IGP consisted of 14 soil series datasets. Six PCs were obtained for the upper IGP and five PCs were obtained for the lower IGP. In case of extended dataset consisting of 92 soil series data for the lower IGP, six PCs each were obtained for both sets of data. This indicated that the variability in the two sets of data, viz. hotspots and extended data is uniform and variability among the datasets in the IGP in general is high, as six PCs were obtained to maintain a cumulative variance of more than 80%. The MDS for soil quality for extended data (surface soils) of the IGP are generally among clay, OC, sHC, ESP, BD, Ca/Mg (or EMP), moisture retention at 1500 kPa, $CaCO_3$ equivalent and BS[57]. In case of the subsurface, some additional parameters like pH and EC come into consideration. EO suggested MDS are generally sHC, clay, EMP, ESP, pH (BD) and OC. EO also suggested MDS are based on research output of several years[46,50,53,54,58–61] at the National Bureau of Soil Survey and Land Use Planning, Nagpur under the aegis of the Indian Council of Agricultural Research, New Delhi. It is interesting that the MDS obtained by PCA and EO are quite similar, except their order of appearance or weightages is different. This is reflected in SQI calculations and ranking of soil according to their SQI values. Nevertheless, the rankings of major soils by both the methods are comparable[17]. The SQI for the extended dataset gave higher values for Belar and Birati soils in West Bengal by both the methods. Similarly, soils with poor SQI were Birundhi and Nagaria in Uttar Pradesh by both the methods. This indicates that selection of MDS and calculation of SQI can be done to a greater extent by experts who have comprehensive knowledge of soils, their land use and landscapes of a particular region. These methodologies when validated on a larger scale and with other different parameters may be beneficial to forego the various analytical and statistical protocols undertaken for soil quality studies. Belar soil in Hooghly district and Birati soil in 24 Parganas (North) district, West Bengal had higher SQI compared to other soils in the IGP, because these soils had higher values of sHC (>40 mm h^{-1}), clay (>35% of shrink–swell type), and OC (>8 g kg^{-1}) and lower values of ESP (<2) and BD (<1.4 Mg m^{-3}). By contrast, Biraundhi in Etawah district and Nagaria in Sahjahanpur district, Uttar Pradesh had relatively lower values of SQI because of lower values of sHC (<0.8 mm h^{-1}), clay (<10% of micaceous type) and OC (<0.39 g kg^{-1}) and higher values of ESP (>25 and up to 97) and BD (>1.8 Mg m^{-3}). These datasets also corroborate well with hotspots data which showed higher values of SQI and RSQI (Figure 4). As the present study deals with the development of a soil information system of the entire IGP on a smaller scale, SQI and RSQI developed here are unlikely to favour specific management goals[57,62–64]. However, major management goals which include yields of long-term cropping systems can be taken into account for evaluating the SQI. In the present study, the relationship between SQI and yield of rice ($R^2 = 0.57$) and wheat ($R^2 = 0.55$) indicated that the derived values of SQI are directly proportional to some major management goals. These types of information are useful in assessing present cropping systems[65] and also help in suggesting alternate cropping systems in a particular region.

Information on soil and land quality is useful in assessing cropping systems[65] and also to suggest alternate cropping systems in a particular region. The soils which have poor soil quality generally belong to the arid and semi-arid regions where the major problems of soils are related to poor drainage due to formation of pedogenic $CaCO_3$ and concomitant development of sodicity[52,59,61]. Management interventions to reduce the effect of pedogenic $CaCO_3$ are vital for amelioration of these soils for higher productivity by the dissolution of $CaCO_3$ through root exudates and improving the soil quality[53].

Conclusion

The data on soils of the IGP showed marked differences in soil quality between the upper and lower IGP. PCA seems to be an effective tool for integrating various soil properties and for obtaining the independent MDS. The MDS obtained by PCA matched well with that obtained from expert opinion, with few exceptions. The soil quality indices showed a modest estimate of correlation with rice ($R^2 = 0.557$) and wheat ($R^2 = 0.556$) yield. The SQI was higher in those soils which were well managed. Proper addition of organic manures as well as inorganic fertilizers along with irrigation helped maintain the soil quality. SQI and RSQI provided a sound database for geospatial soil information system of the IGP. SQI and RSQI of the IGP were in the low range for the surface soils, but the subsurface soils were dominated by high and very high categories (about 84% area) of soil quality, indicating the importance of pedological studies for managing these soils.

The surface soils of the IGP are overstressed as indicated by their low SQI values. Similar observations were made when total K stock was estimated for the IGP and compared with black soil regions[66]. LQI calculated from SQI and CQI is a variable option to indicate the minimum datasets to interpret the quality of land and also for proper land-use planning in a particular region.

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