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Soil Quality Index in Rice-Rice Cropping System under Long Term Fertilizer Experiment in Lateritic Soils of Humid Tropics

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Abstract

The Soil Quality Index (SQI) of various nutrient management practices under a rice-rice cropping system was evaluated after 23 years of residual effects in a long-term fertilizer experiment (LTFE) conducted at RARS, Pattambi, Kerala. The LTFE comprised twelve treatments involving different levels of NPK application, imbalanced nutrient combinations, and integrated nutrient management practices. Principal Component Analysis (PCA) was performed using 28 soil indicators encompassing physical, chemical and biological properties. Four principal components with eigenvalues greater than one were retained, together explaining 83.1% of the total variance. The maximum SQI was recorded in treatment T8, which received 100% NPK in combination with farmyard manure (FYM). Overall, SQI values ranged from 1.82 to 3.01. Relative Soil Quality Index (RSQI) values were calculated to classify the nutrient management practices into poor, medium, and high soil quality categories. The results indicated that integrated and balanced fertilizer applications were most effective in sustaining and improving soil quality in laterite soils. Integrated nutrient management treatments (T8, T9, T10, and T11), along with the lime-amended treatment (T4), were categorized under medium soil quality, whereas the remaining treatments fell into the poor soil quality category.

Keywords: LTFE, Soil quality index, principal component analysis, Minimum data set

Introduction

Long-term fertilizer experiments (LTFEs) generate valuable information on the effects of continuous application of fertilizers, using different combinations of organic and inorganic sources, on soil fertility and crop productivity. Such experiments provide a reliable framework for monitoring long-term changes in soil fertility and productivity while safeguarding soil health (Haefele, 2002). In addition, LTFEs offer an effective means to evaluate the sustainability of agricultural management practices. Under the All India Coordinated Research Project on Long-Term Fertilizer Experiments, a field experiment was initiated in 1997 at the Regional Agricultural Research Station, Pattambi, to study the long-term impact of continuous application of plant nutrients (NPK), applied in organic and inorganic forms and in various combinations, on sustainable productivity in a rice-rice cropping system. Assessment of soil quality in LTFEs thus provides comprehensive insights into the long-term sustainability of nutrient management practices.

The concept of soil quality encompasses both the productive potential of soil and its environmental functions (Parr *et al*., 1992). It governs essential soil processes such as serving as a medium for plant growth, regulating water movement, recycling nutrients, and providing habitat for soil biota (Karlen *et al*., 1997). Soil quality is defined as the capacity of soil to function within ecosystem boundaries so as to sustain biological productivity, maintain environmental quality, and support plant and animal health (Doran and Parkin, 1994). Among the various indicators, soil organic matter is considered a critical determinant of soil quality. Enhancement of soil organic carbon (SOC) stocks through sequestration is a key strategy for improving soil health while simultaneously mitigating climate change. Moreover, greater stabilization of SOC in passive pools with longer residence times contributes to increased carbon sequestration in soils (Samal *et al*., 2017). In the same long-term rice–rice cropping system on lateritic soils of the humid tropics, integrated nutrient management was found to enhance soil carbon pools and carbon management indices (John *et al.,* 2025). Evidence from recent rice nutrition studies shows that integrated use of organic amendments with recommended fertilizer doses enhances crop productivity and soil health, with enriched organics like Geoxol.com contributing to improved soil quality in rice-based systems (Manasa *et al.*, 2025). Crop productivity was reported to be higher when vermicompost was integrated with chemical fertilizers (Rama Lakshmi *et al.,* 2025).

The soil quality concept is closely linked to the pursuit of agricultural sustainability. Evaluation of soil quality in rice ecosystems is essential for understanding and managing factors that influence crop productivity and long-term sustainability. Soil quality assessment is inherently purpose-specific and site-dependent (Karlen *et al.*, 1994). Although the term soil quality is relatively recent, it is well recognized that soils differ in quality and that soil quality is dynamic, responding to land use and management practices. Soil systems are defined by interacting attributes that operate within functional limits (Karlen *et al.,* 1992). Maintaining soil quality at optimal levels is therefore complex due to the combined influence of climatic conditions, soil properties, crop management, and human interventions. This complexity is further intensified in rice-based cropping systems (Atanu Mukharjee and Rattan Lal. 2014).

Materials and Methods

The All India Coordinated Research Project on Long-Term Fertilizer Experiments (LTFE) was initiated at the Regional Agricultural Research Station, Pattambi, in 1997 and has been continued with the primary objective of evaluating the long-term effects of continuous application of plant nutrients (NPK), applied in organic and inorganic forms and in various combinations, on sustainable productivity in a rice-rice cropping system.

The long-term fertilizer experiment (LTFE) comprised twelve treatments, namely, T1: 50 per cent NPK (as per KAU POP recommandation), T2: 100 per cent NPK, T3: 150 per cent NPK, T4 : 100 per cent NPK + 600 kg ha $^{-1}$ $CaCO_3$, T5: 100 per cent NPK, T6: 100 per cent NP, T7: 100 per cent N, T8: 100 per cent NPK + FYM @ 5 t ha $^{-1}$to the *virippu* crop only, T9: 50 per cent NPK + FYM @ 5 t ha $^{-1}$, T10: 100 per cent NPK + *in situ* growing of *Sesbania aculeata* (for *Virippu* crop only), T11 : 50 per cent NPK + *in situ* growing of *Sesbania aculeata* (for *Virippu* crop only) and T12 : Absolute control (No fertilizers or manures). The Package of Practice Recommendation of 90:45:45 kg/ha N, P_2O_5 and K_2O is followed as the 100 per cent Full dose of P fertilizer as Rajphos, ½ dose of N as urea and ½ dose of K as MOP were applied basally. Remaining ½ N and ½ K applied as top dressing at 1 month after basal application. Lime @ 600kg/ha is applied in two splits in T4; 350 kg ha^{-1} at 2 weeks before transplanting and 250 kg ha^{-1} as top dressing after one month after transplanting or 10 days before top dressing of fertilizers. In treatments T10 and T11, *dhaincha* (*Sesbania aculeata*) seeds were sown at a rate of 12.5 kg ha^{-1} and incorporated into the soil during land preparation. Soil samples were collected after the harvest of the *Kharif* crop in 2020 and analyzed for a range of soil physical, chemical, and biological properties.

Formulation of MDS and SQI

Minimum data set (MDS) for soil quality assessment was established with principal component analysis (PCA) (Dunteman, 1989) performed with R software which is the statistics-based model to create soil quality index (SQI). All measured soil properties were compared in PCA, principal components were selected to get a cumulative proportion of more than 80%. In each PC, the parameter with highest loading and those parameters coming within 10% of the highest loading were selected. The minimum data set (MDS) were finally constituted from the selected parameters by considering the correlation aspects between parameters, ease of measurement, logic and interpretability (Andrews *et al*., 2002).

After selecting the indicators for the minimum data set (MDS), nonlinear scoring functions were applied to derive scores for each parameter across different treatments. Based on the nature of the indicators, three standard scoring functions were employed: more is better, less is better, and optimum is better. For indicators classified under the more is better category, each observed value was normalized by dividing it by the maximum value recorded in the entire dataset, thereby assigning a score of 1 to the highest observed value. In the case of less is better indicators, the minimum value in the dataset was divided by each observation, ensuring that the lowest value attained a score of 1. For optimum is better indicators, values up to a defined threshold were scored using the more is better approach, while values exceeding the threshold were scored following the less is better function (Mukherjee and Lal, 2014). The resulting normalized scores, ranging from 0 to 1, were then integrated using a weighted additive method, as described by Liebig *et al*., (2001), to compute the soil quality index for the different LTFE treatments.

$$SQI = \Sigma \text{ weight} \times \text{individual soil parameter score}$$

The computed soil quality index was compared with the theoretical maximum soil quality index derived from the PCA results, and the relative soil quality index (RSQI) for each treatment was calculated and expressed as a percentage.

Results and Discussion

Principal component analysis (PCA) was the statistical method used to develop the minimum data set for soil quality assessment. PCA was performed on standardized 28 soil attributes. The attributes were bulk density, particle density, porosity, maximum water holding capacity, pH, EC, organic carbon, water soluble carbon, permanganate oxidizable carbon, total N, P, K available N, P, K, Ca, Mg, S, B, Fe, Cu, Mn, Zn, dehydrogenase, urease, acid phosphatase, aryl sulfatase and microbial biomass carbon.

In the PCA conducted for 28 variables, four PCs with Eigen value more than one and a cumulative proportion of variance greater than 80% were selected. The four principal components together accounted for 83.1% of the total variability in the dataset. Principal components explaining 7.1% or more of the total variance were retained for further analysis **(Table 1)**. In the PC1 the variables qualified for MDS were microbial biomass carbon, permanganate oxidizable carbon, acid phosphatase, aryl sulfatase, available nitrogen, total nitrogen, and bulk density. In second PC available sulphur was the highly weighed variable. In third PC the highest weighed variable was pH and in fourth PC group porosity was the highly weighed variable.

Suresh *et al*., (2017) identified soil parameters such as bulk density and available sulphur as key components of the minimum data set (MDS) in a long-term fertilizer experiment with 15 years of cropping history and residual effects. In contrast, Saikia *et* *al.,* (2019) emphasized the importance of biological indicators, reporting that enzyme activities including β-glucosidase, cellulase, and phenol oxidase were highly sensitive and reliable parameters for evaluating the Soil Quality Index (SQI) in a rice–wheat cropping system.

Table 1: Total variance explained by PCA

	PC1	PC2	PC3	PC4
Eigen value	14.96	3.759	2.531	2.010
Proportion of Variance	0.534	0.134	0.090	0.071
Cumulative Proportion	0.534	0.669	0.759	0.831

The principal component analysis (PCA) of the soil parameters under twelve nutrient management treatments in the rice–rice cropping system is presented in **(Table 2)**. The results showed that the first principal component (PC1), which accounted for 53.4% of the total variance, exhibited strong positive loadings for microbial biomass carbon, followed by permanganate oxidizable carbon, acid phosphatase, aryl sulfatase, available nitrogen, total nitrogen, and bulk density, all falling within 10% of the highest loading value (0.248). The second principal component (PC2), explaining 13.4% of the variance, showed a high positive loading for available sulphur (9.745). Although bulk density also appeared within the 10% loading range in PC2, it was already represented in PC1. The third principal component (PC3), which explained 9.0% of the variance, had a strong positive loading for soil pH (0.520), with no additional variables meeting the 10% criterion. The fourth principal component (PC4), accounting for 7.1% of the variance, was characterized by a high negative loading for porosity (-0.566). As suggested by Andrews *et al.,* (2002), selection among highly correlated variables may also be guided by their practical applicability. Accordingly, microbial biomass carbon, permanganate oxidizable carbon, acid phosphatase, aryl sulfatase, available nitrogen, total nitrogen, and bulk density were selected for the minimum data set (MDS) from PC1. Available sulphur was chosen from PC2, pH from PC3, and porosity from PC4 as the most influential indicators.

Table 2: Principal component analysis of various soil parameters based on various treatments in LTFE

Parameters	PC1	PC2	PC3	PC4
BD	**-0.242**	-9.315	0.072	-0.098
PD	-0.099	-3.888	-0.137	0.233
Porosity	0.1058	9.149	-0.055	**-0.566**
Max.WHC	0.222	-4.018	-0.029	-0.251
pH	0.071	-6.665	**0.520**	0.001
EC	0.0640	2.392	0.113	0.261
OC	0.027	0.020	-0.109	-0.303
WSC	0.203	-2.017	-0.0150	-0.2113
KMnO4 C	**0.247**	5.951	0.035	0.0495
Avail. N	**0.224**	-1.648	0.1472	-0.071
P	0.160	-3.469	0.026	-0.117
K	0.161	-3.594	-0.055	0.038
Total N	**0.224**	-1.191	-0.0348	-0.209
Total P	0.013	-4.562	0.070	0.200
Total K	0.154	-1.547	-0.407	-0.041
Ca	0.188	-2.00	0.355	-0.038
Mg	0.210	1.93	-0.066	0.214
S	0.211	**9.745**	0.038	0.313
B	0.200	1.894	-0.167	0.068
Fe	0.198	1.196	-0.32	0.154
Cu	0.155	1.495	0.244	-0.182
Zn	0.081	4.998	0.210	0.267
Mn	0.153	2.304	0.183	0.145
DHA	0.204	2.135	0.062	-0.115
Urease	0.219	-1.819	-0.001	-0.051
Phosphatase	**0.245**	1.074	-0.064	-0.067
Sulfatase	**0.234**	4.919	0.203	-0.072
MBC	**0.248**	-5.182	-0.055	-0.055

In our study on a rice–rice cropping system with 23 years of cropping history and residual effects, ten soil parameters representing physical, chemical, and biological properties-available N, total N, $KMnO_4$-oxidizable carbon, pH, available S, acid phosphatase, aryl sulfatase, microbial biomass carbon, bulk density, and porosity-were selected for computing the Soil Quality Index (SQI). These parameters were scored as "more is better" (for nutrients and biological indicators), "less is better" (for bulk density), or "optimum is better" (for porosity). The scores were converted to unitless values, weighted using PCA, and summed to calculate the SQI; the results for each LTFE treatment are presented in **(Table 3)**, with the contribution of each parameter shown in (**Figure 1**).

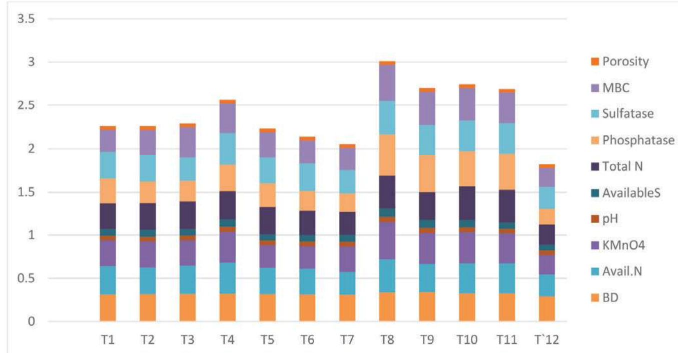

Figure 1: Contribution of each soil attributes in MDS towards SQI as affected by different treatments under LTFE

Table 3: Computed SQI values of different parameters for the treatments in LTFE

Treatments	BD	Avail. N	$KMnO_4$ C	pH	S	Total N	Phospha-tase	Sulfatase	MBC	Porosity
T1	0.315	0.327	0.300	0.052	0.079	0.298	0.286	0.309	0.250	0.041
T2	0.317	0.308	0.303	0.053	0.080	0.313	0.250	0.301	0.289	0.043
T3	0.319	0.328	0.296	0.053	0.076	0.321	0.237	0.268	0.348	0.041
T4	0.323	0.362	0.352	0.060	0.085	0.331	0.300	0.365	0.347	0.043
T5	0.317	0.305	0.265	0.053	0.070	0.311	0.279	0.298	0.290	0.041
T6	0.316	0.296	0.260	0.054	0.076	0.278	0.237	0.313	0.264	0.042
T7	0.313	0.261	0.296	0.053	0.080	0.262	0.223	0.265	0.256	0.041
T8	0.340	0.378	0.434	0.055	0.100	0.381	0.476	0.394	0.412	0.040
T9	0.343	0.321	0.364	0.054	0.093	0.324	0.423	0.350	0.388	0.041
T10	0.327	0.347	0.360	0.055	0.085	0.393	0.404	0.354	0.377	0.043
T11	0.327	0.347	0.348	0.052	0.071	0.383	0.413	0.351	0.360	0.039
T`12	0.294	0.253	0.225	0.055	0.066	0.229	0.179	0.261	0.218	0.038

The SQI values of BD varied from 0.294 (T_{12}-absolute control) to 0.343 (T_9- 50 per cent NPK+FYM). The SQI of available N ranged from 0.253 to 0.378. The highest value of 0.378 was obtained in T_8 where 100 per cent NPK+FYM were applied and the lowest value (0.253) was in T_{12} (absolute control). In permanganate oxidizable carbon the SQI varied from 0.225 (absolute control – T_{12}) to 0.434 (T8- 100 per cent NPK+FYM). SQI of pH ranged from 0.052 in T_1 (50 per cent NPK) and T_{11}(50 per cent NPK + in situ growing of *Sesbania aculeata* (for *Kharif* crop only)) to 0.060 in T_4 (100 per cent NPK+lime @ 600 kg ha $^{-1}$). SQI of available sulphur ranged from 0.066 to 0.100. The highest SQI was observed in T_8 where 100 per cent NPK+FYM applied and lowest in absolute control (T_{12}). In total N SQI varied from 0.229 (T_{12}- absolute control) to 0.393 (T_{10}- 100 per cent NPK + *in situ* growing of *Sesbania aculeata* (for *Kharif* crop only)). The SQI values of acid phosphatse varied from 0.179 (T_{12}- absolute control) to 0.476 (T_8- 100 per cent NPK+FYM). The aryl sulfatase values were ranged from 0.261 (T_{12}) to 0.394 (T_8). In MBC the SQI varied from 0.218 (T_{12}- absolute control) to 0.412 (T_8-100 per cent NPK+FYM). The SQI values of porosity ranged from 0.038 (absolute control - T_{12}) to 0.043. The highest value of 0.043 were observed in T_2 (100 per cent NPK), T_4 (100 per cent NPK + lime @ 600 kg ha^{-1}) and T_{10} (100 per cent NPK + *in situ* growing of *Sesbania aculeata* (for *Kharif* crop only)).

The Soil Quality Index (SQI) values varied from 1.82 to 3.01 across the treatments. A declining trend in SQI was observed in the order: T8 > T10 > T9 > T11 > T4 > T3 > T2 = T1 > T5 > T6 > T7 > T12. With increase in fertilizer load from 50% NPK to 150% NPK there was an increase in SQI. Thus increasing fertilizer levels helped in maintaining SQI. Sharma *et al*., (2005) and Suresh *et al*., (2017) also reported an increasing SQI with increasing level of fertilizers. This increase in SQI with 150% NPK is due to the positive effect of higher dose of fertilizers on certain parameters which came under MDS *i.e,* increased loading of available nitrogen and total nitrogen which came under MDS. In LTFE treatments, highest SQI was recorded by the treatment with integrated use of NPK and FYM (T_8-0.62). However, the SQI was low (0.37) for the absolute control (T_{12}) due to continuous nutrient removal by crop without restitution. Furthermore, the application of 50% NPK, 100% NPK, 150% NPK, 100% NP, and 100% N alone did not result in a substantial improvement in soil quality, indicating a weaker cumulative influence of the soil parameters identified through PCA. In contrast, the integrated application of the recommended dose of fertilizers in combination with organic manure (100% NPK + FYM) was rated as the most effective treatment, as reflected by the highest SQI values among all treatments. A similar advantage of farmyard manure and in situ green manuring in improving crop productivity and soil organic carbon in this rice–rice system was reported earlier by Thulasi *et al.* (2016). The grain and straw yields exhibited a similar response pattern across treatments, further supporting the superiority of integrated nutrient management practices. Comparable findings were reported by Suresh *et al.,* (2017), who also observed the dominance of integrated nutrient management over other fertilizer management strategies in a long-term fertilizer experiment conducted in Telangana.

The computed RSQI values were used for the categorization of different management practices into poor, medium and high soil quality groups. Integration of inorganic fertilizers and balanced applications are the best way for restoring and maintaining soil quality in LTFE and these treatments (T_8), (T_9), (T_{10}), (T_{11}), and (T_4) came under medium soil quality category, as presented in **(Table 4)** and illustrated in **(Figure 2)**. Masto *et al.,* (2007), in a long-term fertilizer experiment conducted at the Indian Agricultural Research Institute, reported that the combined application of NPK fertilizers and organic manures resulted in the highest Soil Quality Index (SQI).

Table 4: Mean RSQI (%) of different treatments of LTFE soil

	RSQI (%)	Soil quality class
T1	46.53	Poor
T2	46.55	Poor
T3	47.19	Poor
T4	52.98	Medium
T5	45.97	Poor
T6	44.04	Poor
T7	42.31	Poor
T8	62.11	Medium
T9	55.69	Medium
T10	56.61	Medium
T11	55.50	Medium
T12	37.49	Poor

Conclusion

In the present study conducted under a rice–rice cropping system with 23 years of continuous cultivation and residual effects, the Soil Quality Index (SQI) values ranged from 1.82 to 3.01. The SQI followed a decreasing trend in the order: T8 > T10 > T9 > T11 > T4 > T3 > T2 = T1 > T5 > T6 > T7 > T12. An increase in SQI was observed with increasing fertilizer levels from 50% NPK to 150% NPK (T1 to T3), indicating a positive response to higher nutrient inputs. Further enhancement in SQI was noted when fertilizer application increased from 50% to 100% NPK in combination with farmyard manure or in situ green manuring, highlighting the role of integrated fertilizer levels in sustaining soil quality.

The relative soil quality index (RSQI) values were used to classify the nutrient management practices into poor, medium, and high soil quality categories. The results demonstrated that integrated and balanced fertilizer applications were more effective in restoring and maintaining soil quality under long-term fertilizer experimentation. Accordingly, the integrated nutrient management treatments (T8, T9, T10, and T11) and the lime-amended treatment (T4) were categorized under the medium soil quality group, while all remaining treatments were classified as poor. Overall, integrated nutrient management practices and lime incorporation contributed to the long-term maintenance of soil quality, whereas the control and fertilizer-only treatments resulted in comparatively lower SQI values.

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