Sustaining soil quality, resilience and critical carbon level under different cropping systems in semi-arid tropical Alfisol soils

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Subsistence agriculture practice and a combination of harsh climate and fragile soils along with increasing demographic pressure are matters of great concern from the viewpoint of resource management and long-term sustainability in the semi-arid tropical Alfisol soils of India. In this study, soil quality index (SQI) has been computed on 190 sites of farmers' fields in southern India to evaluate the possible effect of land management practices on soil degradation and determine the critical levels of soil organic C stock to maintain a desirable SQI and also suggest appropriate management practices. In all, 26 predominant physical, chemical and biological properties of soils were studied and based on principal component analysis, moisture retention at field capacity, available soil N, available P, DTPA-extractable Zn, exchangeable sodium percentage, C-mineralization and bulk density were identified as the key indicators of the study region. SQI was also computed using four soil functions, viz. nutrient cycling, availability of water, resistance of soil to degradation, and salinity and sodicity. Soil resilience index was computed using data on substrate-induced respiration after exposing the soil to heat stress. SQI was highest under paddy followed by permanent fallow, maize, cotton, intercropping, redgram, and was lowest under castor system. Based on the results, it was observed that the soils which had higher SQI were also productive and they exhibited higher resilience capacity. An amount of 8.6 Mg ha^{-1} soil organic C stock per 15 cm depth was found essential to maintain soil quality and 2.2 Mg ha^{-1} of organic matter was needed every year to maintain this stock. On-farm participatory research trial was conducted using SQI as a tool for sustainable land-management practices.

Keywords: Cropping systems, organic carbon stock, soil quality and resilience, sustainable land management.

THE need for maintaining soil quality (SQ) and its resilience is attaining increasingly importance because of growing public interest in understanding the impact of managing land on the sustainability of the soil resources, particularly in fragile arid and semi-arid tropical (SAT) region. Alfisols are found in abundance in the SAT regions; they account for nearly 16% in the tropics and 33% in the SAT region. In the Indian subcontinent, about 24% of the total geographical area or 79.7 M ha of soil is represented by Alfisol, making it the most dominant soil order in dryland regions of India[1]. Alfisols in peninsular India are often coarse-textured, inherently low in fertility, have low organic matter content and poor water-holding capacity. They are also easily susceptible to wind and water erosion. The two important features, viz. light texture of the topsoil and predominance of kaolinite clay minerals make these soils structurally inert and prone to crusting and hard setting. Rainfall events are highly erratic and difficult to predict, and crops frequently suffer due to lack of soil moisture and drought even during normal rainfall periods. This ultimately results in lower crop productivity and large yield gaps[2]. Inadequacy in assured soil moisture does not support higher cropping intensity and consequently, the contribution of root biomass towards organic matter is significantly low. Farmers in rainfed SAT regions are not able to use adequate and balanced amount of fertilizer nutrients because of poverty, and uncertainty of rainfall and the associated likely risk of crop failure. Low and imbalanced fertilizer use and lack of crop residue recycling result in multi-nutrient deficiencies[3]. Maintaining good soil health and desired level of crop productivity amidst continuous monocropping with a fallow period of more than seven months annually is a major challenge in the rainfed regions of peninsular India.

The degrading effect of soil management practices can be quantified by performing a thorough assessment of the quality of the soil resources using suitable response indicators. A better working knowledge of soil quality is essential for sustainable land-use management[4], to provide early warning signs of adverse trends, identify problem areas[5], and provide a base against which subsequent

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and future measurement can be evaluated. Several minimum datasets have been suggested in the literature based on long-term field experiments with controlled treatments using various indexing techniques[6,7].

Attempts to assess the quality of soil in farmers' field under varying land-management options and cropping systems are few and inadequate. Assessing soil quality under farmers' field using key indicators will help in measuring the functioning ability of the soil, and associated constraints and deficiencies. These indicators identified for a given location will act as a key for expressing soil as an ultimate source for nourishment, ecosystem functions and sustainability[8].

It is a well-established fact that soil organic matter (SOM) is the most important indicator of SQ and agronomic sustainability because of its significant role and impact in influencing the other physical, chemical and biological properties of the soil[9]. SOM also improves the soil resilience capacity and impacts the ecosystem restoration. Soils under semi-arid region, managed by exhaustive crop husbandry practices on long-term basis have been severely depleted of soil organic carbon (SOC) pool[3]. Therefore, reversing the declining trend of SOC stock is essential to enhance crop productivity through balanced application of plant nutrients and application of biomass-C. Our hypothesis is that sustainable land management options through balanced fertilization in combination with organics and chemical fertilizers as well as addition of soil amendments might favourably influence the SOC content and help sustain the SQ and productivity of the system. The soils having higher SQI would not only produce more, but also have higher resilience capacity towards disturbances.

Recognizing the importance of soil quality and resilience, and maintaining organic matter in the SAT region, the present study was carried out in farmers' fields to identify the key indicators suitable for assessing soil quality of Alfisols of the SAT region of India and to develop an overall soil quality index (SQI) and soil resilience index (SRI) for this agricultural system. Considering the soil quality information, we have derived a threshold level of soil carbon for the Alfisol soils of the region in order to maintain its sustainable use. We also conducted an on-farm participatory study to use SQI as a tool for sustainable land-management practices.

Materials and methods

Study area

This study was conducted at farmers' fields in two districts, viz. Nalgonda (lying between 16°22′N and 17°49′N and 78°37′E and 80°05′E) and Warangal (lying between 17°19′N–18°39′N, and 78°49′E–80°40′E), Telangana, India, under agro-eco-sub region (AESR) 7.2, North Telangana Plateau, a hot, moist, semi-arid eco-sub-region of India[10]. The agro climate of this sub-region is represented by hot, semi-arid, moist zone, having dry summers and mild winters. In this sub-region, the mean annual temperature ranges from 25°C to 29°C. The mean summer (April–June) and mean winter (December–February) temperature ranges from 32°C to 39°C and 20°C to 24°C respectively. The mean annual rainfall of the region varies from 700 to 1000 mm, meeting 42–45% of the mean annual potential evapo-transpiration (PET) ranging between 1600 and 1800 mm. The onset of the southwest monsoon in the area is around second–fourth week of June with 90% probability, extending till the first week of October, covering 85% of the mean annual rainfall. Mid-season agriculture drought is quite frequent in Telangana zone. Also, 40.5% of the net sown area of the agro-eco-region is under irrigation. Alfisols constitute 52% of the soil in Nalgonda district and 38% in Warangal districts.

Soil sampling, processing and analysis

Composite soil samples were collected from the farmers' field under Alfisol soils in 190 sites comprising 113 sites from 15 villages of Nalgonda district, and 77 sites from 12 villages of Warangal district during 2009–10. Soil samples were collected from the dominant cropping systems of the districts after the harvest of rainy season crops from 0 to 15 cm depth. Paddy (*Oryza sativa*), cotton (*Gossypium hirsutum*), redgram (*Cajanus cajan*) and castor (*Ricinus communis*) were the dominant cropping systems for Nalgonda district. In case of Warangal district, paddy, cotton and maize (*Zea mays*) were the dominant cropping systems. The latitude, longitude and elevation of all the sampling locations were marked with global positioning system (GPS). In each village, at least one composite soil sample was collected from undisturbed fallow site and considered as pristine sample. Around 500 g of each of the composite soil samples was separately stored in a refrigerator for microbiological study. Remaining part of the samples was dried and sieved for physical and chemical analysis. A total of 26 physical, chemical and biological properties of the soil were analysed for each samples using standard procedure as mentioned in the literature[11–13].

Detailed information pertaining to the agriculture management practices such as crop rotation, tillage, fertilization, irrigation, and crop yield was collected from each of the soil sampling sites.

Soil quality assessment

The SQI was computed using an assessment framework that included a minimum dataset (MDS), scoring technique and additive indices (Figure 1). The MDS was

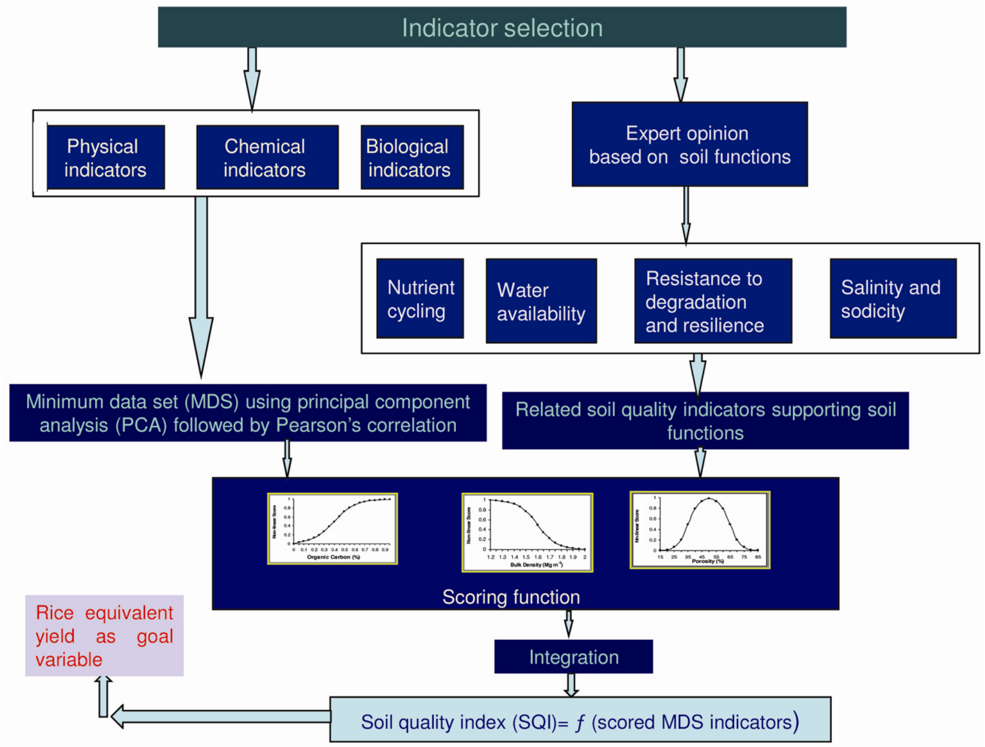


Figure 1. Flow chart for assessing soil quality index using principal component analysis and expert opinion.

selected based on two procedures, one using principal component analysis (PCA) and another based on expert opinion. In the PCA method, those principal components (PCs) which acquired higher eigen values, and variables which attained relatively high factor loading were treated as the best representative of the system attributes and retained for the MDS. When more than one factor was retained under a single PC, multivariate correlation coefficients were used to ascertain if the variables could be declared as redundant, and therefore, eliminated from the MDS[14].

To assess the suitability of the MDS in representing the management system goals, multiple regressions were run using the final MDS indicators as independent variables and management goals as dependent variables.

In case of expert opinion, a conceptual approach was used to choose the MDS. In this approach, only those indicators were included which were considered important to contribute to the function of interest. The four soil functions considered were: nutrient cycling, water availability, resistance to degradation, and salinity and sodicity (Table 1). MDS variables in each supporting soil function and their scoring were chosen from the available data according to the consensus of the project investigators, recommendations given in the literature[15,16], and common management concern in the region. The choice of soil functions was also driven by concerns voiced by participating farmers during the project work.

Farmers were interviewed regarding crop yield information, which was used as a goal variable to validate the evaluation of soil quality. As farmers were growing diverse crops, the yield data of all the crops were converted to rice equivalent yield by multiplying with a factor considering the prevailing market price of each crop in India. To illustrate, rice yield was multiplied with 1, maize with 0.78, redgram with 2.56, cotton with 2.56, and castor with 2.22 for converting to rice equivalent yield.

Once the MDS indicators were identified, each indicator was transformed to values ranging from '0' to '1' using a linear scoring method based on the performance of soil functions[16–18]. After transformation into scores, the MDS indicators for each observation were weighted using the PCA results. To obtain SQI (using PCA; denoted here as PCASQI), the weighted MDS indicator scores for each observation were summed up.

For calculating SQI based on expert opinion (denoted here as SQI), the MDS indicators were converted into scores and then multiplied with the weight of the indicator (Table 1) and weight of the respective soil function. All four soil function values were added to get the final SQI value.

Soil resilience study

Soil resilience studies in general, are conducted to assess a particular soil property or function prior to, during and following imposition of stress[19]. We followed the procedure of Andrew *et al.*[19] for assessing SRI. Since SOM is one of the fundamental soil properties, we hypothesized

Table 1. Conceptual framework of soil functions and their weights along with related indicators

Supporting soil function	Weight	Indicators	Weight
Nutrient cycling	0.40	Total N	0.1
		Available N	0.2
		Available P	0.1
		Available K	0.1
		Available micronutrients, only Zn	0.1
		CEC (cation exchange capacity)	0.1
		Organic C	0.1
		Microbial biomass carbon	0.1
		Soil respiration	0.1
Water availability	0.30	Available water capacity	0.5
		Bulk density	0.2
		Soil organic C	0.3
Resistance to degradation and resilience	0.15	Soil organic C	0.5
		% Clay	0.5
Salinity and sodicity	0.15	pH	0.5
		ESP (exchangeable sodium percentage)	0.5

that resilience would be controlled by it. The soils were subjected to heat stress in the laboratory and its effect was monitored on biological function (substrate-induced respiration) in terms of C-mineralization over a period of 23 days (Figure 2) using alkali trap method[20]. Andrew *et al.*[19] used powdered barley shoot (*Hordium vulgare* L.; 46% C, 5% N) as substrate, whereas in the present study, locally available powdered dry gliricidia (*Gliricidia sapium*) leaf (C% 44.1; N% 3.73) having similar C : N ratio of barley shoot and easily decomposable in incubation study was used as substrate. Soil stability and SRI were calculated using the equations

$$\text{Soil stability index} = \frac{\mathrm{C\,min}_{\text{Heat}}}{\mathrm{C\,min}_{\text{Control}}},$$

where $\mathrm{Cmin}_{\text{Heat}}$ and $\mathrm{Cmin}_{\text{Control}}$ refer to C-mineralization potential of soil after heat treatment and C-mineralization potential of original soil (without heat treatment).

$$\mathrm{SRI} = \frac{\mathrm{Cmin}_{\text{Control+Gli}} - \mathrm{Cmin}_{\text{Heat}}}{\mathrm{Cmin}_{\text{Control+Gli}}} \times \frac{\mathrm{Cmin}_{\text{Heat+Gli}} - \mathrm{Cmin}_{\text{Heat}}}{\mathrm{Cmin}_{\text{Heat+Gli}}},$$

where $\mathrm{Cmin}_{\text{Heat+Gli}}$ and $\mathrm{Cmin}_{\text{Control+Gli}}$ refer to C-mineralization potential of heat-treated soil mixed with glyricidia leaf powder and C-mineralization potential of original soil mixed with gliricidia leaf powder respectively.

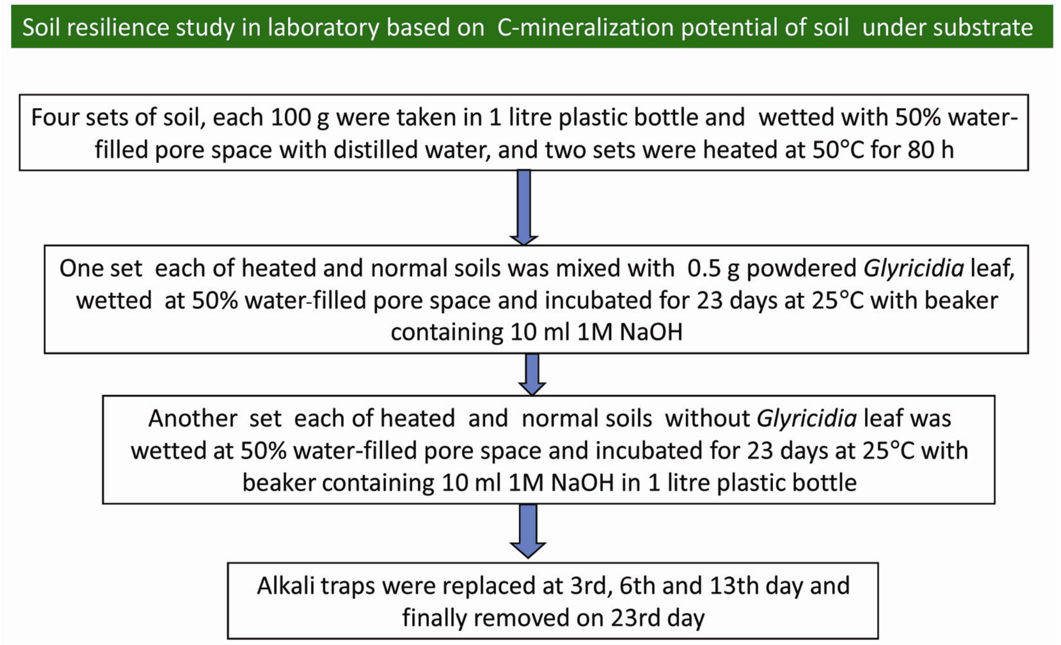
Estimating critical carbon levels for soils

To determine the critical values of SOC, relative yield (RY) and relative SQI (denoted here as RSQI for SQI calculated based on expert opinion and RPCASQI for SQI calculated using PCA) were used as its goal effects. SOC values that helped in attaining 0.8 and 0.5 of RY and RSQI could be taken as its optimum and threshold values respectively, based on the Cate and Nelson[21] method of soil test correlation for ascertaining critical level of nutrients.

RY was calculated by converting the yield value of all crops into rice equivalent yield and dividing this by the maximum rice equivalent yield (7000 kg ha^{-1}) obtained in the region during the study period. The relative SQI was calculated by dividing the SQI values obtained using both the procedures (PCA and expert opinion) with maximum SQI. The SOC stock was calculated by multiplying the carbon concentration determined by Walkey–Black with soil depth (15 cm) and bulk density. Also, a relationship was developed from the available data between SOC stock and organic matter input.

On-farm trial

The objective of this on-farm trial was to choose suitable land-management treatments for producing high yields while preserving SQ and its resilience. Considering soil-related constraints, four on-farm trials were conducted, three in Nalgonda district and one in Warangal district during the rainy seasons of 2010 and 2011. In each trial, three farmers were selected under the same cropping systems that have similar soil characteristics. The experimental sites received low and erratic annual rainfall. The soils of the experimental sites are Alfisols and have light texture, are low in fertility, especially organic carbon and nitrogen. The decision about the test crop for on-farm trail was made based on farmers' preference. The composite soil samples from 0 to 15 cm depth were collected before and after two years of conducting



Soil resilience study in laboratory based on C-mineralization potential of soil under substrate

Four sets of soil, each 100 g were taken in 1 litre plastic bottle and wetted with 50% water-filled pore space with distilled water, and two sets were heated at 50°C for 80 h

One set each of heated and normal soils was mixed with 0.5 g powdered *Glyricidia* leaf, wetted at 50% water-filled pore space and incubated for 23 days at 25°C with beaker containing 10 ml 1M NaOH

Another set each of heated and normal soils without *Glyricidia* leaf was wetted at 50% water-filled pore space and incubated for 23 days at 25°C with beaker containing 10 ml 1M NaOH in 1 litre plastic bottle

Alkali traps were replaced at 3rd, 6th and 13th day and finally removed on 23rd day

Figure 2. Flow chart for soil resilience study in the laboratory based on C-mineralization potential of soil under substrate.

the trial and analysed. The trial in each farmer's field was laid out with two treatments and four replications. The treatments comprised: (i) farmers' fertilizer and manure input (FFMI), and (ii) recommended management packages (RMPs) based on target yield. In FFMI treatment, all the three farmers in a trial followed the same dose of fertilizer and manure application, and adopted similar crop husbandry practices. The RMP was decided based on the principle of balanced fertilization not only for major plant nutrients, but also for micronutrients. The fertilizer doses were calculated based on soil test crop response (STCR) recommendation for individual farmer's field[22,23], considering balanced uptake of nutrients and target yield to be achieved (www.stcr.gov.in). The nutrient recommendation in RMP-based approach was worked out by taking into account the native nutrient supplying capacity of the soil, nutrient balance in the concerned field at the cropping system level, and level of target yield to be achieved.

The target yield was decided based on SQI as well as crop type and characteristics of growing environment like water availability (irrigated, fully rainfed, rainfed with supplemental irrigation) and calculated as

$$\begin{aligned}\text{Target yield} = {} & \text{Minimum yield} \\ & + (\text{maximum achievable yield} \\ & - \text{minimum yield}) \times \text{SQI}.\end{aligned}$$

A minimum yield for each crop was considered based on the minimum yield of the respective crop in the trial village. Maximum achievable yield is the maximum yield reported for the respective crop for the entire study area. Each treatment was imposed in approximately 400–600 sq. m plots. Nitrogen and phosphorus were provided to crops as urea and diammonium phosphate; Zn was supplied as zinc sulphate and gypsum as an amendment for sodicity control. Castor and cotton were grown as rainfed crops; however, supplementary irrigation was applied to maize. In RMP, there were two or three splits for N, whole P was applied at or soon after sowing, and K was applied once or twice depending on the rate and crop type. Certified seed of popular local crop variety was sown during mid-June after the onset of monsoon for the on-farm trial. The trails were mainly managed by farmers under the technical guidance of researchers, but the latter were responsible for collecting relevant data from the experimental plots. Grain yields were determined from a harvested area of 10 sq. m in the middle of each plot.

The data on crop productivity and soil parameters were analysed for analysis of variance (ANOVA), and treatment means in each trial were worked out using least significant difference (LSD) test and compared at $\alpha \leq 0.05$ level of significance.

We also evaluated the profitability of treatments based on total variable cost, gross return, gross margin and BCR (benefit : cost ratio) for on-farm trials. Total variable cost was computed considering the costs of inputs (seed, fertilizer and pesticide); costs of human labour for land preparation, irrigation, fertilizer and pesticide application, harvesting and threshing; and costs of hiring a tractor or power tiller for land preparation and an irrigation pump in the irrigated system. Gross return was calculated by multiplying the amount of produce (grain and straw) by its corresponding market price at harvest. The gross margin and

Table 2. Physical, chemical and biological properties of soils of the study sites under Alfisols

	Cultivated sites (n = 159)		Undisturbed fallow sites (n = 31)	
Soil parameters	Range	Mean ± SEM	Range	Mean ± SEM
Bulk density (mg m^{-3})	1.31–1.87	1.53 ± 0.01	1.35–1.83	1.63 ± 0.02
Moisture @ 0.33 bar or field capacity (w/w%)	4–28.7	12.6 ± 0.46	4.3–22.2	12.5 ± 1.28
Moisture @ 15 bar or permanent wilting point (w/w%)	1.2–17.2	6.2 ± 0.28	1.5–17.6	6.5 ± 0.69
Available water capacity (mm m^{-1})	22.5–263.8	97.8 ± 3.87	34.2–330.5	97.3 ± 11.3
% Clay	7–58	30.9 ± 0.7	21–48	32.6 ± 1.5
% Silt	1–17	5.4 ± 0.3	1–11	5.7 ± 0.5
% Sand	39–82	63.6 ± 0.8	42–74	61.6 ± 1.7
pH	5.4–9.3	7.7 ± 0.07	5.5–8.8	7.3 ± 0.12
Electrical conductivity (dS m^{-1})	0.03–0.78	0.2 ± 0.01	0.05–0.34	0.14 ± 0.01
Total N (%)	0.031–0.192	0.08 ± 0.002	0.041–0.194	0.08 ± 0.006
Total C (%)	0.299–3.512	0.95 ± 0.052	0.374–3.78	0.894 ± 0.116
Available N (kg ha^{-1})	82.8–469.1	173.3 ± 5.14	89.7–270.9	159.4 ± 7.33
Available P (kg ha^{-1})	3.4–105.9	21.7 ± 1.26	2.5–32.3	11.7 ± 1.26
Available K (kg ha^{-1})	62.1–630	228.8 ± 7.9	107.6–563.9	240.9 ± 18.8
Organic carbon (%)	0.17–1.21	0.60 ± 0.02	0.31–1.26	0.66 ± 0.05
DTPA-extractable Zn (mg kg^{-1})	0.101–2.99	0.549 ± 0.04	0.165–1.82	0.48 ± 0.07
DTPA-extractable Cu (mg kg^{-1})	0.13–2.7	0.67 ± 0.04	0.14–1.54	0.55 ± 0.07
DTPA-extractable Fe (mg kg^{-1})	1.4–53.4	12.1 ± 0.87	2.2–28.9	10.5 ± 1.34
DTPA-extractable Mn (mg kg^{-1})	0.4–142.2	9.1 ± 1.06	1.7–94	12.8 ± 2.86
Available B (mg kg^{-1})	0.08–2.03	0.76 ± 0.03	0.14–1.1	0.51 ± 0.04
CEC (cmol kg soil^{-1})	4.7–47.2	17.2 ± 0.67	6.9–37.8	17 ± 1.35
ESP (%)	0.9–22.4	4.9 ± 0.31	1.1–14.9	3.3 ± 0.51
Dehydrogenase activity (DHA; mg kg^{-1} h^{-1})	0.23–9.79	3.09 ± 0.15	0.52–12.25	3.23 ± 0.52
Microbial biomass C (MBC; mg kg^{-1})	40.4–502.2	215.3 ± 10.04	42.9–514.9	258.9 ± 25.3
Mean weight diameter (MWD; mm)	0.05–1.086	0.217 ± 0.01	0.109–0.59	0.253 ± 0.02
Exchangeable Ca + Mg (cmol kg soil^{-1})	1.1–27.9	9.4 ± 0.45	1.1–21.3	9 ± 0.97

SEM, Standard error of mean.

Table 3. C- and N-mineralization of soils of the study sites under Alfisols

	Cultivated sites (n = 159)		Undisturbed fallow sites (n = 31)	
Parameters	Range	Mean ± SEM	Range	Mean ± SEM
C-mineralization				
After three days incubation (mg C-CO_2 kg soil^{-1} day^{-1})	1.0–44.00	11.97 ± 0.69	2–45.5	15.6 ± 2.27
After six days incubation (mg C-CO_2 kg soil^{-1} day^{-1})	1–43	14.57 ± 0.62	4–32	17.4 ± 1.25
After 13 days incubation (mg C-CO_2 kg soil^{-1} day^{-1})	0.21–20.14	6.51 ± 0.18	0.22–24.86	10.86 ± 0.99
After 23 days incubation (mg C-CO_2 kg soil^{-1} day^{-1})	0.3–22.2	5.33 ± 0.15	2.1–14.4	7.39 ± 0.55
Total C-mineralization after 23 days incubation (mg C-CO_2 kg soil^{-1})	51–423	178.5 ± 5.44	115.3–462	248.8 ± 16.5
Average C-mineralization per day (mg C-CO_2 kg soil^{-1} day^{-1})	2.22–18.39	7.76 ± 0.24	5.01–20.09	10.82 ± 0.72
N-mineralization				
N-mineralization without incubation (mg kg soil^{-1})	14–196	52.4 ± 2.32	14–126	54.6 ± 4.75
N-mineralization with incubation (mg kg soil^{-1})	35–231	97.02 ± 3.12	35–175	88.72 ± 6.52
N-mineralization (mg kg soil^{-1})	13.3–165.9	44.62 ± 2.63	14–147	34.08 ± 5.92

BCR were computed as follows: gross margin = gross return – total variable cost, and BCR = gross return/total variable cost. The economic analysis was carried out by taking into account the prevailing market prices of inputs, labour and produce during the year 2011–12.

Results and discussion

Assessment and interpretation of soil quality index

In all, 26 soil physical, chemical and biological properties were studied for each composite soil sample. Soils were mostly coarse-textured with low available water capacity, relatively high bulk density and very poor soil structure as represented by mean weight diameter (MWD) of the water-stable aggregates (Table 2). A summary of chemical analysis of soil sampling sites reflected that the study area had wide pH range, from acidic to alkali, low electrical conductivity, low to high organic C, low available soil nitrogen, medium to high Olsen-P, and medium to high exchangeable K.

Soil biological properties, viz. dehydrogenase activity (DHA) and microbial biomass C (MBC) were highly variable. Generally, C-mineralization gradually increased

Table 4. Results of principal component (PC) analysis of soil parameters for the soil sampling sites under Alfisols

Statistics	PC#1	PC#2	PC#3	PC#4	PC#5	PC#6	PC#7
Eigenvalue	7.05	2.52	1.80	1.29	1.25	0.99	0.90
Percentage of variance	32.06	11.45	8.18	5.86	5.68	4.51	4.08
Cumulative %	32.06	43.52	51.70	57.56	63.24	67.75	71.83
Factor loading/eigenvector							
Variables							
Clay%	0.666	–0.523	–0.033	–0.030	0.081	0.016	–0.054
pH	0.582	0.106	0.370	–0.284	–0.318	0.021	–0.126
EC	0.639	0.132	0.513	0.146	–0.237	0.020	0.099
Available N	0.203	0.572	–0.233	–0.254	0.113	0.405	–0.124
Available P	0.187	0.454	–0.265	–0.314	0.044	–0.002	0.667
Available K	0.580	–0.131	–0.173	–0.292	0.231	–0.098	0.004
CEC	0.764	–0.447	–0.112	–0.034	–0.177	0.123	–0.024
ESP	0.287	0.308	0.771	0.056	–0.221	0.078	0.060
DTPA-extractable Zn	0.284	0.233	0.196	0.056	0.540	–0.270	0.047
Organic C	0.712	0.453	–0.237	0.110	–0.002	–0.129	–0.033
DHA	0.540	0.419	0.179	0.099	–0.073	–0.275	0.216
Bulk density	–0.298	0.110	0.349	0.371	0.412	0.301	0.114
Water retention at 15 bar	0.859	–0.247	–0.152	0.000	0.015	0.127	0.105
Water retention at 0.3 bar	0.880	–0.247	0.011	–0.105	0.141	0.189	0.113
Available water capacity	0.618	–0.153	0.246	–0.133	0.320	0.255	0.109
MBC	0.432	0.068	–0.284	0.399	0.190	0.047	0.005
Mineralizable-C	0.414	–0.085	–0.286	0.552	–0.312	–0.237	0.178
MWD	–0.032	0.393	–0.242	0.355	–0.211	0.569	–0.032
Mineralizable-N	0.015	0.383	–0.229	–0.348	–0.333	0.002	–0.032
Total N	0.657	0.491	–0.164	0.154	0.125	–0.156	–0.228
Total C	0.666	0.349	0.030	–0.045	0.133	–0.101	–0.470
Exchangeable Ca + Mg	0.828	–0.325	–0.055	0.076	–0.162	0.076	0.004

Underlined factor loadings are considered highly weighted, i.e. having values within 10% of variation of the absolute values of the highest factor loading in each PC.

up to sixth day and then decreased drastically from the 13th day (Table 3). On an average, in all the studied soils, C-mineralization varied between 2.2 and 20.1 mg C-CO_2 kg soil^{-1} day^{-1} with a mean value of 8.3 mg C-CO_2 kg soil^{-1} day^{-1}. Soil biological parameters were comparatively better in fallow (permanent) sites than cultivated field because of regular tillage or perturbation leading to oxidation of labile fraction of soil organic C in cultivated field. The N-mineralization varied between 13.3 and 165.9 mg kg^{-1} with a mean value of 42.9 mg kg^{-1}.

All 26 soil properties analysed were used for the computation of SQI. Among the three particle size distributions (sand, silt and clay), the per cent clay content was considered for PCA as it had the highest correlation coefficient ($r = 0.38$) with rice equivalent yield (goal variable). Among the five micronutrients (DTPA-extractable Zn, Cu, Fe, Mn and available B) more than 70% of the sampling sites were deficient in available Zn. For other micronutrients, in most of the cases, only less than 10% sampling sites were found deficient. No deficiency symptoms were noticed in plants for other micronutrients and hence they were not considered for PCA. Finally, 22 soil parameters were considered for PCA (Table 4). The results illustrate that 71.8% of the variation in the data could be explained by the first seven PCs having eigenvalues greater than 0.90. Ten highly-weighted variables resulted from PCA. To reduce the redundancy of variables, Pearson's correlation coefficients and correlation sums were computed for each of the ten highly-weighted variables; three variables, i.e. soil moisture at 15 bar or permanent wilting point (PWP), exchangeable Ca + Mg, and % clay were dropped because they were highly correlated with soil moisture at 0.33 bar or field capacity (FC). The final seven MDS variables for Alfisols soils resulting from PCA followed by correlation were soil moisture retention at FC, available N, P and Zn, exchangeable sodium percentage (ESP), MWD and C-mineralization.

PCA has become a powerful tool to identify patterns in the data and for expressing the data in such a way as to highlight their similarities and differences. Further, it helps screen the important indicators without much loss of information[8,17]. Andrews *et al.*[24] showed that the indicator groups or MDS used to indirectly measure soil function must be sufficiently diverse and flexible to represent the chemical, biological and physical properties and processes of complex systems.

When all the seven indicators that were retained in the MDS were regressed as independent variables with management goal, i.e. rice equivalent yield as dependent variables, the coefficient of determination (R^2) was 0.317 ($\alpha < 0.001$).

Table 5. Soil quality index based on soil function (SQI) and using principal component analysis (PCASQI), soil stability index and soil resilience index of different land-use systems under Alfisols

	SQI		PCASQI		Soil stability index		Soil resilience Index	
Crops	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Castor	0.427–0.497	0.464a	0.379–0.398	0.388a	0.365–0.806	0.640a	0.277–0.687	0.466a
Cotton	0.419–0.697	0.527bc	0.319–0.637	0.442b	0.325–0.981	0.701b	0.253–0.841	0.539b
Intercrop	0.398–0.660	0.497b	0.257–0.609	0.409a	0.168–0.966	0.677b	0.153–0.770	0.507b
Maize	0.413–0.661	0.544c	0.299–0.548	0.440b	0.356–0.978	0.751c	0.201–0.905	0.533b
Paddy	0.384–0.742	0.573d	0.277–0.689	0.480c	0.429–0.986	0.767c	0.229–0.908	0.580c
Redgram	0.403–0.668	0.511b	0.290–0.625	0.420b	0.414–0.973	0.702b	0.282–0.799	0.546bc
Irrigated	0.384–0.742	0.552A	0.277–0.689	0.461A	0.327–0.981	0.741A	0.201–0.908	0.567A
Rainfed	0.394–0.697	0.507B	0.256–0.637	0.415B	0.168–0.986	0.670B	0.153–0.905	0.514B
Cultivated	0.384–0.742	0.530D	0.256–0.689	0.439D	0.168–0.986	0.707C	0.153–0.908	0.541C
Permanent fallow	0.389–0.850	0.552D	0.309–0.770	0.442D	0.374–0.994	0.783D	0.301–0.978	0.604D

Within a column, numbers followed by the same upper or lowercase letters are not significantly different at $P < 0.05$ level.

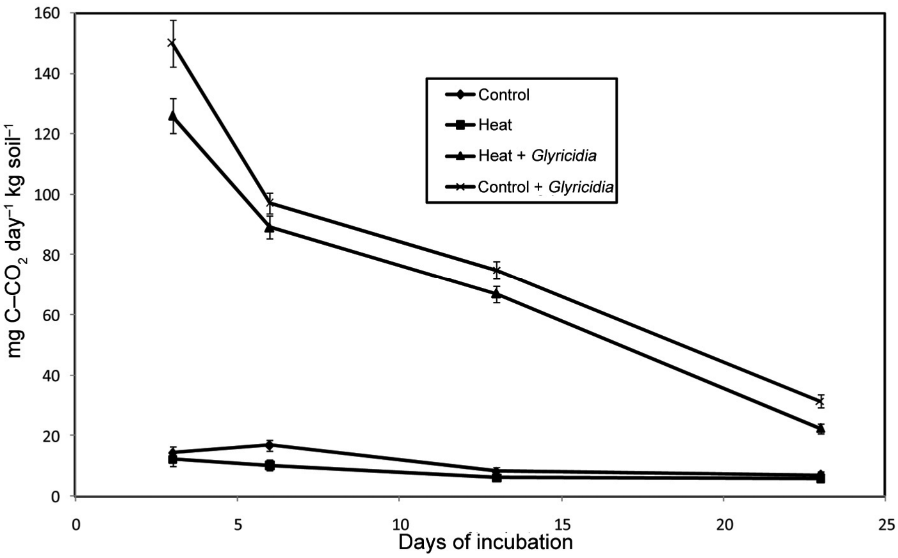


Figure 3. Carbon mineralization study over a 23-day period for computing soil resilience index. Here heat, control, heat + gliricidia and control + gliricidia specify C-mineralization potential of soil after heat treatment, C-mineralization potential of original soil, C-mineralization potential of soil after heat treatment and mixed with gliricidia leaf powder, and C-mineralization potential of original soil with glyricidia leaf power respectively. Error bars represent the standard error of the mean values over different land-use systems.

For conceptual approach to compute SQI based on expert opinion, the MDS of indicators was identified to define the respective soil function through consensus of participating project partners. Pearson correlation coefficient was computed to find the relationship between four soil functions, viz. nutrient cycling, water availability, resistance to degradation and salinity–sodicity and crop productivity. The nutrient cycling, water availability and resistance to degradation functions showed positive relationship ($\alpha < 0.01$), whereas there was a negative relationship between soil salinity function and rice equivalent yield. A multiple regression was also run to determine how the four soil functions were related to overall goal variables, i.e. rice equivalent yield. The coefficient of determinant was 0.348 ($\alpha < 0.001$) and the regression model indicated that out of the four soil functions, beta values for water availability and nutrient cycling were significant at $P < 0.05$ level. The seven key indicators resulting from PCA for each soil order broadly performed three categories of soil functions, i.e. water supplying capacity, nutrient availability and salinity–sodicity.

When SQI was calculated using PCA, the contribution of each MDS or key indicators towards soil quality index (PCASQI) was highest from moisture retention at FC (33.3%), followed by ESP (23.3%), available N (13.2%), DTPA-extractable Zn (11.4%), available P (8.3%), C-mineralization (7.6%), while lowest from MWD of aggregate (2.9%).

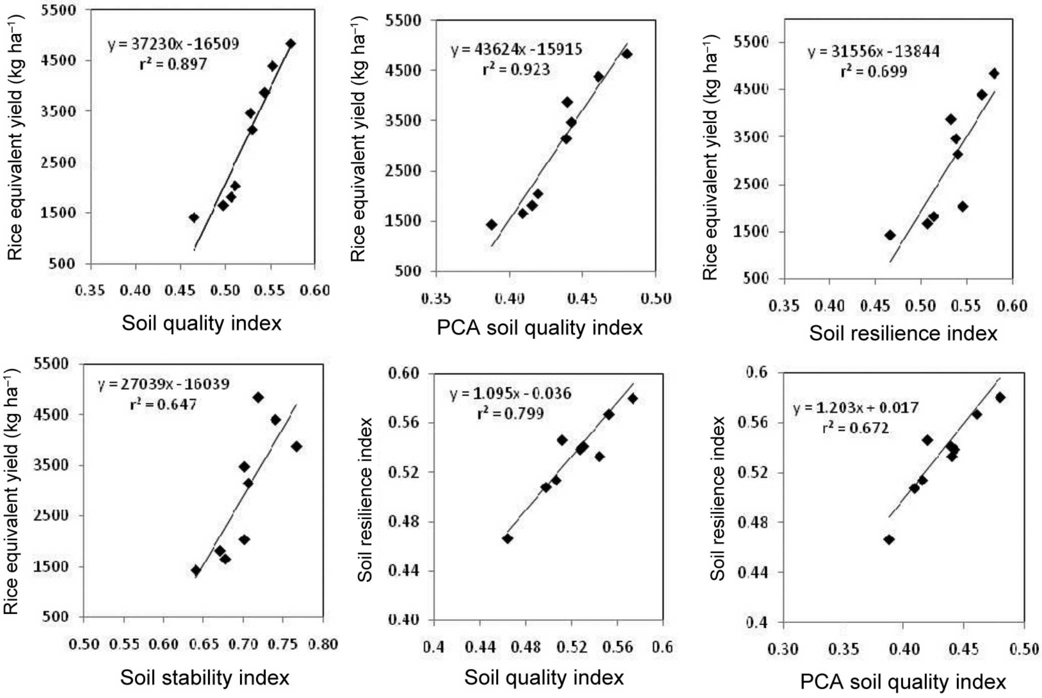


Figure 4. Relationship between soil quality index (calculated using soil function), PCA soil quality index (calculated using PCA), soil resilience index and rice equivalent yield.

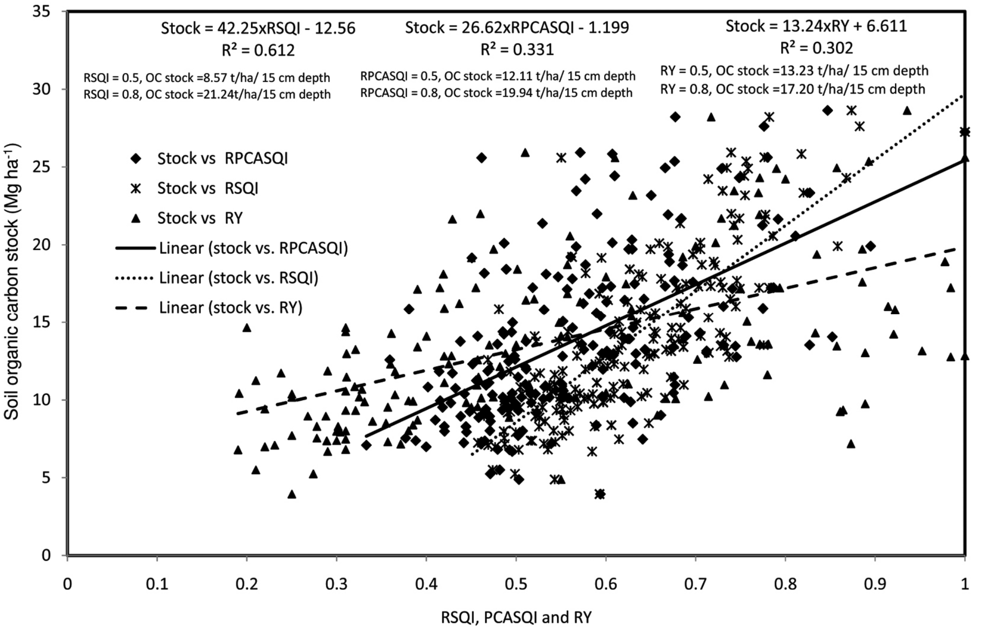


Figure 5. Critical limits (optimum and threshold) of soil organic C stock in Alfisols calculated based on the relationship between relative soil quality index and relative yield with soil organic C stock (Stock, Soil organic C stock. RSQI, Relative soil quality index calculated based on expert opinion; RPCASQI, Relative soil quality index calculated using PCA and RY, Relative yield.)

Among the four soil functions, on an average, nutrient cycling contributed 36.3% to SQI followed by water availability (26.0%), salinity (23.4%), whereas the lowest contribution was from soil function resistance to degradation (14.3%).

In the present study, for calculating SQI using soil function, maximum weights were given for nutrient cycling capacity of soils. In the tropics, cultivated soils are likely to develop nutrient deficiencies under continuous cropping without applying adequate fertilizer inputs.

It has been reported that smallholder farmers in sub-humid Africa and Asia are facing food insecurity due to severe depletion of nitrogen and phosphorus in many of their soils[25]. Therefore, identification and quantification of parameters that reflect these nutrient deficiencies is an important challenge for assessing soil quality in the tropics. The major soil factors which adversely affect agriculture in India are: depletion of nutrients and loss of SOM rather than nutrient pollution, which is common in temperate-zone countries. Other than nutrients, water in soil constitutes another important constraint for increasing good production. Eroded, coarse-textured Alfisol soils with low water-holding capacity mainly contribute to poor yield of the region. Sahrawat *et al.*[26] reported that in order to sustain higher productivity and maintain soil quality at the watershed or catchment level in the SAT, integrated use of soil and water conservation practices with balanced plant nutrition is essential.

The higher r^2 (0.768; $\alpha < 0.001$) value between two procedures of assessing SQI ascertained that both had good relationship with each other. The average SQI value was 0.534 and maximum value was 0.85 under fallow in Abbapur village of Mulugu Mandal, whereas minimum value of 0.38 was also recorded in a paddy field under Venkatapura village, both in Warangal district. Among the five sites that had SQI more than 0.7, three were under paddy system and two under permanent fallow. Among the other five sites that recorded SQI less than 0.4, three were under paddy system, one was under intercrop and one was under permanent fallow. Though farmers mostly used balanced nutrients along with organics for paddy cultivation, few paddy fields were coarse-textured, low in available water capacity and had very low SQI, which were not suitable for paddy cultivation. Among the various land-use systems, overall SQI was highest under paddy followed by permanent fallow, maize, cotton, intercrop, redgram, and was lowest under castor system (Table 5). Irrigated system maintained higher soil quality than rainfed system.

We consider the undisturbed permanent fallow soils under virgin conditions as benchmark soil. Comparing the fragility of the agricultural production system caused by the traditional way of farming to the benchmark soil, most of the dominant rainfed cropping systems of the region, i.e. castor, cotton, maize, intercropping system, even redgram indicated degradation of the system (Table 5). Even the irrigated system of maize and cotton showed signs of degradation of soil quality compared with the benchmark soil. This is in contrast to the results of Mandal *et al.*[18], where intensive irrigated agriculture resulted in aggradation of soil quality when compared with soil that had remained uncultivated for a long time. Furthermore, rice is grown under submerged, anaerobic conditions that reduce the rate of decomposition of organic matter and also the effect of sodicity, and help in preserving SQ.

Soil resilience study

Overall, heat stress reduced the respiration up to sixth day of incubation to the extent of 17%. There was hardly any reduction in respiration under heat stress condition after 13th day of incubation (Figure 3). Among the four conditions (normal soil or control, soil under heat treatment, soil under heat treatment with gliricidia leaf and normal soil with gliricidia leaf), maximum respiration rate was noted under normal soil with gliricidia leaf, followed by heat-treated soil with gliricidia, normal soil and lowest in heat-treated soils. Overall, stability index was relatively more than SRI. Under different land-use systems, maximum SRI was found under pristine fallow sites followed by paddy, redgram, cotton, maize, intercrop, and lowest under castor system. The trend for soil stability index was permanent fallow > paddy > maize > redgram > cotton > intercrop > castor. Irrigated system also showed higher resilience than rainfed system. A regression equation was developed between soil quality index, resilience index and rice equivalent yield (Figure 4).

There is no standard protocol for routinely assessing or quantifying soil resilience[27]. Thus, we need to develop practical methods of assessing soil resilience, as this would help in predicting the long- and short-term effects of soil disturbance for a given site.

Biological resilience in soil was quantified by determining the changes in the short-term mineralization of plant residues, dissolved organic carbon and catabolic function in response to disturbance. Kuan *et al.*[28] assessed the biological resilience of selected Scottish soils by measuring CO_2 evolution from the soil with powder barley shoots as substrate, after either a transient (heat) or persistent (copper) stress. The soils were heated at 40°C for 18 h and recovery from heat stress was on an average

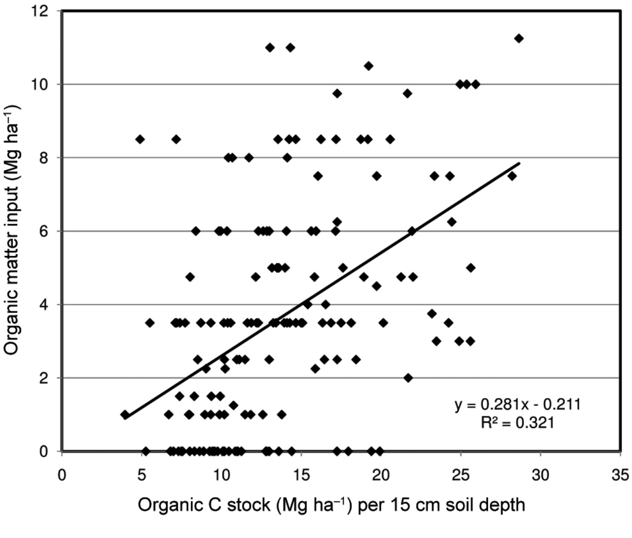


Figure 6. Relationship between soil organic C stock and organic matter input applied in Alfisol soils.

Table 6. Soil characteristics before starting on-farm trial during 2010–11

On-farm trial	District/ village	Soil type	Land use	pH	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})	Organic C (%)	DTPA-extractable Zn (mg kg^{-1})	ESP (%)	SQI	Soil Resilience Index	Target yield kg ha^{-1} (crop)
Trial 1	Nalgonda/ Sakali seripalli	Alfisols sandy loam	Castor + redgram-fallow	7.2–7.8	119–135	16–23	271–306	0.37–0.41	0.56–0.64	17–22	0.37	0.297	1000 + (2200–1000) × 0.37 = 1444 ≈ or 1500 (castor)
Trial 2	Nalgonda/ Sakali seripalli	Alfisols Sandy clay loam	Cotton–fallow	6.6–7.0	132–169	22–26	201–239	0.41–0.53	0.58–1.11	5–11	0.389	0.521	1000 + (1800–1000) × 0.389 = 1311 ≈1300 (cotton)
Trial 3	Nalgonda/ Sakali seripalli	Alfisols sandy clay	Maize–fallow	7.7–8.1	140–153	25–32	215–264	0.22–0.31	0.21–0.29	14–19	0.608	0.648	3000 + (8000–3000) × 0.608 = 6040 ≈6000 (maize)
Trial 4	Warangal/ Jafferguda	Alfisols Sandy clay loam	Maize–fallow	8.5–8.9	153–172	15–23	196–219	0.31–0.39	0.48–0.56	17–23	0.414	0.462	3000 + (8000–3000) × 0.414 = 5070 ≈5000 (maize)

Table 7. Treatment details of recommended management practices (RMP) and farmers' fertilizer and manure input (FFMI), yield, SQI, and soil resilience index after two years of on-farm trial

On-farm trial	Crop	Treatment	Fertilizer/manure and amendment dose	Irrigation/ rainfed	Average yield (2010 and 2011) kg ha^{-1}	SQI	Soil resilience index
Trial 1	Castor + redgram	RMP	2 t ha^{-1} FYM N : P : K (kg ha^{-1}) :: 66 : 35 : 12; Gypsum@ 2t ha^{-1}	Rainfed	Castor: 1220 Redgram: 180	0.463	0.404
		FFMI	Farmers' practice: N:P (kg ha^{-1}):: 40:20		Castor: 954 Redgram: 144	0.392	0.329
		LSD (0.05)			Castor: 201 Redgram: 30	0.032	0.029
Trial 2	Cotton	RMP	3 t ha^{-1} FYM N : P : K (kg ha^{-1}) :: 90 : 45 : 70; $ZnSO_4$ @ 10 kg ha^{-1}	Rainfed	1538	0.492	0.681
		FFMI	Farmers' practice: N : P (kg ha^{-1}) :: 80 : 50		1315	0.408	0.554
		LSD (0.05)			148	0.051	0.110
Trial 3	Maize	RMP	3 t ha^{-1} FYM N : P : K (kg ha^{-1}) :: 130 : 55 : 100; $ZnSO_4$ @ 10 kg ha^{-1}; Gypsum 2 t ha^{-1}	Irrigated	5822	0.616	0.624
		FFMI	2.5 t ha^{-1} FYM N : P : K (kg ha^{-1}) :: 80 : 60 : 75		4900	0.541	0.514
		LSD (0.05)			290	0.053	0.101
Trial 4	Maize	RMP	3 t ha^{-1} FYM N : P : K (kg ha^{-1}) :: 110 : 60 : 90; $ZnSO_4$@ 10 kg ha^{-1}; Gypsum 2 t ha^{-1}	Irrigated	6621	0.492	0.483
		FFMI	2.5 t ha^{-1} FYM N : P : K (kg ha^{-1}) :: 80 : 60 : 75		5250	0.435	0.462
		LSD (0.05)			450	0.051	NS

NS, Not significant at $P = 0.05$.

almost completed at 28 days. In the present study, initially, soils were heated at 40°C, but there was no change in CO_2 evolution with respect to control soils. Only when soils were heated at 50°C for 80 h, noticeable changes of heat stress in terms of CO_2 evolution were recorded. The temperature of 50°C was chosen as soils in the SAT region often warm up to that value during April–May. Overall, these tropical soils were biologically more resilient than temperate soils of Scotland. Also, recovery time of these soils was less or faster than temperate soils.

In the present study, SRI was developed based on its definition and conception where recovery rate after heat stress was computed under substrate-induced respiration. This is a simple way to depict the resilience characteristics of soils under various land-use systems. Maximum SRI was found under fallow, because less perturbation of fallow virgin soils made them more resilient than soils from arable land. Higher organic level in rice fields made it more resilient and resistant to degradation than any other land-use system.

Estimating critical carbon levels for soils

The critical and optimum SOC levels for Alfisols were found to be 8.57 Mg ha^{-1} per 15 cm depth (organic carbon 0.369%) and 21.24 Mg ha^{-1} per 15 cm depth (organic carbon 0.914%, considering bulk density 1.55 Mg m^{-3}), when the RSQI was considered as the goal variable (Figure 5). Similarly, when RPCASQI was considered as the goal variable, the critical and optimum SOC levels for the studied soils were 12.11 Mg ha^{-1} per 15 cm depth (organic carbon 0.521%) and 19.94 Mg ha^{-1} per 15 cm depth (organic carbon 0.858%, considering bulk density 1.55 Mg m^{-3}; Figure 5). However, when RY was considered as the goal variable, the critical and optimum SOC levels were 13.23 Mg ha^{-1} per 15 cm depth (organic carbon 0.569%) and 17.20 Mg ha^{-1} per 15 cm depth (organic carbon 0.739%, considering bulk density 1.55 Mg m^{-3}).

In the present study, a critical SOC stock of 8.6 Mg ha^{-1} (0.37% organic C) per 15 cm soil depth was considered essential to maintain soil quality at 50% level. Similarly, an optimum soil C stock of 17 Mg ha^{-1} (0.73% organic C) per 15 cm was estimated to maintain 80% of maximum achievable yield. Perusal of the data indicated that out of the total 190 sites, around 26 had SOC less than the critical value (organic C 0.37%).

We also developed a relationship between SOM inputs and SOC stock to find the amount of organic matter to be applied to achieve the optimum level of SOC stock (Figure 6). The present study indicated that to maintain 17 Mg ha^{-1} of SOC stock at surface depth (corresponding to 70% SQI and 80% RY), we need to apply 4.57 Mg ha^{-1} organic matter, whereas around 2.2 Mg ha^{-1} of organic matter is needed to maintain critical level of SOC stock of 8.6 Mg ha^{-1} in surface depth in semiarid Alfisols soils.

To build up C stock in the soil, sufficient amount of C needs to be added to it through crop residues and/or other organic amendments. Critical C inputs were calculated for long-term fertilizer experiments based on the relationship between SOC sequestered (current–initial) and cumulative C input to ensure zero change in SOC for different agro-eco-regions of India. The estimated values (2.31–5.16 Mg ha^{-1}), however, varied widely by a few orders of magnitude for different sites under different agro-eco-regions of the country[29,30].

In the present study, a critical value of SOC stock was determined based on its relationship with RY and RSQI. Then the amount of organics needed to be applied to maintain this critical SOC was evaluated based on input of organic matter and SOC relationship. In general, tropical soils contain less than 0.5% SOC. To maintain SOC to the level of 0.7% in Alfisols, around 4.6 Mg ha^{-1} organics are required to be applied. In most of the cases after harvesting, around 1–2 Mg ha^{-1} crop residues were left in the soils through root biomass and stubbles. The present study shows that around 2.5–3 t ha^{-1} organics need to be applied to maintain SQ and sustain productivity. During the investigation, it was observed that in many cases farmers applied more than 10 t ha^{-1} organics. As these tropical soils have limited capacity to sequester carbon, addition of very high amounts of organics leads to faster decomposition of organic matter, ultimately leading to more addition of greenhouse gases to the environment. It is prudent to apply organics to the extent of 2.5–3 t ha^{-1} on a regular basis, rather than to add them in high amounts once in a couple of years.

Response of recommended management in field trials

The soils in the experiment sites were low in organic carbon and available N, medium in available P and available K, and out of four trials sites, two were deficient in Zn and in sodicity problem (Table 6). Trial sites were decided based on the soil related constrains and SQI value (calculated based on soil function). SQI and SRI varied between 0.37 and 0.613, 0.297 and 0.648 respectively, in the trial sites.

Results from 12 farmers' fields across four trials in four sites showed that RMP treatment increased yield by 16–26%, which increased the gross return by INR 3720–11,280, as well as BCR over FFMI (Table 7 and Figure 7). Compared with FFMI, RMP reduced fertilizer P by 5 kg ha^{-1}, enhanced fertilizer K and did not significantly change fertilizer N.

The STCR approach comprehensively considers the native soil fertility and works out a balance between the nutrients already available in the soil and those required for achieving predetermined yield target of a given crop. RMP ensures adequate amount of all the nutrients (N, P, K as

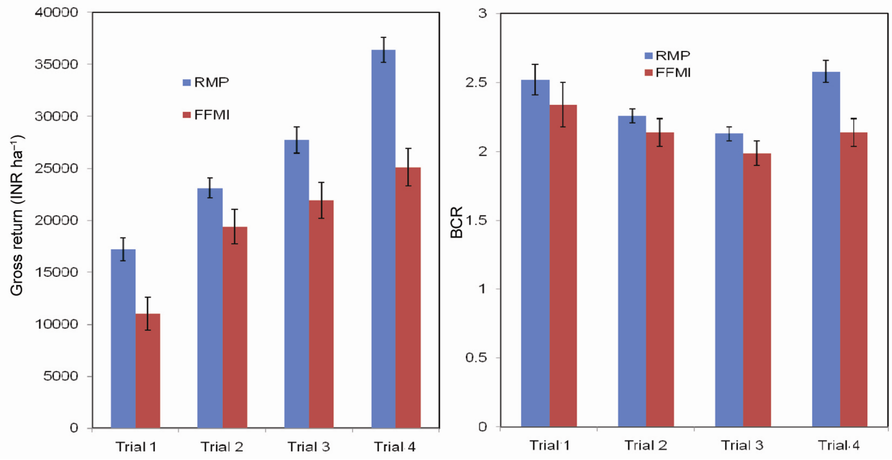


Figure 7. Gross margin and BCR (benefit : cost ratio) of four on-farm trials using farmers' fertilizer and manure input (FFMI) and recommended management practices (RMP). Error bars represent the standard error of the mean values.

well as secondary and micronutrients, when deficient), and soil amendments required to support the yield goal are applied at the critical growth stages of the target crop. In RMP, FYM was applied on the basis of critical C level analysis; thus it helps maintain soil fertility. On the other hand, practices used by the farmers to fertilize their crops were almost sub-optimal with respect to rate and time of application. Similar type of on-farm trial was conducted in farmers' fields of Karnataka, where application of balanced nutrients (NPK + S + Zn + B) significantly increased grain yield and aboveground dry matter in pearl millet which provided resilience against drought through enhanced water productivity[31]. In FEMI, inadequate and unbalanced application of nutrients can decrease the nutrient use efficiency and profitability, and may increase environmental risks linked with the loss of unutilized nutrients through emission or leaching.

At the end of two years, SQI and SRI were determined to assess if there was any aggradation or degradation of soil quality in the field trials and all the four trials responded positively. Thus, the target yield based on SQI provides a comprehensive potential productivity of the soils and RMP approach for soil management helps increase yield and revenue, and maintain or improve the soil quality as well as sustainability of the agro-ecosystem.

Recommendations

We have studied the soil resources of small holder farmers in semi-arid Alfisols soils and developed a SQI and SRI in order to select the best management strategies according to their impact on soils functions. Most of the dominant rainfed cropping systems of the region, i.e. castor, cotton, maize intercropping system, even redgram under subsistence agricultural practices indicated degradation of soil quality. Thus restoration of these soils and ecosystems carbon pools in the rainfed systems is essential for enhancing agronomic productivity and agricultural sustainability. Rice-based systems with integrated nutrient management under submerged conditions could reduce the rate of decomposition of organic matter and help in preserving SQ and its resilience. The indexing approach of SQ and its resilience by choosing MDS indicators can be a useful tool to monitor the impact of management practices on the functional ability of the soil and its limitations. We recommend a sustainable land-management system through application of balanced nutrients from chemical fertilizers and organics as well as appropriate amendment to enhance SOC stock, improve SQ and its resilience, and sustain agronomic productivity even in soils of low inherent fertility and in harsh climate.

Conclusion

In the present study, the technical aspect of soil quality restoration involves establishment of critical limits of key soil properties that determine its quality, development of the database to understand changes in these properties in relation to the restorative measures, and establishing the cause–effect relationships between soil quality and productivity for different management systems. This is a holistic approach for addressing sustainable land-management practices in the SAT region of India. In this study, a standard methodology of identifying key indicators and computation of soil quality and resilience has been adopted. The procedures adopted and the findings of the present study would be useful (i) in identifying the predominant dynamic indicators for a particular soil type under a given cropping system/farming system and (ii) to evaluate and identify the most robust, environment-friendly soil and nutrient management practices for maintaining higher sustainable yields, checking soil degradation and further improving soil quality using SQI approach.

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