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Research article

A 25-year record of carbon sequestration and soil properties in intensive agriculture

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Abstract – As a major carbon pool on earth, soil organic carbon may act either as a sink or a source of atmospheric CO_2, a greenhouse gas. Soil organic carbon is also impacting fertility, and, in turn, crop yields. However, knowledge of the impact of cropping techniques on the long-term behavior of soil carbon is scarce. Several studies have shown that continuous cropping decreases soil organic carbon stocks, rapidly in the initial years then at a slower rate, approaching a new equilibrium after 30 to 50 years. For instance, a study of intensive corn cropping for 35 years on temperate soils showed a 50% decrease in soil organic carbon. Our study is located in the North Indian state of Punjab. It is the most intensively cultivated region in the country with a cropping intensity of 190%, predominantly of a rice-wheat system. Due to high nutrient demand and its continuous cultivation, the cropping system is presumed to adversely affect soil organic carbon and other soil properties. However, this has been postulated without any real-time data analysis on a regional scale. Therefore, we evaluated soil data for 25 years from 1981/82 to 2005/06 to investigate the impact of intensive agriculture on C sequestration and soil properties on a regional scale. The results showed that, unexpectedly, intensive agriculture has resulted in improved soil organic carbon (SOC) status. As a weighted average for the whole state, SOC increased from 2.9 g kg^{-1} in 1981/82 to 4.0 g kg^{-1} in 2005/06, an increase of 38%. Increased productivity of rice and wheat resulted in enhanced C sequestration in the plough layer by 0.8 t C ha^{-1} per ton of increased grain production. Soil pH declined by 0.8 pH units from 8.5 in 1981/82 to 7.7 in 2005/06. This pH decline has positive implications for availability of phosphorus and micronutrients such as Zn, Fe and Mn. Changes in plant-available P in soil were related to the amount of fertilizer P applied. The status of available P in soils increased from 19.9 kg ha^{-1} in 1981/82 to 29.2 kg P ha^{-1} during 2005/06. The status of plant-available K in soil remained almost unaltered and averaged 106 and 123 mg kg^{-1} soil in 1981/82 and 2005/06, respectively. The analysis showed that intensive cultivation of a rice-wheat system unexpectedly resulted in improved C sequestration, a favorable pH environment and amelioration of the soil salinity.

carbon sequestration / soil quality / soil pH / available nutrient status / intensive agriculture / rice-wheat sustainability / yield

1. INTRODUCTION

Soils constitute the largest pool of actively cycling C in terrestrial ecosystems and stock about 1500–2000 Pg C in various organic forms to a depth of 1 m (Nieder and Benbi, 2008). It has been estimated that cultivated cropland soils of the world have lost 41 to 55 Pg C in the past (Houghton and Skole, 1990; Paustian et al., 1998). Several studies have shown that conversion of forest lands to permanent cropping decreases the soil organic carbon stocks, rapidly in the initial years and at a slower rate thereafter, approaching a new equilibrium after 30 to 50 years (Mann, 1986; Balesdent et al., 1988; Arrouays et al., 1995; Nieder and Benbi, 2008). Arrouays and Pelissier (1994) demonstrated that soil organic carbon (SOC) storage in the 0–50 cm soil horizon declined by about 50% after 35 years of intensive corn cropping in temperate soils. Decline in organic matter content of tropical soils due to continuous cultivation has also been reported in some studies (Brown and Lugo, 1990; Lugo and Brown, 1993). Bernoux et al. (2006) suggested that any modification of land use or land management can induce variations in soil carbon stocks, even in agricultural systems that are perceived to be in a steady state.

The North Indian state of Punjab is the most intensively cultivated region in the country with a cropping intensity of about 190 percent, meaning thereby that, on average, 1.9 crops are harvested per unit area per year. Rice-wheat is the dominant cropping system occupying a 2.5-million-hectare (mha) area of the state, constituting 78 per cent of the gross cropped area. In the last three decades, the area under the two crops has increased tremendously, resulting in the replacement of N-efficient cereals, pulses and legumes by the less N-efficient rice-wheat system. This system occupies around 13.5 mha in the Indo-Gangetic Plains (IGP) of Bangladesh, India, Nepal and Pakistan and 10.3 mha in China (Ladha et al., 2000). Globally, the two crops contribute 45 percent of the digestible

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energy and 30 percent of the total protein in the human diet, as well as a substantial contribution to feeding livestock (Evans, 1993).

Both rice and wheat are exhaustive feeders, and the cropping system is heavily depleting the soil of its nutrient content. A rice-wheat sequence that yields 7 t ha^{-1} of unhusked rice and 5 t ha^{-1} of wheat removes more than 300 kg N, 30 kg P and 300 kg K per ha from the soil. Even with the recommended rate of fertilization in this system, a negative balance of the primary nutrients still exists (Singh et al., 2000). The system, in fact, is now showing signs of fatigue and is no longer exhibiting increased production with increases in input use. The nutrient-use efficiency of the added fertilizers is dropping; so the farmers must add increasing amounts of fertilizer in order to merely maintain yields. For example, the partial factor productivity of NPK for food grain production has dropped from 80.9 in 1966–67 to 16.0 kg food grain per kg NPK application in 2003–04 (Benbi et al., 2006). Questions are now being raised about the sustainability of the rice-wheat cropping system in Indian Punjab.

The underlying reasons for decline or stagnation of crop yields are not precisely known, though it has been attributed to changes in quantity and quality of soil organic matter, and a gradual decline in the supply of soil nutrients, causing macro- and micronutrient imbalances (Ladha et al., 2000). Studies by Bhandari et al. (2002) and Regmi et al. (2002) attributed the reduced productivity of the rice-wheat system, *inter alia*, to declining soil organic matter (SOM) content and decreased soil fertility. However, the concerns about declining SOM and soil fertility are either hypothesized or extrapolated from limited data sets. While some reports (Abrol et al., 2000; Duxbury, 2001) on temporal trends of rice and wheat yields in the region are available, there are no real-time trends on C sequestration and soil properties vis-à-vis intensive agriculture at regional or smaller levels of spatial aggregation available. We analyzed the soil test data of cultivators' fields from the North Indian state of Punjab for the last 25 years with the aim (i) of studying the impact of intensive agriculture, predominantly with the rice-wheat system, on C sequestration and changes in soil properties and (ii) of evaluating if there is any relationship between productivity of the rice-wheat system and soil C sequestration. The recommendations derived from this study may contribute to sustainability in the rice-wheat system of the Indo-Gangetic Plains.

2. MATERIALS AND METHODS

2.1. Site characteristics

The North Indian state of Punjab, located between 29°30' and 32°32'N latitude and 73°55' and 76°55'E longitude, has a subtropical, semiarid and monsoonal climate with topography varying from sand dunes to piedmont plains. The average monthly air temperature ranges between 13 °C in January and 34 °C in June. Annual rainfall ranges from 1250 mm in the North to 350 mm in the Southwest. More than 70 percent of the annual rainfall occurs during the monsoon season from July to September.

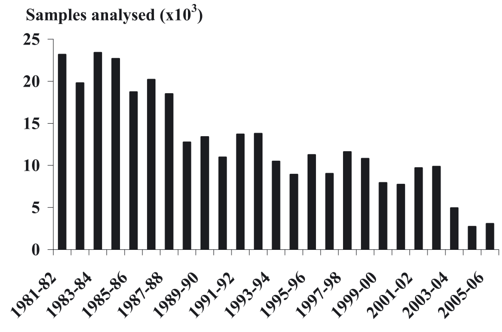

Figure 1. Number of soil samples analyzed during the years 1981/82 to 2005/06.

The soils of Punjab have developed on alluvium brought from the Himalayas by the rivers of the Indus systems. The soils are generally rapidly percolating, coarse-textured and poorly structured. Soil moisture regimes are udic, ustic, and aridic, whereas the soil temperature regime is mainly hyperthermic. An intensive and irrigated agriculture is followed in this region, which is a major contributor to the country's cereal pool. About 97 percent of the cultivated area in the state is irrigated by ground- or canal water. General fertilizer management practices include application of 120 kg N ha^{-1} (through urea) to irrigated rice, maize and wheat. For rainfed crops, the fertilizer dose is reduced to 80 kg N ha^{-1} for maize and wheat. In addition to N fertilizers, P and K are applied on a soil test basis.

The Soil Testing Laboratory at Punjab Agricultural University, Ludhiana, receives soil samples for soil fertility evaluation and fertilizer recommendations from the farmers' fields across the whole of the North Indian state of Punjab. During the last 25 years, 1981/82 to 2005/06, a total of 0.319 million soil samples have been analyzed in the Soil Testing Laboratory (Fig. 1). The samples, which were drawn from the plough layer (0–20 cm), were air-dried and ground to pass a 2-mm sieve. Soil samples were analyzed for pH (1:2 soil : water suspension), electrical conductivity (1:2 soil : water supernatant), organic carbon (Walkley and Black, 1934), 0.5M $NaHCO_3^-$ extractable P (Olsen et al., 1954) and 1N ammonium acetate (AmOAc)-extractable K (Merwin and Peech, 1950). The samples analyzed during a given year were categorized into different classes, based on soil test values, with respect to pH, electrical conductivity (EC), soil organic carbon (SOC), Olsen P and AmOAc-K. With respect to pH the samples were grouped into pH less than 6.5, 6.5–8.7, 8.7–9.3 and greater than 9.3. With respect to electrical conductivity the samples were categorized into less than 0.8, 0.8–1.6, 1.6–2.5 and greater than 2.5 dS m^{-1} classes. Electrical conductivity less than 0.8 dS m^{-1} is considered safe for all types of crops, 0.8–1.6 is considered marginal, where only moderately salt-tolerant crops such as barley, wheat, millet, mustard and spinach can be grown, and EC more than 1.6 dS m^{-1} is considered harmful for all types of crops (Gupta and Abrol, 1990). As per the soil fertility evaluation and fertilizer recommendations

Table I. Soil test limits for classifying the soils into different categories.

Soil property	Very low	Low	Medium	High	Very high
Organic carbon ($g\ kg^{-1}$ soil)	<2	2–4	4–7.5	7.5–9.0	>9.0
Olsen P ($mg\ kg^{-1}$ soil)	<2	2–5	5–9	9–20	>20
Ammonium acetate K ($mg\ kg^{-1}$ soil)		<46	46–112	>112	

in the state, soils containing less than 4.0 $g\ kg^{-1}$ organic carbon are classified as low, 4.0–7.5 $g\ kg^{-1}$medium and greater than 7.5 $g\ kg^{-1}$ as high in fertility, particularly for supplying nitrogen to the growing crops (Tab. I). Soils containing less than 5 $mg\ kg^{-1}$ Olsen P are classified as low, 5–9 $mg\ kg^{-1}$ as medium and greater than 9 $mg\ kg^{-1}$ as high in plant-available phosphorus. Similarly, the rating limits for potassium are less than 46, 46–112 and greater than 112 $mg\ K\ kg^{-1}$ (Muhr et al., 1965). The general fertilizer recommendations in the state are made for medium category soils, and for low and high category soils the fertilizer dose is increased or decreased by 25 percent.

In order to evaluate the overall effect of cropping and agricultural management on soil properties over the years, a weighted average for each soil property was calculated for each year. The weighted average for a given soil property in a year was calculated by multiplying the middle value of a soil test category (Tab. I) by the number of samples falling into that category, adding up the products and dividing by the total number of samples analyzed in a given year (Eq. (1)).

$$X_{WA} = 1/n\Sigma X_i \times f_i \quad (1)$$

where X_{WA} represents the weighted average for a given soil property, X, such as soil pH, EC, SOC, Olsen P or AmOAc-K; X_i is the middle value of X in the ith category; f_i is the frequency, i.e. the number of samples falling into the ith category, and n is the total number of samples analyzed in the year. In the highest category the middle value for a property was chosen based on the maximum soil test value obtained for that property during any year. The middle values chosen for the highest category were 9.5 $g\ kg^{-1}$ for SOC, 25 $mg\ kg^{-1}$ for P, 200 $mg\ kg^{-1}$ for K, 9.6 for pH and 3.0 $dS\ m^{-1}$ for EC.

Linear and power functions were fitted to the time trends in soil properties and crop productivity by the least squares method (Gomez and Gomez, 1976). The significance of the regression coefficients was tested at the 5% level of probability ($P < 0.05$) and only the regressions with significant variables and coefficient of determination (R^2) are presented. Carbon input to the soil from rice-wheat cropping was computed based on crop grain yields, their harvest index taking a grain: straw ratio of 1:1.5 for wheat and 1:2.2 for rice (Beri et al., 2003) and carbon concentration in root biomass, stubble and rhizodeposition. There is little addition of straw from the two crops in the field as 82 percent of the rice straw is burnt in the fields and about 5 percent is used for fodder. Of the wheat straw 59% is used for fodder, 17% is burnt in the fields and the rest is removed from the field for other purposes (Beri et al., 2003). Based on crop yields and the root biomass reported for rice (Kukal et al., 2008b) and wheat (Gajri and Prihar, 1985) grown in the region, it was estimated that roots constitute 10 and 15 percent of the aboveground biomass in wheat and rice, respectively. Stubble and rhizodeposition constitute 2.5 and 15 percent, respectively, of the total aboveground rice biomass harvested at maturity. The corresponding values for wheat stubble and rhizodeposition are 3.0 and 12.6 percent, respectively (Bronson et al., 1998; Majumder et al., 2007). The carbon concentrations in root biomass, stubble and rhizodeposition have been reported to be 41.2, 38.1 and 74 percent for rice and 39.1, 35.2 and 74 percent for wheat, respectively (Majumder et al., 2007).

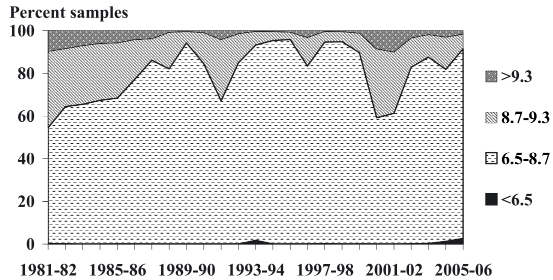

Figure 2. Frequency (%) of soil samples falling into different pH classes during the years 1981/82 to 2005/06 in soils of Indian Punjab.

3. RESULTS AND DISCUSSION

3.1. Soil pH

The soils were generally alkaline in reaction, and the frequency distribution of soil samples in various pH classes during the 25-year period showed that the number of samples in the pH 6.5–8.7 class increased, and that in the 8.7–9.3 and greater than 9.3 classes generally declined with time (Fig. 2). During the period 1981/82 to 1984/85 around 54 to 67 percent of the samples had pH between 6.5 and 8.7, while during 2002/03 to 2005/06 about 81–89 percent of the samples fell into this class. During 1981/82 to 1984/85, 33–46 percent of the samples had pH greater than 8.7, while during the period 2002/03 to 2005/06 the percentage had declined to around 9–19 percent with only 1.6–3.4 percent of the samples having pH greater than 9.3. The weighted average for soil pH showed that with progressive increase in years of rice-wheat cultivation the soil pH declined by 0.8 pH units; from 8.5 in 1981/82 to 7.7 in 2005/06 (Fig. 3). A power function best described the relationship between soil pH and years of rice-wheat cropping (Eq. (2))

$$\text{Soil pH} = 8.49t^{-0.031} \quad R^2 = 0.82 \quad (2)$$

where t represents the number of years.

The decline in soil pH with years of cropping may be attributed to soil submergence during the rice-growing period and use of the urea form of fertilizer over the years. It is well known that when an aerobic soil is submerged, its pH decreases during the first few days (Ponnamperuma, 1972),

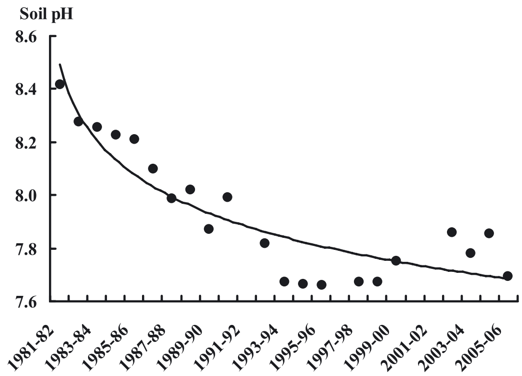

Figure 3. Weighted average of soil pH during the years 1981/82 to 2005/06 in the soils of Indian Punjab. Points indicate measured values and the smooth line represents the best fit to the power function: $y = 8.491x^{-0.031}$, $R^2 = 0.818$.

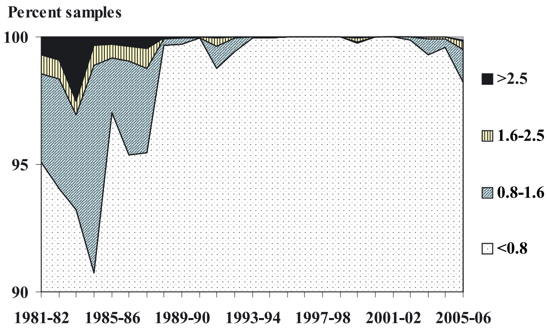

Figure 4. Frequency (%) of soil samples falling into different electrical conductivity (EC, ds m^{-1}) classes during the years 1981/82 to 2005/06 in soils of Indian Punjab.

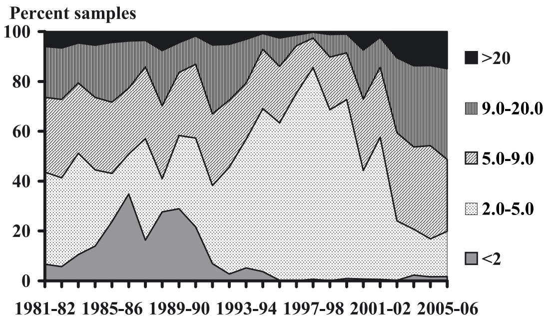

Figure 5. Frequency (%) of soil samples falling into different classes of $NaHCO_3$-extractable P concentration in soil (mg kg^{-1} soil) during the years 1981/82 to 2005/06 in Indian Punjab.

subsequently reaches a minimum, and then increases asymptotically to a fairly stable value of 6.7–7.2 a few weeks later. The overall effect of submergence is to increase the pH of acid soils and to depress the pH of sodic and calcareous soils. Thus, submergence makes the pH values of acidic soils and alkaline soils converge to 7. Draining and exposure to air reverse the pH changes in paddy soils. Apparently, repeated submergence and the use of the urea form of N fertilizer over the years resulted in a pH change that did not reverse to the original value. The decrease in pH is further magnified due to the build-up of soil organic matter. Organic matter has been reported to magnify the decrease in pH of sodic and calcareous soils (Ponnamperuma, 1972). The decrease in pH has implications for the availability of phosphorus and micronutrients. Phosphorus availability is greatest in the pH range 6.5–7.5 and the availability of micronutrients such as Zn, Cu, Fe and Mn increases with decrease in pH. The decline in the frequency of samples having pH greater than 9.3 shows that the problem of alkalinity that affected 6–10 percent of the soils during the early 1980s in the state has virtually been ameliorated. This has generally been caused due to reclamation of alkaline soils through application of gypsum along with keeping the soil flooded with water. Cultivation of rice has helped to some extent as the submerged conditions helped to leach the soluble salts to deeper layers. The results show that long-term intensive cultivation of rice-wheat cropping has resulted in a favorable pH environment by decreasing the pH of alkaline soils, leading to increased nutrient availability in soils and reclamation of the alkaline soils.

3.2. Electrical conductivity (EC)

There has been not much change in the electrical conductivity of the soils and more than 90 percent of the samples had EC less than 0.8 dS m^{-1} (Fig. 4). In the initial period of study, viz. 1981/82 to 1987/88, between 2 and 8 percent of the samples had EC ranging from 0.8 to 1.6 dS m^{-1}; subsequently, almost all the samples had EC less than 0.8 dS m^{-1}. The weighted average for the state showed that over the years the soil EC virtually remained unaltered, ranging between 0.40 and 0.50 dS m^{-1}. Low EC values indicate that soils in the state do not suffer from salinity.

3.3. Available phosphorus

The available, $NaHCO_3$-extractable, P status during the period 1981/82 to 1997/98 generally declined and the frequency of samples with a P concentration ranging between 2 and 5 mg P kg^{-1} increased (Fig. 5). During 1981/82, the first year of the study, approximately 37 percent of the samples contained between 2 and 5 mg P kg^{-1} as compared with around 85 percent of the samples in the same class during 1997/98. Correspondingly, the number of samples in the medium and high classes declined. However, since 1998/99 the trend has been reversed and the frequency of samples in the 2 to 5 mg kg^{-1} class decreased and that in the medium to high and very high classes increased. The weighted average for available P in soils showed that its content decreased from 19.9 kg ha^{-1} in 1981/82 to 10.5 kg ha^{-1} in 1997/98. Thereafter, the available P content in soil progressively increased to 29.2 kg P ha^{-1} during 2005/06 (Fig. 6).

The changes in soil P status were related to the amount of fertilizer P used (Fig. 6). The three years' moving average provided similar curves for soil P content and fertilizer P applied. As the fertilizer use decreased from 19.1 kg fertilizer P ha^{-1} in

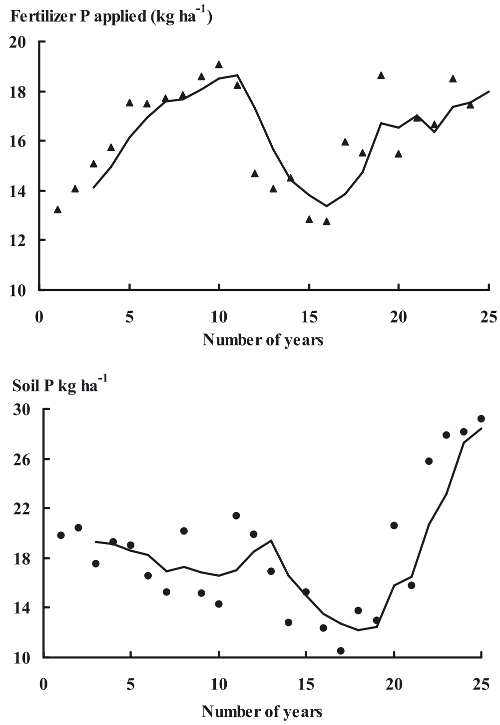

Figure 6. Changes in weighted average of soil P status as compared with fertilizer P applied during the 25-year period of 1981/82 to 2005/06. The lines indicate a 3-year moving average.

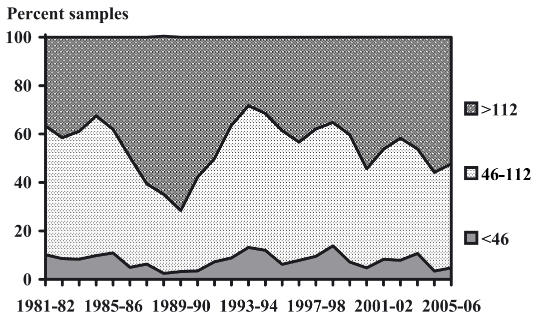

Figure 7. Frequency (%) of soil samples falling into different K fertility classes (mg kg^{-1} soil) during the years 1981/82 to 2005/06 in soils of Indian Punjab.

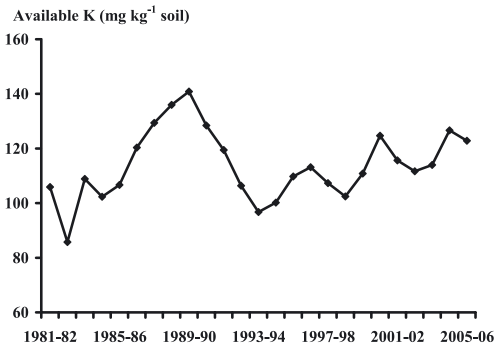

Figure 8. Weighted average of available K content in soil during the years 1981/82 to 2005/06 in Indian Punjab.

1990–91 to 12.8 kg ha^{-1} in 1996–97 the available P content in soils declined from 21.4 to 10.5 kg P ha^{-1} during the period. Subsequent to 1996/97, as the fertilizer P use progressively increased to 17.5 kg P ha^{-1} the available P status of soils improved to 29.2 kg P ha^{-1}. It is well known that the efficiency of fertilizer P use is low, generally ranging between 20–30 percent of the applied P and the unused fertilizer P accumulates in the soil. Results of long-term experiments on rice-wheat and maize-wheat cropping systems from this region have shown that with continuous application of P-containing fertilizers for 12 to 22 years the initial low status of available P in soil was raised to high and very high commensurate with P application (Benbi and Biswas, 1999; Rekhi et al., 2000). The results of our study show that continuous application of phosphatic fertilizers leads to build-up of soil P status commensurate with the amount of fertilizer applied annually. Therefore, to attain high fertilizer P-use efficiency the soil P status must be regularly monitored so that the fertilizer P application rates may be adjusted accordingly.

3.4. Available potassium

The status of available K did not change appreciably during the 25 years of study, with the exception of the period 1986/87 to 1991/92, during which the K fraction greater than 112 mg K kg^{-1} soil increased (Fig. 7). During the initial years of study, i.e. 1981/82 to 1984/85, 8.4 to 10.2 percent of the samples were low in available K and contained less than 46 mg K kg^{-1} soil, 49.9 to 57.7 percent of the samples were in the medium category containing between 46 and 112 mg K kg^{-1}, and 32.5 to 41.5 percent of the samples were in the high category containing more than 112 mg K kg^{-1} soil. However, during the period 1985/86 to 1989/90 the frequency of samples in the medium category progressively declined from 51 to 25.2 percent with a proportional increase in the high category; from 38.0 to 71.6 percent. In the subsequent period of 1990/91 to 1993/94, the frequency of samples in the medium category again increased to 58.4 percent in 1993/94 and that in the high category decreased to 28.3 percent. The increase in the status of available K in soils during 1986/87 to 1991/92, followed by its decrease to the initial level, could be associated with the transformation processes of micaceous minerals present in soils of the region. As the intensity of removal of K by plants progresses, micas, especially illite, which is a clay-size mica constituent, show the tendency of edge and layer weathering processes. These processes in the beginning hold K^+ along the preferential weathering plane with lower selectivity coefficients than illites. Thus, K^+ ions can be exchanged with NH_4^+ more easily than when they were held with a high energy level in the wedge zones of mica particles. Once these K^+ ions are exchanged freely, sites become slowly accessible to other hydrated ions, and ultimately percent K saturation becomes an important player (Fanning et al., 1989). With the fall in K saturation percent, available K, which is fundamentally exchanged by NH_4^+, falls to the original level.

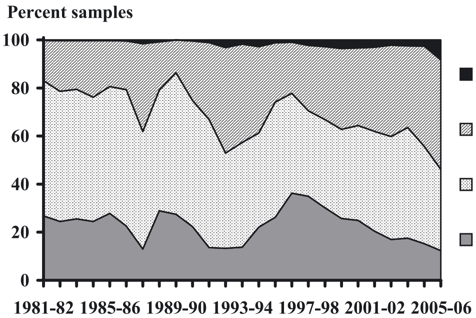

Figure 9. Frequency (%) of soil samples falling into different SOC classes (g kg^{-1} soil) during the period 1981/82 to 2005/06 in soils of Indian Punjab.

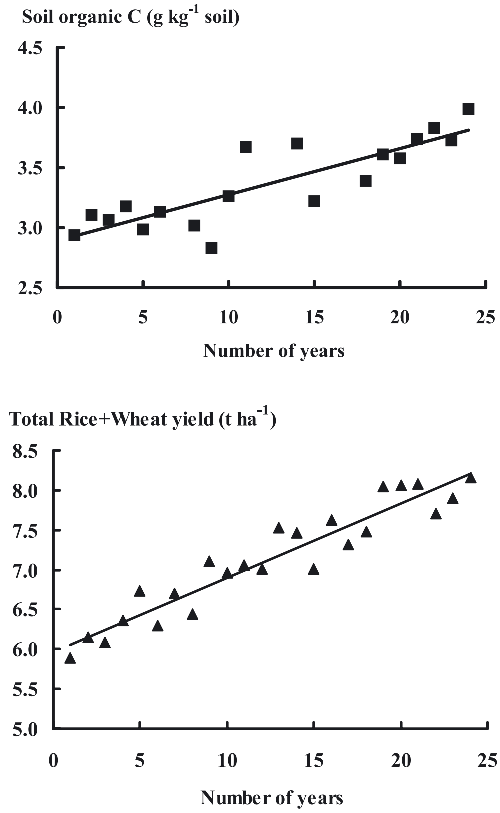

Figure 10. Temporal trends in weighted average of soil organic carbon (SOC) and total rice plus wheat grain yield during the 25-year period, viz. 1981/82 to 2005/06 in soils of Indian Punjab. Points indicate measurements and the line represents the best fit to the linear regression: SOC = 2.89 + 0.038x, R^2 = 0.728 and Yield = 5.968 + 0.0931x, R^2 = 0.902.

The weighted average for the available K content in soils showed that it did not change appreciably and ranged between 106 mg kg^{-1} in 1981/82 and 123 mg K kg $^{-1}$ soil in 2005/06 (Fig. 8). This happened despite removal of about 25 kg K per tonne of rice-wheat grain production. The generally unaltered available K status of soils may be ascribed to the addition of substantial amounts of potassium through irrigation water in the rice-wheat system and the state of K-bearing minerals in soils. The K content of groundwater in the state averages 6.2 mg L^{-1} and it is estimated that around 93 kg K ha^{-1} is added annually through 20 irrigations of 7.5 cm each applied to the rice-wheat system (Brar and Chhibba, 1997). In the soils of Punjab, muscovite and biotite are the dominant K-containing minerals in sand and silt fractions and illite is the most dominant mineral in the clay fraction, followed by vermiculite (Brar et al., 2008), which release substantial amounts of non-exchangeable K towards K uptake by plants. This results in depletion of non-exchangeable K in soils, as observed by Benbi and Biswas (1999), and Mavi and Benbi (2007). Benbi and Biswas (1999) did not observe a change in available K status of soil despite a negative balance of K, based on the approach of an input-output relationship in 22 cycles of maize-wheat-fodder-cowpea cropping, indicating significant depletion of non-exchangeable K. Depletion of soil K has been suggested as a general cause for yield decline in long-term rice-wheat experiments in Asia (Ladha et al., 2003). The results of the study suggest that the prevalent fertilizer practices in the region failed to build up the potassium status of the soil, and there appears to be continuous release of K from non-exchangeable reserves due to intensive rice-wheat cropping. Therefore, 1N ammonium acetate-extractable K, which represents water-soluble and exchangeable K together, may not be a good indicator of plant-available K in soil unless it is augmented with non-exchangeable K.

3.5. Soil organic carbon (SOC)

Frequency distribution of samples in different SOC classes showed (Fig. 9) that during the study period the number of samples falling into the low category, viz. less than 4 g kg^{-1}, generally decreased with corresponding increase in the medium, 4–7.5 g kg^{-1}, and high, greater than 7.5 g kg^{-1}, categories. During the period 1981/82 to1984/85, more than 52 to 56 percent of the samples contained 2–4 g kg^{-1}SOC, whereas during 2002/03 to 2005/06 only 33.7–46 percent of the samples fell into this class. The frequency of samples falling into the medium and high categories during the periods 1980/81 to 1985/86 and 2000/01 to 2005/06 increased from 16.8–23.4 to 33.9–45.6 percent and 0.2–0.4 to 2.2–8.3 percent, respectively. The weighted average for SOC showed that it increased from 2.94 g kg^{-1} in 1980/81 to 4.0 g kg^{-1} in 2004/05 (Fig. 10). Ignoring data for some outliers showed that there existed a linear relationship between the weighted SOC content and years of rice-wheat cropping (Eq. (3)),

$$\mathrm{SOC} = 2.891 + 0.038t \quad R^2 = 0.73 \tag{3}$$

where SOC represents soil organic carbon (g kg^{-1} soil) and t is the number of years.

These results are in contrast to earlier reports (Abrol et al., 2000) that attributed the declining trend in crop production of the rice-based cropping system in Indo-Gangetic Plains in India to the declining C contents in soil. Our analysis does not support the above view: rather, we have observed that the fertilized rice-wheat cropping being followed in the state has resulted in an improved SOC level. Results of long-term experiments have also shown that with optimum application of inorganic fertilizers, the SOC content has either been maintained or slightly increased over the years (Biswas and Benbi, 1997). The increase in C content in soil as observed in this study was firstly due to the progressive increase in the productivity of the rice-wheat cropping system, and secondly due to the soils being under flooded conditions for 3–4 months under rice crops, which retarded the rate of C oxidation in soils. The rate of soil organic matter decomposition is lessened in lowland rice fields, apparently due to excessively reduced conditions (Watanabe, 1984). Because of the lack of oxygen under submerged conditions even a modest oxygen demand for microbial activity cannot be met if large pores are filled with water, resulting in a decreased rate of decomposition (Jenkinson, 1988). Therefore, there is incomplete decomposition of organic materials and decreased humification of organic matter under submerged conditions, resulting in net accumulation of organic matter in soils (Sahrawat, 2004). Bronson et al. (1998) indicated a possible conservation of or increase in C stocks in soil in the lowland tropics due to the relatively slow rate of soil C mineralization under anaerobic conditions. Recently, Kukal et al. (2008a) reported that continuous cultivation of rice-wheat cropping improved soil organic carbon content by 1.7–6.2 $g\,kg^{-1}$ in the 60-cm soil profile. The increase was greater by 30–50 percent under a rice-wheat as compared with a maize-wheat cropping system.

The increase in SOC content was significantly ($P < 0.05$) related to the increase in rice-wheat productivity (Fig. 10). On the other hand, improvement in SOC could have also influenced productivity of the succeeding crops positively. The total rice and wheat productivity during the 25-year period increased linearly from 5.9 $t\,ha^{-1}$ in 1981/82 to 8.1 $t\,ha^{-1}$ in 1999/00. Since the year 2000/01 the productivity of the cropping system has either slightly declined or stagnated around 8.2 $t\,ha^{-1}$. However, the SOC content during the period 2000/01 to 2004/05 increased from 3.6 to 4.0 $g\,kg^{-1}$ soil. Apparently, the stagnating productivity was not related to SOM though the increased SOC levels per se did not counteract the observed stagnation in crop yield. Earlier, Duxbury (2001) also reported that the increase in SOM content or addition of organic inputs did not affect the sustainability of a rice-wheat system in long-term experiments and in the northwestern Indian states of Punjab and Haryana. The results of our study show that enhanced soil fertility and convergence to near neutral pH encouraged the restoration and accumulation of carbon in agricultural soils.

3.6. Crop productivity and C sequestration

The relationship presented in Figure 11 shows that a one tonne increase in productivity of the rice-wheat system resulted in an increase of 0.38 g SOC kg^{-1} soil in the plough layer. Assuming a bulk density of 1.5 $g\,cm^3$ for the 0–15 cm plough layer, a one tonne increase in total productivity of rice and wheat resulted in a sequestration of 0.85 $t\,C\,ha^{-1}$. Considering the area and productivity of other cereal crops, such

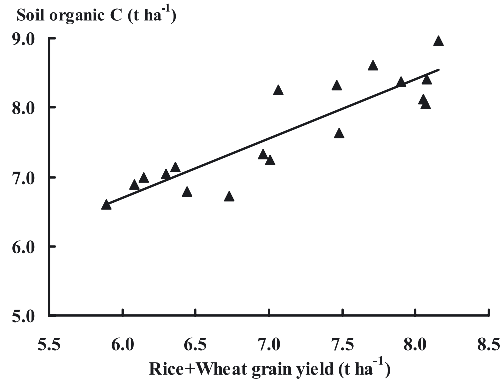

Figure 11. Relationship between soil organic carbon (SOC) stocks in the plough layer and total rice and wheat grain yield during the 25-year period. Points indicate measurements and the line represents the best fit to the linear regression: SOC = 1.589 + 0.852x, R^2 = 0.789.

as maize in summer and barley in winter, grown in the region along with rice-wheat, a slightly lower C sequestration rate of 0.79 $t\,C\,ha^{-1}$ per tonne of cereal productivity was obtained (Eq. (4)).

$$\text{SOC}\ (t\,ha^{-1}) = 2.098 + 0.794 \times \text{Cereal productivity} \quad R^2 = 0.782 \quad (4)$$

The relatively greater C accumulation under rice-wheat as compared with the total cereals is because of its high productivity, resulting in greater C input to the soil and anaerobic conditions prevailing during the rice season. For 25 years' average rice-wheat productivity of 7.2 $t\,ha^{-1}\,year^{-1}$, the calculated C transport belowground could be 3.29 $t\,C\,ha^{-1}$ (Tab. II). This includes 1.93 $t\,C\,ha^{-1}$ from rice and 1.37 $t\,C\,ha^{-1}$ from wheat. Assuming that 70 percent of the root biomass and rhizodeposits are in the plough layer, total C input to the plough layer from rice-wheat is estimated to be 2.4 $t\,C\,ha^{-1}$. These estimates are similar to those of Kuzyakov and Domanski (2000), who reported that on average, 1.5 $t\,C\,ha^{-1}$ is translocated into the soil by cereals during a single vegetation period. The authors (Kuzyakov and Domanski, 2000), based on a literature survey, found that on average, cereals transfer 20–30 percent of total assimilated C into the soil. Half of this amount is subsequently found in the roots and about one-third in CO_2 evolved from the soil by root respiration and microbial utilization of root-borne organic substances. The remaining part of belowground translocated C is incorporated into the soil microorganisms and soil organic matter. Our results indicate that about 26 percent of C transported to the soil accumulates in the plough layer and the remainder is emitted from the soil by root and microbial respiration. It may be added here that these are rough estimates to get an insight into the C input and accumulation balance under intensive rice-wheat cropping. Comparison of these estimates with those from several published studies suggests that differences occur due to the stage of growth of the plant, the environmental conditions, soil type and microbial activity. Using data from long-term experiments can further refine the estimates for the C budget.

Table II. Average rice and wheat grain yield and estimated C input through root biomass, stubble and rhizodeposition (t ha^{-1}) during 1981 to 2005.

Parameter	Rice	Wheat	Total
Grain yield	3.34 (± 0.27)	3.83 (± 0.51)	7.17 (± 0.78)
Aboveground biomass	10.67 (± 0.86)	9.58 (± 1.28)	20.26 (± 1.91)
Root C	0.66 (± 0.05)	0.37 (± 0.05)	1.03 (± 0.09)
Stubble C	0.09 (± 0.01)	0.10 (± 0.01)	0.19 (± 0.02)
Rhizodeposition	1.18 ((± 0.10)	0.89 (± 0.12)	2.08 (± 0.19)
Total C input	1.93 (± 0.16)	1.37 (± 0.18)	3.29 (± 0.30)

Figures in parenthesis indicate standard deviation.

Because of historic losses of C from soils, agricultural soils have significant capacity to mitigate atmospheric CO_2 through enhanced C sequestration. Management practices that increase C input to the soil and decrease output/losses of C lead to C sequestration in soils. Practices that increase C input to the soil include return of aboveground or belowground biomass to the soil, exogenous supply of organic materials, intensification of agriculture and adoption of agroforestry systems. A management practice that decreases decomposition or soil respiration such as reduced or no-tillage, mulch farming, reduced bare fallow, etc. will reduce C losses from soil (Nieder and Benbi, 2008). The results of our study reveal that intensive cultivation of a rice-wheat system enhanced C sequestration due to improved crop productivity, greater belowground C transport to the soil and reduced organic matter decomposition during the wetland rice season.

4. CONCLUSIONS

The analysis of 25 years' data has shown that intensive cropping, predominantly with rice-wheat, had no adverse effect on SOC and other soil properties. The results of the study clearly show that:

(1) rice-wheat cropping in alkaline soils creates a favorable pH environment by lowering soil pH towards neutrality. During the 25-year period, the soil pH declined from 8.8 to 7.7, which resulted in enhanced soil nutrient availability, especially that of phosphorus and micronutrients.

(2) Cultivation of wetland rice coupled with the adoption of reclamation measures helped in amelioration of soil salinity.

(3) Continuous application of phosphatic fertilizers led to build-up of soil P, and the magnitude of accumulation was proportional to the amount of fertilizer applied. Therefore, to achieve higher fertilizer P-use efficiency, the soil P fertility should be regularly monitored and doses readjusted according to soil P status.

(4) The prevalent fertilizer practices in the region failed to sustain soil K status and it appears that there is continuous release of K from non-exchangeable reserves. In soils that are dominated by micaceous minerals, ammonium acetate-extractable K may not be a good indicator of soil K fertility status and should be augmented with non-exchangeable K. To calculate the potassium input-output balance in the soil-plant system, it is essential to account for the contribution from irrigation water towards K input.

(5) Contrary to common belief, intensive rice-wheat cropping did not result in depletion of soil organic carbon, but it yielded improved SOC concentration by 38 percent, from 2.9 g kg^{-1} to 4.0 g kg^{-1}, over the 25-year period.

(6) Intensive cultivation of an irrigated and optimally fertilized rice-wheat system led to C sequestration due to improved crop productivity and greater C transport to the soil. A one tonne increase in productivity of the rice-wheat system improved SOC by 0.38 g kg^{-1} soil. Therefore, intensive cultivation is a viable strategy for biotic C sequestration in agricultural soils and for mitigating CO_2 emissions to the atmosphere.

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