A new index to assess soil quality and sustainability of wheat-based cropping systems

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ORIGINAL PAPER

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A new index to assess soil quality and sustainability of wheat-based cropping systems

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Abstract Sustainability index was calculated to assess soil quality under the influence of different fertilizer management practices. It is based on the area of the triangle in which nutrient index, microbial index and crop index of soil represented the three vertices of a triangle. Nutrient index reflected the nutrient status of soil and was calculated from the measurements of various soil chemical parameters. Microbial index was calculated by determining various soil microbial and biochemical activities and crop index by measuring of crop yield parameters. Eighteen soil indicators were determined to assess nutrient index, microbial index and crop index in order to compare the effect of different sources of nutrients such as green manure, farmyard manure and chemical fertilizer in a rice/corn–wheat rotation. The indices were applied to assess the sustainability of five field experiments with respect to the different fertilizer treatments. The long-term application of organic manures in rice/corn–wheat cropping system increased the index value because it increased the nutrient index, microbial index and crop index of soils. The use of only chemical fertilizers in the rice–wheat cropping system resulted in poor soil microbial index and crop index. In corn–wheat system, additional application of FYM at 10 t ha^{-1} before sowing corn made the system more sustainable than application of 100%NPK; the sustainability index values were 2.43 (the highest for this system) and 0.93, respectively.

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Introduction

Rice–wheat system covers about 32% of total rice area and 42% of the total wheat area in the Indo-Gangetic plains (IGP) and accounts for one quarter to one third of the total rice and wheat production (Ladha et al. 2000). In recent years, the food grain production in rice–wheat system has stagnated or shown a declining trend (Flinn and DeDatta 1984; Cassman and Pingali 1995; Ladha et al. 2000). There are increasing concerns for long-term sustainability of high-input rice–wheat rotation in the IGP. Many long-term experiments conducted at several locations in India have indicated that there is a declining trend in the productivity of rice or wheat or both after a few years of continuous cropping (Hegde and Sarkar 1992; Nambiar 1994; Yadav 1998; Duxbury et al. 2000). The causes for yield stagnation or decline are not well known and may include changes in soil quality parameters.

Several indices have been proposed to assess soil quality, which were mostly microbial in nature. Determination of microbial biomass can be useful if long-term changes in soil quality are monitored (Nannipieri et al. 1990). Nannipieri et al. (2002) discussed two approaches to assess the soil microbial activity: one is the use of single index and the other is based on the measurements of number of soil enzyme activities to estimate microbial functional diversity. He emphasised integrating enzyme activities limiting the rate of metabolic processes. Stefanic et al. (1984) used a weighed average to calculate the biological index of fertility (BIF) given as:

$$\mathrm{BIF} = \frac{\mathrm{DA} + K\mathrm{CA}}{2}$$

where DA and CA represent dehydrogenase and catalase activity, respectively, and K is a proportional coefficient. In another approach, Beck (1984) proposed enzyme activity number (EAN) as biological index based on five different enzymes given by the expression:

$$\mathrm{EAN} = 0.2\left[\mathrm{TPF\ (mg)} + \frac{\mathrm{Catalase\ (\%)}}{10} + \frac{\mathrm{phenol}(\mu\mathrm{g})}{40} + \frac{\mathrm{amino\text{-}N}(\mu\mathrm{g})}{2} + \frac{\mathrm{amylase\ (\%)}}{20}\right]$$

The use of different units of measurement for deriving a single index does not support the universal applicability of such indices. Moreover, the methods used by Stefanic et al. (1984) and Beck (1984) were not as sensitive as currently used to determine enzyme activity in soil (Nannipieri 1994). In case of EAN index, the choice of amylase rather than cellulase activity was also criticized because cellulose is more important than starch in plant residues (Stevenson 1986). These indices do not take into account the content of main nutrients in soil and thus its nutrient-supplying capacity that is important for plant growth. In the present study, we have used a triangular approach to evaluate sustainability of a cropping system emphasising the above-mentioned factors. This approach is based on measurements of soil microbial index (calculated from microbial counts and enzyme activities), soil nutrient index (calculated from organic C, total N, $NaHCO_3$ extractable P, NH_4OAc extractable K and KCl extractable NO_3^-–N and exchangeable NH_4–N contents) and crop index (calculated from dry matter yield and N, P and K uptake by crop).

Materials and methods

The study was conducted on Typic Ustochrept soils of five field experiments at the experimental farm of the Punjab Agricultural University, Ludhiana (30°54′N latitude and 75°27′E longitude) in Punjab, India. These experiments included different fertilizer treatments including the use of sole chemical fertilizers and also the integrated application of organic sources with chemical fertilizers to soil. The details of each experiment comprising of year of start, fertilizer treatments and cropping sequence are presented in Table 1. Soil samples, collected from plough layer (0- to 15-cm depth) prior to the growing of rice or corn crop during the first fortnight of May 2000 were air dried under shade, pounded to break large clods, sieved (<2 mm) and stored at 10°C prior to chemical and biological analysis.

The choice of parameters to be measured has been carried out so as to cover nutrient status, microbial activity and the productivity (crop response) of soil. Most of the selected parameters (Table 2) are listed in the minimum data set (MSD) proposed by Larson and Pierce (1991) for assessing soil health. The methods used for determining the various soil quality indicators are presented in Table 2. The analysis of variance of the data was done by GENSTAT statistical package using complete randomised design.

Nutrient index of soil (NI_i)

The nutrient index was calculated by determining the following chemical parameters: organic C, total N, $NaHCO_3$ extractable P (Olsen et al. 1954), NH_4OAc extractable K (Merwin and Peech 1950) and 2 M KCl extractable NO_3^-–N and NH_4–N contents. In calculating the nutrient index, each parameter value was divided by the respective threshold value (arithmetic mean value of treatments for a parameter in field experiment). Thus each parameter has five calculated threshold values, and each field experiment is being considered as a separate system with a different equilibrium (with respect to nutrient status, microbial activity and productivity). For dry matter yield, a value 20% higher than the arithmetic mean was used as a threshold value (Gomez et al. 1996). The index value of parameter (I_{ij}) calculated by dividing the value by the respective threshold of a parameter is given as:

$$\mathrm{I}_{ij} = \frac{\mathrm{A}_{ij}}{\mathrm{Th}_j}$$

where I_{ij} is the index value for ith treatment corresponding to jth parameter in an experiment, A_{ij} is the actual measured value for ith treatment and jth parameter in an experiment and Th_j is the threshold value for jth parameter.

The nutrient index was calculated as an average of index values (I_{ij}) of all the six parameters in an experiment:

$$\mathrm{NI}_i = \frac{1}{6}\sum_{j=1}^{6}\mathrm{I_{ij}}$$

where NI_i is the nutrient index for ith treatment and j is the number of parameters considered in deriving nutrient index.

Microbial index of soil (MI_i)

Microbial index of soil was calculated as the nutrient index; the measured microbial parameters were microbial biomass C, microbial biomass N, potentially mineralizable N, soil respiration, bacterial population on one fourth potato dextrose agar (PDA) media, mycorrhizal infection of corn roots, dehydrogenase and phosphatase activities. The microbial index for each treatment was calculated as an average of index values of all the eight parameters in each experiment:

$$\mathrm{MI}_i = \frac{1}{8}\sum_{j=1}^{8}\mathrm{I_{ij}}$$

Crop index (CI_i)

A pot experiment was conducted at International Crop Research Institute for Semi-Arid Tropics, Patancheru, India, to determine crop yield and consequently the nutrient-

Table 1 Details of long-term experiments with fertilization approaches

Field experiment	Rotation	Fertilizer treatment	Fertilization detail
Experiment I (1971)[a]	Corn–wheat–cowpea	Control	No fertilizer was applied
		100%NPK	120 kg N ha^{-1}, 26 kg P ha^{-1} and 25 kg K ha^{-1} were applied to corn and wheat and 20 kg N ha^{-1}, 17.5 kg P ha^{-1} and 16.5 kg K ha^{-1} were applied to cowpea
		100%NPK+FYM	Farmyard manure FYM at 10 t ha^{-1} was applied once a year before the sowing of corn in addition to 100%NPK treatment
Experiment II (1982)	Rice–wheat	Control	No fertilizer was applied
		100%NPK	120 kg N ha^{-1}, 26 kg P ha^{-1} and 25 kg K ha^{-1} were applied to rice and wheat each
		GM+FYM	*Sesbania aculeata* green manure (GM) and 60 kg N ha^{-1} were applied to rice and 120 kg N ha^{-1} was applied to wheat 15 t ha^{-1} farmyard manure (FYM) and 80 kg N ha^{-1} to rice and 90 kg N ha^{-1} to wheat were applied (GM and FYM were applied on alternative years)
Experiment III (1983)	Rice–wheat	Control	No fertilizer was applied
		100%NPK	120 kg N ha^{-1}, 26 kg P ha^{-1} and 25 kg K ha^{-1} were applied to rice and wheat each
		50%NPK+50%N (WS)	Wheat straw (WS) at the rate of 6 t ha^{-1} with 60 kg N ha^{-1}, 13 kg P ha^{-1} and 12.5 kg K ha^{-1} were applied to rice and 100%NPK was applied to wheat
		50%NPK+50%N (GM)	*S. aculeata* green manure (GM) and 60 kg N ha^{-1}, 13 kg P ha^{-1} and 12.5 kg K ha^{-1} were applied to rice and 100%NPK was applied to wheat
		50%NPK+50%N (FYM)	6 t of farmyard manure (FYM) and 60 kg N ha^{-1}, 13 kg P ha^{-1} and 12.5 kg K ha^{-1} were applied to rice and 100%NPK was applied to wheat
Experiment IV (1988)	Rice–wheat	Control	No fertilizer was applied
		N120	120 kg N ha^{-1} was applied to the rice crop. 90 kg N+26 kg P+25 kg K ha^{-1} was applied to wheat
		WS+GM	3.85 t ha^{-1} (dry weight) of wheat straw (WS) and 3.5 t ha^{-1} of *S. aculeata* (dry weight) were applied to the rice crop and 90 kg N+26 kg P+25 kg K ha^{-1} was applied to wheat
		FYM+N75	3.8 t ha^{-1} of farmyard manure (FYM) with 90 kg N ha^{-1} was applied to the rice crop and 90 kg N+26 kg P+25 kg K ha^{-1} was applied to wheat
		FYM+GM	Only farmyard manure (FYM) at 3.8 t ha^{-1} and *S. aculeata* green manure at 3.5 t ha^{-1} (dry weight) were applied to the rice crop and 90 kg N+26 kg P+25 kg K ha^{-1} was applied to wheat
Experiment V (1996)	Rice–wheat	Control	No fertilizer was applied to the soil
		100%NPK	120 kg N ha^{-1}was applied to rice and 120 kg N ha^{-1}, 26 kg P ha^{-1} and 25 kg K ha^{-1} were applied to wheat
		100%NPK+2VV	2 t ha^{-1} of rice straw compost[b] (dry weight basis) was applied to both rice and wheat in addition to 100%NPK treatment
		8CC	8 t ha^{-1} of rice straw compost[b] was applied to both rice and wheat

[a]Figures in parentheses show year of start of field experiments
[b]Rice straw compost was prepared from rice straw and rock phosphate inoculated with *Aspergillus awamori* and burying in pit for 2 months

supplying capacity of these soils. In this experiment, corn (variety Deccan 101) grown in the glasshouse was used as an indicator crop. Three plastic pots (20 cm in diameter and 30 cm in height) were filled with 10 kg of each soil and were randomly placed. Three plants were sown in each pot and thinned to one within 1 week, and no weeds were allowed to grow. The plants were regularly watered with deionised water to maintain soil at 50% WHC.

Table 2 Lists of various methods

Measured soil and plant parameters	Method
A. Soil parameter (units of measurement)	
Organic C (%)	Wet digestion method (Walkley and Black 1934, rapid titration method)
Total N (kg ha^{-1})	Modified Kjeldahl method (Dalal et al. 1984)
Mineral N (kg ha^{-1})	Kjeldahl distillation method (Keeney 1982)
	The dried soil was extracted with 2 N KCl and distilled with 0.2 g of MgO and distilled. The distillate containing NH_4 and NO_3^-–N form was titrated against 0.025 N H_2SO_4
Available P (kg ha^{-1})	Colorimetric method (Olsen et al. 1954)
	The dried soil sample was extracted with 0.5 N $NaHCO_3$ (pH 8.5) and then treated with ammonium molybdate and stannous chloride. The intensity of the blue color formed was measured at a wavelength of 660 nm using a red filter
Available K (kg ha^{-1})	Flame photometer method (Merwin and Peech 1950)
	The soil sample was extracted with neutral normal ammonium acetate solution. The filtrate was aspirated into the atomizer of the calibrated flame photometer, and electrical current produced was measured by the galvanometer of the flame photometer
Microbial count of bacteria (log of microbial population per dry weight of soil)	Two-plate method (Rupela and Gopalakrishnan 1999
	Potato 200 g, dextrose 20 g, $MgSO_4$ 200 mg, distilled water 1 l, pH 6.0
Microbial biomass C, MBC (mg per kg)	Chloroform fumigation and incubation method (CFIM) (Jenkinson 1988)
Microbial biomass N, MBN (mg per kg)	Chloroform fumigation and incubation method (CFIM) (Jenkinson 1988)
Soil respiration (mg CO_2–C kg^{-1} 10 $days^{-1}$)	CO_2–C evolution method (Anderson and Domsch 1978)
	The amount of CO_2 evolved during the 10-day incubation period was absorbed by 1 N NaOH
Dehydrogenase activity (μg TPF g^{-1} 24 h^{-1})	Colorimetric method (Casida et al. 1964)
	The measurement of dehydrogenase activity involves determination of triphenyl formazan (TPF) produced by the reduction of 2,3,5-triphenyltetrazolium chloride (TTC), and the intensity of red color was measured at 485-nm wavelength
Phosphatase activity (μg *p*-nitrophenol g^{-1} h^{-1})	Colorimetric method by Eivazi and Tabatabai (1977)
	It determines the enzymatic hydrolysis of *p*-nitrophenyl phosphate to *p*-nitrophenol which was extracted by $CaCl_2$–NaOH solution. The intensity of yellow color of *p*-nitrophenol was measured at 420-nm wavelength
Potentially mineralizable nitrogen, PMN (mg kg^{-1} 7 $days^{-1}$)	Anaerobic incubation method (Keeney 1982)
B. Plant (corn) parameter	
Dry matter yield (g $plant^{-1}$)	The root and shoot samples of plant were dried at 70°C, and the weight of each sample was measured
Plant nutrient uptake (mg $plant^{-1}$)	The plant N, P and K contents were measured as described by Walinga et al. (1989)
Root mycorrhizal infection (%)	The fine roots stained with Trypan blue solution were observed for the presence of vesicles and arbuscules under the microscope at 40× magnification

Fifty-two days after sowing, fine roots (2 g) were carefully washed and analysed for mycorrhiza infection. Both roots and shoots were oven-dried at 70°C for 2 days, and their dry weight was recorded. The crop index of soil was estimated on the basis of dry matter yield and N, P and K uptake by the corn plant. The crop index for each treatment was measured as an average of index values of all the four parameters in each experiment:

$$CI_i = \frac{1}{4}\sum_{j=1}^{4} I_{ij}$$

where CI_i is the crop index for *i*th treatment and *j* is the number of parameters. Of course, I_{ij} was calculated as reported before.

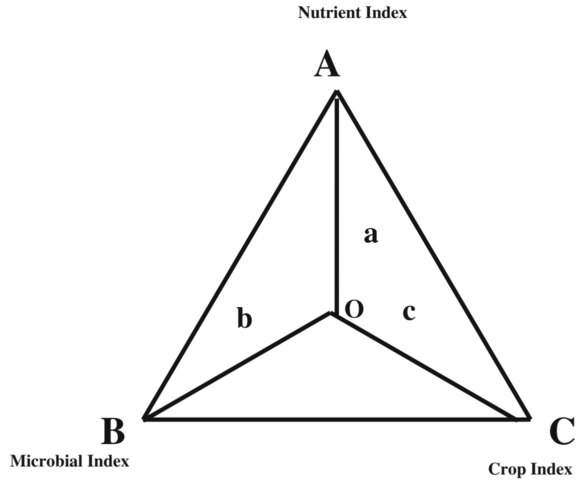

Fig. 1 Measurement of sustainability of system from the triangle area

Sustainability index

The sustainability index of the soil was measured as the area of the triangle with nutrient index, microbial index and crop index of soil at three vertices; they were represented in radar graph as a, b and c, respectively, which are the three lines of different lengths originating from a common point 'O'. By joining the tail ends of these three lines, triangle is formed as shown in Fig. 1. The sustainability index of the system is given as:

$$\begin{aligned}\text{Sustainability of system} &= \text{Area of } \Delta\text{ ABC}\\ &= \text{Area of } \Delta\text{ AOB} + \text{Area of } \Delta\text{ BOC} + \text{Area of } \Delta\text{ COA}\\ &= 1/2\text{ ab }\sin(120^\circ) + 1/2\text{ bc }\sin(120^\circ)\\ &\quad + 1/2\text{ ca }\sin(120^\circ) = \frac{\sqrt{3}}{4}(\text{ab} + \text{bc} + \text{ca}) \qquad (1)\end{aligned}$$

In order to have a sustainable system, the absolute value of each parameter should be equal to or greater than its threshold value, and the sustainability index should be always positive and greater than 1.30; the higher the value, the more sustainable the system. The least value of sustainability index (1.30) is calculated from Eq. 1 by putting the corresponding indices of nutrient status (a), microbial activity (b) and productive potential (c) equal to 1. If there are more than three factors, then polygonal approach can be used to measure the sustainability.

Results and discussion

Nutrient status

The nutrient status considers the instant availability of nutrients in soil. The average values of chemical parameters of soil in each experiment are presented in Table 3. In all the long-term experiments, the application of organic manures significantly increased the soil organic C content (OC), whereas chemical fertilizers had no effect. The increase in soil organic C content can depend on both organic inputs and higher crop residue fall to soil. Bhandari et al. (1992) and Kumar and Yadav (1995) in a rice–wheat cropping system and Sharma et al. (1984) in corn–wheat cropping system also observed an increase in the soil organic C content with application of inorganic fertilizers and FYM.

The results also showed that the Olsen-P content of soil significantly increased with application of organic sources except in experiment II, whereas the effect on total N content was not significant (Table 3). Both NO_3^-–N and NH_4–N contents of soil also increased with the application of organic sources probably as a result of mineralization of organic residues.

The wheat straw proved less effective in increasing the available nutrient status of soil, which may be attributed to wide C/N ratio of wheat straw and its inability to decompose rapidly in the field (Bhandari et al. 1992). The use of chemical fertilizers alone was not effective in improving the nutrient status of soil. Biswas and Benbi (1997) also observed that inorganic N, P and K application for 8 years was unable to sustain crop yield as observed in the initial year of the experiment.

Microbial activity

The application of organic residues increased the number of heterotrophic bacteria grown on one fourth PDA media, microbial biomass C, microbial biomass N, potentially mineralizable N and basal respiration (Table 4). Thus all these parameters were positively affected by the increase in available organic C of soil.

The increase in bacterial numbers in response to chemical fertilizers may be attributed to a better nutrient status of soil. The effect was greater in the green manure treatment. Martynuik and Wagner (1978), Doran (1980), Bolton et al. (1985), Ramsay et al. (1986) and Alleoni et al. (1995) also reported increases in microbial counts in response to fertilization.

The lower effect of chemical fertilization on soil respiration may be attributed to the increased respiratory activity in the control treatment (without any fertilizer) because of low microbial efficiency in using wheat residues by microbes under N stress (Houot and Chaussod 1995). The effect of green manure in improving the microbial biomass, potentially mineralizable N and phosphatase activity, was more pronounced than by FYM and wheat straw treatments, probably because green manure degrades faster than FYM and wheat straw (Beri et al. 1989).

Both dehydrogenase and phosphatase activities were stimulated by the application of organic manures and depressed by inorganic fertilizers. These increases may be attributed to the increase of microbial processes, whereas the decrease in dehydrogenase activity by chemical fertilization may be due to poor physical conditions and lack of organic substrates in soils. Houot and Chaussod (1995),

Table 3 Average values of chemical parameters of soil

	OC (%)	Total N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})	NO_3^-–N (kg ha^{-1})	NH_4–N (kg ha^{-1})
Experiment I						
Control	0.35	1,045	20.5	106.0	28.4	11.7
100%NPK	0.39	1,248	106.9	119.4	35.9	29.6
100%NPK+FYM	0.53	1,408	156.6	155.4	43.9	20.1
Threshold	0.42	1,233.67	94.67	126.93	36.07	20.47
LSD (P=0.05)	0.110	NS	41.72	14.36	NS	12.12
CV (%)	12	11	19	5	18	26
Experiment II						
Control	0.38	1,242	19.6	106.8	26.3	12.5
100%NPK	0.41	1,411	54.4	124.0	36.4	19.5
FYM+GM	0.60	1,645	50.5	123.2	64.8	20.8
Threshold	0.46	1,432.67	41.50	118.00	42.50	17.60
LSD (P=0.05)	0.062	NS	NS	NS	20.14	4.54
CV (%)	5	11	35	17	21	11
Experiment III						
Control	0.47	1,292	33.3	83.6	26.7	12.69
100%NPK	0.50	1,299	34.3	93.4	32.0	14.34
50%NPK+50%N (FYM)	0.63	1,508	150.7	115.0	30.1	15.75
50%NPK+50%N (WS)	0.52	1,236	45.3	79.2	12.2	14.11
50%NPK+50%N (GM)	0.58	1,442	62.3	90.4	46.0	15.61
Threshold	0.54	1,355.40	65.18	92.32	29.40	14.50
LSD (P=0.05)	0.048	NS	39.83	19.76	10.42	NS
CV (%)	5	10	33	11	19	22
Experiment IV						
N_0	0.59	1,266	29.0	100.0	4.1	16.8
N_{120}	0. 64	1,537	37.2	96.4	12.2	13.0
WS+GM	0.66	1,694	27.5	95.6	12.3	20.4
FYM+N_{75}	0.64	1,578	132.0	129.2	18.6	13.7
FYM+GM	0.67	1,668	88.8	107.6	8.1	22.3
Threshold	0.64	1,548.60	62.90	105.76	11.06	17.24
LSD (P=0.05)	0.034	NS	21.28	21.68	8.82	NS
CV (%)	3	5	18	11	42	48
Experiment V						
Control	0.45	981	34.6	90.4	14.5	15.2
8CC	0.62	1,286	61.6	189.6	20.2	10.6
100%NPK+2VV	0.62	1,125	42.2	94.8	20.5	11.5
100%NPK	0.54	1,074	57.1	112	17.4	15. 3
Threshold	0.56	1,116.50	48.88	121.70	18.15	12.43
LSD (P=0.05)	0.079	NS	18.78	28.02	NS	NS
CV (%)	7	11	19	12	17	22

For fertilizer treatments, see Table 1

Gianfreda and Bollag (1996), Manna and Ganguly (1998) and Kandeler et al. (1999) reported the stimulation of microbial biomass, PMN, soil respiration and enzyme activities with the application of chemical fertilizers, farmyard and green manures.

The mycorrhizal infection of the corn roots was significantly (P=0.05) increased by the application of inorganic and organic fertilizers probably because fertilizers stimulate root growth (Jumpponen et al. 1998). Organic fertilizers were more effective than inorganic fertilizers in increasing the root mycorrhizal infection. Among the organic sources, green manure was superior to FYM probably because it contained more available C and N.

Crop yield

The application of inorganic and organic fertilizers improved soil health and thereby increased the yield and nutrient uptake by corn in the pot experiment. The increase in dry matter yield and nutrient uptake was significant with organic fertilization (Table 5). In experiments II, III and IV,

Table 4 Average values of microbiological parameters of soil

	MBC (mg kg^{-1})	MBN (mg kg^{-1})	PMN (mg kg^{-1} 7 $days^{-1}$)	CO_2-C (mg CO_2-C kg^{-1} 10 $days^{-1}$)	Dehydrogenase activity (µg TPF g^{-1} 24 h^{-1})	Phosphatase activity (µg *p*-nitrophenol g^{-1} h^{-1})	Bacterial count (log number)	Mycorrhizal infection (%)
Experiment I								
Control	133.8	45.8	9.13	3.22	99.2	13.9	1.55	37.9
100%NPK	135.1	49.3	10.38	2.46	84.1	15.6	1.91	49.7
100%NPK+FYM	169.7	58.6	13.49	6.38	129.9	20.2	1.95	52.4
Threshold	146.20	51.23	11.00	4.02	104.40	16.57	1.80	46.67
LSD (*P*=0.05)	32.87	12.68	2.766	3.091	NS	NS	NS	12.83
CV (%)	10	11	11	34	28	19	2	12
Experiment II								
Control	142.3	53.5	10.35	3.64	101.2	15.0	1.45	41.7
100%NPK	145.3	51.7	10.39	2.48	92.5	30.4	1.70	46.0
FYM+GM	161.9	63.4	15.98	7.51	153.7	37.6	2.88	62.8
Threshold	149.83	56.20	12.24	4.54	115.80	27.67	2.01	50.17
LSD (*P*=0.05)	16.88	11.09	5.187	1.875	47.78	NS	0.207	17.41
CV (%)	5	9	19	18	18	35	2	15
Experiment III								
Control	141.1	48.3	5.90	4.14	105.6	15.11	1.32	28.6
100%NPK	157.0	50.7	7.27	2.72	82.2	18.27	1.45	34.4
50%NPK+50%N (FYM)	163.0	55.6	13.59	7.35	123.9	23.19	2.09	51.0
50%NPK+50%N (WS)	153.3	52.1	7.11	4.53	105.6	22.88	1.86	49.6
50%NPK+50%N (GM)	172.8	63.1	15.91	5.53	119.0	27.63	2.04	52.0
Threshold	157.4	53.96	9.96	4.85	107.26	21.42	1.75	43.12
LSD (*P*=0.05)	31.82	7.08	3.551	1.979	34.37	6.550	0.117	12.70
CV (%)	11	7	19	22	17	16	1	16
Experiment IV								
N_0	148.4	51.4	6.42	2.48	154.6	18.87	1.38	47.1
N_{120}	150.9	53.1	9.89	2.31	122.9	15.35	1.91	66.4
WS+GM	155.7	57.2	10.09	4.00	141.7	28.10	2.40	65.5
FYM+N_{75}	152.1	55.3	13.93	7.12	133.7	20.06	1.95	60.8
FYM+GM	158.4	61.2	15.96	6.38	169.9	23.31	2.63	70.3
Threshold	153.10	55.64	11.26	4.46	144.56	21.14	2.05	62.02
LSD (*P*=0.05)	NS	NS	5.528	2.373	NS	3.811	NS	13.28
CV (%)	13	13	26	28	14	10	2	11
Experiment V								
Control	140.7	50.5	5.24	2.68	60.7	16.27	0.89	32.8
8CC	161.8	54.8	11.91	6.92	109.8	19.50	1.23	62.9
100%NPK+2VV	164.2	58.5	14.57	4.92	69.6	18.89	1.55	56.4
100%NPK	155.7	53.4	6.74	2.20	57.0	18.46	1.51	44.7
Threshold	155.60	54.30	9.62	4.18	74.28	18.28	1.30	49.20
LSD (*P*=0.05)	NS	NS	2.579	1.562	35.18	NS	0.15	15.66
CV (%)	12.18	9.52	13	19	24	9	1	16

For fertilizer treatments, see Table 1

MBC Microbial biomass C, *MBN* microbial biomass N, *PMN* potentially mineralizable N

application of green manure improved N uptake probably due to its narrow C/N ratio that favoured N mineralization (Beri et al. 1989).

Generally, results of the pot experiment confirm those obtained under field conditions. For example, the average grain yield of rice and wheat in experiment IV treated with FYM+GM for 12 years were increased from 3.81 to 5.52 Mg ha^{-1} and from 4.37 to 4.71 Mg ha^{-1}, respectively, over control (Yadvinder-Singh et al. 2004). The increase in average wheat grain yield of experiment III changed from 4.39 to 4.53 Mg ha^{-1} when 50% of the fertilizer-N was replaced by FYM-N (Bhandari et al. 1992). Mineralization of organic manures may be responsible for such increases in crop yields. Another cause might be the solubilizing

Table 5 Average values of yield parameters

	Dry matter yield (g plant^{-1})	N uptake (mg plant^{-1})	P uptake (mg plant^{-1})	K uptake (mg plant^{-1})
Experiment I				
Control	7.0	46.6	8.1	79.6
100%NPK	11.0	48.8	20.7	90.6
100%NPK+ FYM	21.5	112.2	50.8	234.9
Threshold	15.80	69.20	26.53	135.03
LSD (*P*=0.05)	8.14	43.26	18.8	71.0
CV (%)	21.00	28	31	23
Experiment II				
Control	12.1	76.8	12.7	137.6
100%NPK	18.2	108.8	25.5	205.8
FYM+GM	31.4	198.9	34.2	219.9
Threshold	24.68	128.17	24.13	187.77
LSD (*P*=0.05)	12.82	90.01	NS	NS
CV (%)	33	31	31	45
Experiment III				
Control	11.3	72.7	10.5	150.4
100%NPK	20.8	121.8	23.5	168.1
50%NPK+ 50%N (FYM)	26.7	139.5	46.8	281.8
50%NPK+ 50%N (WS)	9.7	60.7	11.8	117.9
50%NPK+ 50%N (GM)	27.8	166.5	37.0	223.5
Threshold	23.11	112.24	25.92	188.34
LSD (*P*=0.05)	5.84	45.25	6.58	57.18
CV (%)	16	21	14	16
Experiment IV				
N_0	12.5	69.3	19.5	162.0
N_{120}	15.7	80.6	20.1	133.2
WS+GM	22.7	122.3	26.9	203.6
FYM+N_{75}	22.5	101.5	49.4	247.7
FYM+GM	25.2	136.3	40.1	242.9
Threshold	23.66	102.00	31.20	197.88
LSD (*P*=0.05)	8.36	40.84	16.0	68.56
CV (%)	23	21	27	18
Experiment V				
Control	15.1	77.1	16.1	159.5
8CC	22.5	116.5	28.9	375.0
100%NPK+2VV	35.2	182.4	38.9	402.8
100%NPK	24.0	141.3	22.2	138.9
Threshold	29.04	129.33	26.53	269.05
LSD (*P*=0.05)	18.92	NS	NS	NS
CV (%)	39	39	46	46

For fertilizer treatments, see Table 1

action of organic acids produced during the degradation of organic materials. Moreover, the increase in mycorrhizal infection due to the addition of organic manures also improved the supply of nutrients particularly P.

Sustainability index

In experiment I, the treatment with farmyard manure (100% NPK+FYM) added to soil for 29 years was the most sustainable for the corn–wheat system. On the contrary, the 100%NPK treatment was unsustainable for the same cropping system (Table 6). Biswas and Benbi (1997) observed that N, P and K applications were unable to sustain high yields, but they did not discuss the underlying mechanism, even if they observed zinc deficiency. The lack of sustainability of the inorganic fertilizer-treated plots was due to the low microbial (0.91) and crop (0.71) indices. On the contrary, the application of farmyard manure that increased the soil organic matter content gave higher nutrient (1.25),

Table 6 Sustainability indices in the various long-term field experiments

Treatment	Nutrient index	Microbiological index	Crop index	Sustainability index
Sustainability indices in 29-year-old experiment in corn–wheat cropping system (experiment I)				
Control	0.68	0.86	0.50	0.59
100%NPK	0.92	0.91	0.71	0.93
100%NPK+ FYM	1.25	1.22	1.66	2.43
Sustainability indices in 18-year-long experiment in rice–wheat cropping pattern (experiment II)				
Control	0.73	0.81	0.59	0.65
100%NPK	1.03	0.87	0.93	1.16
FYM+GM	1.24	1.32	1.35	2.20
Sustainability indices in 17-year-old continuous experiment in rice–wheat system (experiment III)				
Control	0.84	0.79	0.59	0.70
100%NPK	0.92	0.81	0.95	1.03
50%NPK+50% N (FYM)	1.32	1.19	1.42	2.24
50%NPK+50% N (WS)	0.80	0.98	0.51	0.73
50%NPK+50% N (GM)	1.12	1.22	1.33	1.93
Sustainability indices in 12-year-old continuous experiment in the rice–wheat cropping system (experiment IV)				
N_0	0.75	0.80	0.66	0.70
N_{120}	0.89	0.86	0.69	0.86
WS+GM	0.96	1.05	1.01	1.31
FYM+N75	1.30	1.08	1.20	1.84
FYM+GM	1.10	1.21	1.23	1.80
Sustainability indices in 4-year-old experiment in the rice–wheat cropping system (experiment V)				
Control	0.86	0.76	0.58	0.69
8CC	1.17	1.21	1.04	1.69
100%NPK+ 2VV	0.97	1.14	1.40	1.75
100%NPK	1.03	0.88	0.82	1.07

For fertilizer treatments, see Table 1
FYM Farmyard manure, *WS* wheat straw, *GM* green manure

microbial (1.22) and crop (1.66) indices than the application of inorganic fertilizers, thus making the system more sustainable (sustainability index of 2.43).

The nutrient, microbial and crop indices were 1.24, 1.32 and 1.35, respectively, in the FYM+GM treatment of the rice–wheat system of experiment II, with a sustainability index of 2.20 (Table 6). In the 100%NPK treatment, both microbial (0.87) and crop (0.93) indices were low making soils unsustainable. The control soil was characterized by the lowest indices (Table 6).

The rice–wheat system of experiment III was made sustainable by replacing 50% of the inorganic fertilizer N with farmyard manure and green manure N (Table 6). On the contrary, the system was unsustainable when chemical fertilizer alone or wheat straw was added to soil with a sustainability index lower than 1.0.

The combined application of farmyard manure and fertilizer N (25% applied as FYM-N and 75% as urea-N to rice) for 12 years in experiment IV gave the highest sustainability index (1.84). When N was applied as farmyard and green manure, the sustainability index decreased to 1.80.

In experiment V, the application of 8 t of rice straw compost for 4 years gave a sustainability index of 1.69 for the rice–wheat cropping system. Application of chemical fertilizer with 2 t of rice straw compost (100%NPK+2VV) gave a sustainability index of 1.75. Application of chemical fertilizer alone (100%NPK) resulted in an unsustainable system due to low microbial (0.88) and crop (0.82) indices of soil (Table 6).

Conclusions

We have proposed a new approach to assess the sustainability of soil under wheat-based cropping system. This approach consists of calculating a sustainability index from the area of a triangle, where the three vertices are represented by the nutrient, microbial and crop index, respectively.

The sustainability of the rice/corn–wheat cropping system was increased significantly by organic inputs as farmyard manure, rice straw compost or green manure for a number of years. These organic applications increased nutrient status, microbial activity and productive potential of soil. On the other hand, the use of only chemical fertilizers in the cropping system resulted in a poor microbial activity and productive potential of soil.

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