



## Effects of carbon input on soil carbon stability and nitrogen dynamics



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### ABSTRACT

Improved understanding of the process of carbon (C) stabilization is critical to managing emissions from agricultural soils and optimizing crop yield. We assessed soil organic C (SOC) stability and nitrogen (N) dynamics in a long-term fertilization experiment (started in 1972) conducted at three different locations in India (Jabalpur-Vertisol, Palampur-Alfisol and Ranchi-Alfisol). We measured soil organic C (SOC), C pools and stocks in the treatments of no fertilization as control, inorganic fertilization as NPK and integrated fertilization as NPK + farm yard manure (FYM). Quantification of different SOC pools was done by a procedure of acid hydrolysis followed by a long-term (247 days) incubation study. Based on crop yield and C storage, NPK + FYM was the best treatment for improving crop productivity and SOC sequestration. Integrated fertilization for 38 years increased SOC across sites. In the NPK treatment, additional C input (3–9 times higher) in the form of root biomass did not significantly change C pools. Application of FYM in addition to NPK enhanced the acid non-hydrolysable fraction of SOC across sites. Stability of SOC significantly influenced N dynamics in soil and the availability of N in soil is correlated with the amount of C in the acid-hydrolysable pool ( $R^2 = 0.64$ ,  $p = 0.01$ ) but not with SOC ( $R^2 = 0.12$ ,  $p = 0.01$ ). Long-term use of chemical fertilizers did not significantly affect soil total N content.

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### 1. Introduction

Carbon (C) stabilization in soil is critical to influencing the global C cycle. Magnitude of the stable C pool of soil organic matter (SOM) must be increased to enhance soil C sequestration and increase its mean residence time (MRT) (Paul et al., 1997). While soil C pools with different stabilities and turnover rates are important indices to detect the influence of agricultural management on soil quality (Silveira et al., 2008), it is the physical protection of SOM that enhances the MRT (Dungait et al., 2012). Soil organic carbon (SOC) can be stabilized by different mechanisms including selective preservation of biochemically recalcitrant molecules, spatial inaccessibility of SOC for decomposers and enzymes (Dungait et al., 2012) and interactions of SOC with surfaces and metal ions (von Lütow et al., 2008).

Different methods exist to quantify stable forms of SOC (Six et al., 2002; Paul et al., 1997). Acid hydrolysis is used to preferentially remove young, potentially biodegradable compounds and

assess the old or passive C fraction (Leavitt et al., 1996; Paul et al., 1997, 2001). The non-hydrolysable fraction in soil includes old C (Trumbore et al., 1996; Paul et al., 1999). Using  $^{14}\text{C}$  dating, Paul et al. (1997, 2001) reported that non-hydrolysable C can be 1300 years older than total soil C in the surface soil layer. Therefore, determination of bio-chemically more stable C (acid non-hydrolysable pool or resistant C) would serve as an indicator for measuring the impact of long-term management interventions on soil C sequestration. In addition, changes in the acid hydrolysable fraction is an earlier indicator of management effects on SOM pool (Franzuebbers and Stuedemann, 2002; Banger et al., 2009). Hence, isolation and quantification of operationally measured fractions e.g. acid hydrolysable and non-hydrolysable (stable or resistant) C pools provide valuable information to understand SOC dynamics and the underlying mechanisms for specific management practices (Belay-Tedla et al., 2009).

Consumption of nitrogen (N) fertilizer in India has increased since 1960, along with a strong increase in crop yields. Response of soil C pools to long-term N fertilization is known for temperate agro-ecosystems (Neff et al., 2002; Swanston et al., 2004) and effects of long-term N fertilization on soil C and N dynamics are contradictory. While some have observed decline in soil C following long-term application of N fertilizer (Mulvaney et al., 2009),

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others have reported increase with balanced chemical fertilization (Bharadwaj and Omanwar, 1994; Schjonning et al., 1994; Hati et al., 2008). Paustian et al. (1997) described several mechanisms of SOC storage in response to crop residue incorporation and N fertilization, but concluded that much unexplained variation exists between field experiments. Soils of agro-ecosystems of India, inherently low in C and N concentrations, may respond differently to N fertilization than those of the temperate environment. Some studies have reported increase in C sequestration with the use of N fertilizer because of increase in C fixation with increase in photosynthesis (Bharadwaj and Omanwar, 1994; Schjonning et al., 1994; Jagadamma et al., 2007; Hati et al., 2008). Thus, judicious land management practices also enhance the SOC pool (Reay et al., 2007). However, the magnitude of increase and its allocation among different fractions is not understood. The long-term fertilizer experiments in India, initiated in 1972 under diverse climate and soil conditions, offer an opportunity to study the impact of chemical fertilization and manuring on soil C and N dynamics. The hypothesis tested in this study was that long-term fertilization and manuring increases SOC concentration and affects N availability. Therefore, the present study was conducted to assess the long-term impact of chemical fertilization and manuring on SOC and N pools in diverse agroecoregions.

## 2. Materials and methods

### 2.1. Description of long-term fertilizer experiment

A long-term fertilization experiment (LTFE) on arable land in India was established in 1972 in different agro-climatic regions of north and central India under sub-humid climatic conditions (Fig. 1 and Table 1). The Palampur site is located in the mid hills of the western Himalayas under the mountain climatic zone. The other two sites are located in typically sub-tropical climate with hot and wet summer and mild winter. The LTFE at Jabalpur (Vertisol), Ranchi (Alfisol) and Palampur (Alfisol) sites have 10 treatments replicated 4 times and laid out in a randomized block design. However, the present study focused on 3 treatments: no fertilization as control, inorganic fertilization as NPK and integrated fertilization as NPK + farm yard manure (FYM). Response to these treatments was assessed for a double cropping system. Soybean (*Glycine max.*) and maize (*Zea mays*) were grown as rain-fed crops during the rainy season while wheat (*Triticum aestivum*) was cultivated as an irrigated crop during the winter. Soybean-wheat was the cropping sequence studied at Jabalpur and Ranchi; and maize-wheat was the cropping sequence at Palampur. Tillage systems for these sites were those

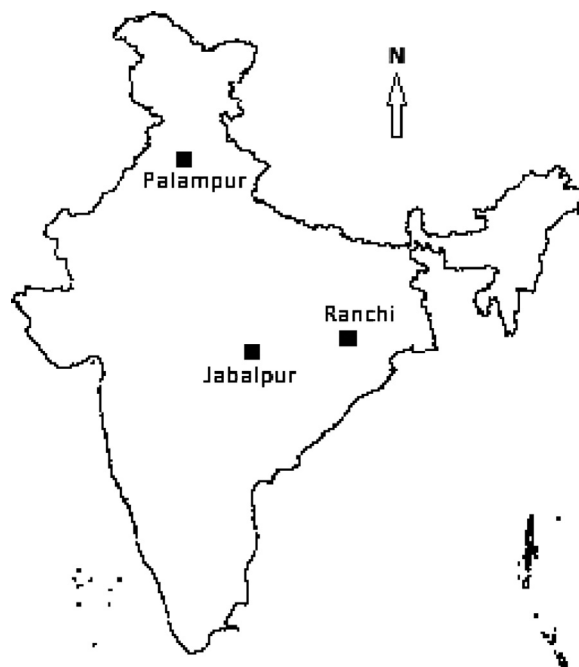


Fig. 1. Location of sampling sites.

practiced in each region, and are conventional tillage involving a plough-based system is widely practiced under these conditions.

NPK was applied at the recommended rate for each site and crop. The annual application rate of N ranged from 105 to 270 kg ha<sup>-1</sup> across sites (Table 2). Manure was applied before seeding of the maize or soybean crop once a year for all sites. The Vertisol at Jabalpur was clayey in texture having neutral to slightly alkaline pH. It is classified as fine montmorillonitic hyperthermic family of Typic Haplusterts (Soil Survey Staff, 2010). The Alfisol at Ranchi is acidic red loam (dominant clay 1:1 type, Kaolinite) and classified as hyperthermic mixed Typic Paleustalfs. However, the Alfisol at Palampur (Alfisol) is acidic silty loam and taxonomically classified as Typic Hapludalfs.

### 2.2. Sampling and analysis

Soil samples from each replicate were collected from 0 to 15 cm depth for each site during May–June 2010. Samples collected from several locations in each replicate were composited, air-dried,

**Table 1**  
Main site characteristics of the three long-term fertilizer experiments in India.

Site characteristics	Jabalpur (Vertisols)	Palampur (Alfisols)	Ranchi (Alfisols)
State	Madhya Pradesh	Himachal Pradesh	Jharkhand
Latitude/longitude	23° N 10' E, 79° N 57' E	32° N, 76° E	23° N 17' E, 85° N 19' E
Climate	Humid subtropical	Montane	Humid subtropical
Altitude (m)	411	1280	625
Mean annual temperature (°C)	25	18	23
Mean annual rainfall (MAR)	1386	2157	1450
Experiment start year (duration)	1972 (38)	1972 (38)	1972 (38)
Plot size (m <sup>2</sup> )	184	15	100
Soil classification	Typic Haplusterts (Vertisol)	Typic Hapludalf (Alfisol)	Typic paleustalf (Alfisol)
pH (1.2.5)	7.6	5.8	5.3
Initial organic C (g kg <sup>-1</sup> )	5.7	7.9	4.5
Available N (kg ha <sup>-1</sup> )	193	736	295
Total N (mg kg <sup>-1</sup> )	845	–	500
Sand (g 100 g <sup>-1</sup> )	25	30	66
Silt (g 100 g <sup>-1</sup> )	18	46	9
Clay (g 100 g <sup>-1</sup> )	57	24	25
Textural class	Clay	Silty loam	Sandy clay loam
Bulk density (Mg m <sup>-3</sup> )	1.30	1.31	1.36

**Table 2**  
Treatment details and doses of mineral fertilizer and organic manure in long-term fertilizer experiments.

Treatments	Nutrients	Jabalpur Soybean-Wheat	Palampur Maize-Wheat	Ranchi Soybean-Wheat
Control	N (kg ha <sup>-1</sup> )	0	0	0
	P (kg ha <sup>-1</sup> )	0	0	0
	K (kg ha <sup>-1</sup> )	0	0	0
	FYM (Mg ha <sup>-1</sup> Y <sup>-1</sup> )	0	0	0
NPK	N (kg ha <sup>-1</sup> )	20, 120	120–150, 90–120	25, 80
	P (kg ha <sup>-1</sup> )	34.93, 34.93	26–43.5, 26–52.5	26.2, 26.2
	K (kg ha <sup>-1</sup> )	33.33, 33.33	33.3–83.3, 25.0–50.0	33.3, 33.3
	FYM (Mg ha <sup>-1</sup> Y <sup>-1</sup> )	0	0	0
NPK+FYM	N (kg ha <sup>-1</sup> )	20, 120	120–150, 90–120	25, 80
	P (kg ha <sup>-1</sup> )	34.93, 34.93	26–43.5, 26–52.5	26.2, 26.2
	K (kg ha <sup>-1</sup> )	33.33, 33.33	33.3–83.3, 25.0–50.0	33.3, 33.3
	FYM (Mg ha <sup>-1</sup> Y <sup>-1</sup> )	15	10	15

NPK were applied through urea, single super phosphate/di-ammonium phosphate and muriate of potash, respectively. Fertilizer rate for double crops are separated by comma (,). FYM-farm yard manure (on dry weight basis).

gently ground and sieved through a 2-mm sieve. A part of each sample was finely ground and passed through 0.25 mm sieve for measurements of SOC, and total nitrogen (TN). Data on soil bulk density were obtained from the annual report of the LTFE centers and these data, along with soil C concentration, were used to compute soil C pool (Mg ha<sup>-1</sup>, 0–15 cm). At the beginning of the experiment (38 years ago), SOC was determined by the wet combustion method (Walkley and Black, 1934). For comparison, therefore, initial SOC was estimated by a regression equation between SOC and wet combustion data on soil C for each site (Jha et al., 2014). The relationship has  $R^2$  value of 0.99 ( $p = 0.0001$ ). Soils sampled in 2010 were analyzed for SOC concentration by the dry combustion method (Nelson and Sommers, 1996) using a Shimadzu SOC (total organic carbon) analyzer (SSM5000A). Since these soils contain less than 0.02% of inorganic C, total C was assumed equivalent to SOC. Soil TN was determined by the method described by Black (1965). Soil available N for plants (alkaline  $\text{KMnO}_4$  oxidizable N) was determined by the method of Subbiah and Asija (1956). Briefly, 10 g of soil was treated with 0.32% alkaline  $\text{KMnO}_4$  solution and distilled  $\text{NH}_3$  was collected in a boric acid solution. The available N concentration was determined by back titration of boric acid with dilute HCl.

### 2.3. Crop and FYM derived C input to soil

C input values for two cropping systems on the LTFE sites were derived from 38 years (1972–2010) of the harvest yield data (Annual Report-LTFE). Empirical equations were developed to estimate crop residue and FYM-derived C inputs (Chander et al., 1997; Johnson et al., 2006). Carbon input to soil was estimated by assuming the harvest index (HI) of 0.45, 0.45 and 0.50 for soybean, wheat and maize, respectively (Johnson et al., 2006) and mean C content of 0.45 kg C kg<sup>-1</sup> in shoot and root (Chander et al., 1997). Similarly C input through FYM was assumed with mean C content of 0.16 kg C kg<sup>-1</sup> of dried FYM (Kundu et al., 2007).

### 2.4. Carbon mineralization and determination of soil organic carbon pools

A C-mineralization experiment (incubation study) was conducted for 247 days using soil samples collected from 0 to 15 cm depth for the selected treatments (control, NPK and NPK + FYM) from all three locations. Moisture content of 100g air-dry soil adjusted to 60% of water-holding capacity (WHC) prior to its incubation in an air tight flask at a constant temperature (25 °C). The amount of C mineralized was determined by a titrimetric method. The  $\text{CO}_2$  evolved was trapped in 10 ml of 1 M NaOH contained in a

vial placed inside the flask. Each treatment was replicated 3 times for each sampling date. The vials were removed periodically at 2, 4, 7, 10, 14, 21, 28, 36, 52, 94 and 247 days after initiating the incubation study, and titrated with standardized 0.5 M HCl after addition of 1 ml of saturated  $\text{BaCl}_2$  using phenolphthalein as a visual indicator. The amount of  $\text{CO}_2$ -C evolved was calculated by using Eq. (1).

$$\text{CO}_2\text{-C evolved (mg kg}^{-1}\text{)} = (A - B) \times N \times 6 \quad (1)$$

where,  $A$  and  $B$  are the volume of HCl consumed for titrating 10 ml of 0.5 M NaOH in control (flask without soil) and amended soil,  $N$  is the normality of HCl and 6 is the equivalent weight of C.

The SOC pool was divided into 3 components (active, slow and resistant). Resistant organic C (acid non-hydrolysable fraction) was determined using the method suggested by Rovira and Vallejo (2007). Briefly, one g of oven-dry sieved (0.25 mm) soil was hydrolyzed with 25 ml of 6 M HCl at 110 °C for 18 h with occasional shaking. After cooling, the un-hydrolyzed residue was recovered by centrifuging at 20 °C. The process of centrifugation and decantation was repeated several times with de-ionized water until samples were free from chloride. Residues were then transferred to pre-weighed vials, dried at 60 °C to the constant weight, and total C was measured by a dry combustion technique using a Shimadzu total organic carbon analyzer (SSM5000A). The C in active + slow pool, also known as the acid-hydrolysable pool, was computed by subtracting acid non-hydrolysable fraction (bio-chemically stabilized C) from the SOC concentration. The SOC pools are divided into active and slow pools according to their turnover time on the assumption that a negligible amount of  $\text{CO}_2$  is evolved from the acid non-hydrolysable fraction ( $C_r$ ) during the incubation period (Paul et al., 1997). Separation of active and slow pools was done using the double decomposition model. The size and turnover rates of each pool were estimated by curve fitting the  $\text{CO}_2$  evolved per unit of time ( $C_t$ ) using a two-component model (Paul et al., 1997) shown in Eq. (2):

$$C_t = C_a e^{-k_a t} + C_s e^{-k_s t} \quad (2)$$

where,  $C_t$  is sum of active ( $C_a$ ) + slow pool carbon ( $C_s$ ) pools;  $C_a$  and  $C_s$  are the sizes of the active and slow carbon pools and  $k_a$ , and  $k_s$  are the decay constants of respective pools.

### 2.5. Model fitting and statistical analysis

The double decomposition equations fitted with the non-linear regression (SPSS window version) was used in the Marquardt algorithm. The parameter values that could minimize the residual sum of squares were determined by an iterative process. The analysis of

**Table 3**  
Mean crop yield ( $\text{kg ha}^{-1} \text{Y}^{-1}$ ) and carbon input ( $\text{kg C ha}^{-1} \text{Y}^{-1}$ ) under different treatments in three different locations of India.

Treatments	Jabalpur (Vertisol)		Palampur (Alfisol)				Ranchi (Alfisol)		
	Soybean yield	Wheat yield	Carbon input	Maize yield	Wheat yield	Carbon input	Soybean yield	Wheat yield	Carbon input
Control	821	1251	969	287	381	206	605	692	637
NPK	1809	4428	2704	3227	2294	1840	1496	2795	1945
NPK + FYM	1999	4862	5381	4660	3102	4167	1867	3327	4754

variance (ANOVA) and least-significant-difference (LSD) methods were applied to compare variable means under different treatments.

### 3. Results and discussion

#### 3.1. Crops yield and carbon input

The average grain yield of crops (pooled over 38 years) is shown in Table 3. At all the three sites, application of NPK and NPK+FYM significantly increased crop yields in comparison to that of the control. In Jabalpur, application of NPK and NPK+FYM increased soybean yield by 2.2 and 2.4 times in comparison to control. In the case of wheat, yield response of NPK and NPK+FYM was 3.5 and 3.9 times in comparison to control. The trend was similar at Palampur and Ranchi albeit with even a greater magnitude of increase. Crop yields for the control were low at all the 3 sites. In general, the application of NPK and NPK+FYM increased C input into the soil by 3–10 and 5–20 times, respectively in comparison to control (Table 3). Nutrient availability is generally low in control under continuous cropping, which adversely affects crop growth and reduces productivity (Singh et al., 2007; Jagadamma et al., 2007). Thus low biomass productivity in control plots also reduced the mean annual C input into soil at all three sites.

#### 3.2. Effects of long-term fertilization and manuring on soil organic carbon content

The data on SOC concentration in the beginning of the experiment at all the three sites is shown in Table 4. After 38 years of cropping, the SOC concentration of the control plot was increased by 20% at Jabalpur but with no change at Palampur. In contrast, SOC concentration of the control treatment at Ranchi decreased strongly probably because of the high sand content. The reason for an increase in SOC concentration at Jabalpur and no significant decrease at Palampur may be due to the higher C stabilization capacity of these soils because of their high silt+clay content (Six et al., 2002; Jha et al., 2010, 2012). The relationship between fertilizer input and soil C is contradictory. Mulvaney et al. (2009) reported a decline in soil C concentration due to long-term

application of N fertilizer, while others have reported build up of soil C under balanced fertilization and NPK+FYM (Bharadwaj and Omanwar, 1994; Schjonning et al., 1994; Hati et al., 2008). The data presented herein do not indicate any decline in SOC concentration with use of balanced fertilization (NPK). However, the buildup of SOC concentration over the control treatment was significant only at Palampur site.

Total SOC concentration with use of NPK+FYM was similar at Jabalpur and Palampur but significantly lower at Ranchi (Table 4). Although FYM was not analyzed for C:N ratio, but quality of C input through FYM in NPK+FYM plot may be superior (N concentration) to that via root biomass in unmanured plot since a well decomposed FYM was applied on dry weight basis at all three sites. Adding large amounts of C over a long period of time ( $10\text{--}15 \text{ Mg FYM ha}^{-1} \text{Y}^{-1}$ ) resulted only in modest C gains in a Vertisol at Jabalpur, but with pronounced effect in an Alfisol at Palampur. Relatively higher C stabilization at Palampur site may be due to favorable soil (high silt+clay content) and climatic conditions (low mean annual temperature and high rainfall). The positive effect of FYM application on SOC concentration was more pronounced at sites with soils containing higher silt+clay contents which were the highest at Jabalpur (Vertisol) followed by those at Palampur (Alfisol), and the least at Ranchi (Alfisol). Response of FYM to SOC concentration was in accord with the silt+clay content of the studied soil (Zinn et al., 2007a,b)

Soil organic carbon Stock (0–15 cm depth) was the highest for the NPK+FYM treatment at all three sites. Compared to the control, increase in C stocks with NPK+FYM was the highest at Ranchi (62%) followed by that at Jabalpur (44%) and Palampur (35%). Application of FYM in addition to NPK resulted in an additional increase in soil C stocks, compared to that by NPK alone by 24%, 28% and 30% in soils at Palampur, Jabalpur and Ranchi site, respectively.

#### 3.3. Effect of long-term fertilization and manuring on soil organic carbon mineralization and stability

Cumulative soil C mineralization under different treatments was the highest in soil at the Jabalpur site followed by those at Palampur and Ranchi (Fig. 2). The cumulative soil C mineralization was the highest for NPK+FYM treatment at all three

**Table 4**  
Changes in carbon content of active, slow and resistant (acid non-hydrolyzable) fractions as affected by different treatments in long-term fertilizer experiment.

Locations/treatments	Initial TOC ( $\text{g kg}^{-1}$ )	TOC ( $\text{g kg}^{-1}$ )	C stock (0–15 cm) ( $\text{Mg ha}^{-1}$ )	$C_a$ ( $\text{g kg}^{-1}$ )	$C_s$ ( $\text{g kg}^{-1}$ )	$C_r$ ( $\text{g kg}^{-1}$ )
Jabalpur	9.4					
Control		11.8 (0.4) a	23.0 a	0.35 (0.03) a	5.28 (0.04) a	6.23 (0.38) a
NPK		13.4 (0.3) a	25.8 a	0.33 (0.06) a	4.34 (0.06) a	8.77 (0.38) a
NPK+FYM		17.6 (0.5) b	33.0 b	0.65 (0.04) a	5.29 (0.04) a	11.66 (0.81) b
Palampur	11.3					
Control		11.0 (0.6) a	22.1 a	0.16 (0.01) a	5.58 (0.01) a	5.32 (0.41) a
NPK		13.2 (0.4) b	24.2 b	0.40 (0.06) a	7.33 (0.06) ab	5.48 (0.47) a
NPK+FYM		17.4 (0.3) c	30.0 c	0.43 (0.02) a	7.89 (0.02) b	9.12 (0.26) b
Ranchi	6.7					
Control		5.8 (0.2) a	12.1 a	0.22 (0.10) a	3.55 (0.11) a	2.05 (0.05) a
NPK		7.4 (0.3) a	15.5 a	0.13 (0.01) a	5.38 (0.01) a	1.98 (0.21) a
NPK+FYM		9.4 (0.1) b	19.6 b	0.25 (0.05) a	5.16 (0.05) a	4.00 (0.13) b

Means followed by the same letter under a particular soil type are not different at 0.05 probability level using Student Newman Keuls test (Value in parenthesis is standard error of mean; TOC indicates total organic carbon). \* Initial TOC value was recalculated by using a regression of TOC and Walkley and Black C data.



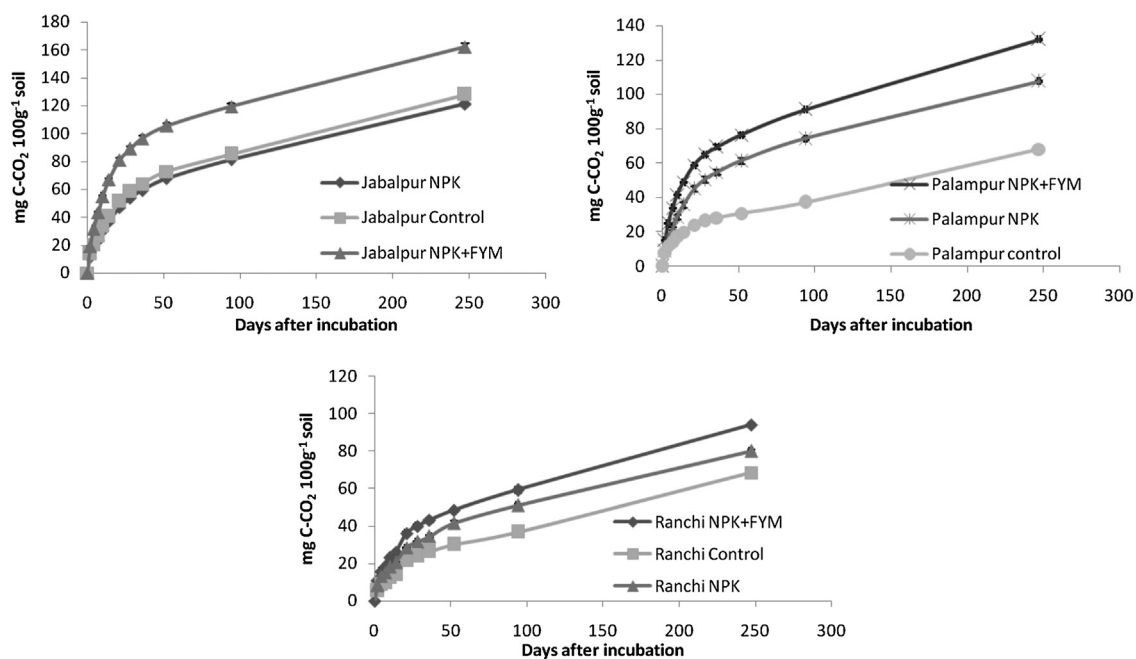


Fig. 2. Cumulative soil carbon mineralization (mg C-CO<sub>2</sub> 100 g<sup>-1</sup> soil) as affected by different treatments at different locations of India ( $n = 3$ , bar indicates standard error of mean).

sites. The mineralization rate (per unit mass of C) was slower in soil of the Palampur compared to those of Jabalpur and Ranchi sites (data not shown). The highest C mineralization rate was observed for an Alfisol from the Ranchi site. The SOC mineralization was faster at the beginning of the incubation study, which progressively decreased with the increase in time (Fig. 2). The decrease in decomposition rate over time is probably due to rising concentrations of structural carbohydrates (such as lignin and hemicelluloses) as a result of the loss of other constituents (sugars and starches) in the detritus (Mfilinge et al., 2002).

A significant difference in C concentration of the acid non-hydrolysable fraction occurred among treatments at the Jabalpur site (Table 4). However, there were no significant differences among treatments in C concentration of the active or slow pools. Further, C concentration of the acid non-hydrolysable fraction was higher than the cumulative C in the acid-hydrolysable pools (active + slow) for all three treatments at the Jabalpur site. The proportion of C in the acid non-hydrolysable fraction was 52%, 65% and 66% under control, NPK and NPK + FYM treatments, respectively. The C concentration of the slow pool in soil treated with NPK fertilizer declined by 18% compared with that of the control. It is thus hypothesized that additional C input in the NPK and NPK + FYM treatments contributed more C toward the acid non-hydrolysable fraction in fine than coarse-textured soils. Neff et al. (2002) and Swanston et al. (2004) also reported that long-term N fertilization significantly accelerated the decomposition of light soil C fractions (with MRT of about a decade, and comparable to C<sub>a</sub> + C<sub>s</sub> component in the present study) while preferentially stabilizing the soil C compounds in heavier, and mineral-associated fractions (with MRT of multi-decadal to century scale, and comparable to C<sub>r</sub> component in the present study). Thus the protective capacity of soil increases with increase in finer fractions (Zinn et al., 2007a,b). Hassink and Whitmore (1997) also reported that the capacity of soil to protect C is primarily based on the silt + clay contents and SOC accumulation in excess of the silt + clay protective capacity would be subject to higher rates of decomposition. Application of NPK + FYM increased the C concentration of the active, slow and acid non-hydrolysable

fractions by 99%, 22% and 33%, respectively over that of the NPK treatment. The increase in acid non-hydrolysable fraction in soil at Jabalpur even with the application of NPK alone indicates that concentration of resistant C may be increased even without the application of FYM in heavy-textured soils because of their high C stabilization capacity. Paul et al. (1999) reported that the mean residence time (MRT) of recently incorporated organic C also depends on clay mineralogy, and is longer in soils dominated by smectite than non-crystalline minerals.

Nutrient management treatments affected C stability differently in soils of Palampur and Ranchi than that of Jabalpur. At these sites, application of NPK alone did not significantly influence the C concentration of the acid non-hydrolysable fraction. In contrast, application of NPK increased C concentration in the slow pool than that in control by 31% and 52%, respectively. Despite 3–10 times more input of C into the soil compared with the control, lack of any change in the resistant C pools in soils of Palampur and Ranchi sites may indicate a priming effect (Fontaine et al., 2004, 2007). Thus, absence of fresh organic C, an essential source of energy for soil microbes, can enhance stability of soil C. It is thus hypothesized that lack of C stabilization capacity of two Alfisols of the present study may be due to 1:1 type clay, low clay content (25%), and the priming effect of added below ground root biomass (generally high C:N ratio owing to N mobility in plants) which prevented the buildup of C in acid non-hydrolysable fraction. Application of FYM to soils of Palampur and Ranchi increased C concentration of slow and acid non-hydrolysable fraction by 41% and 46%, respectively, as compared to that of the control. Furthermore, application of NPK + FYM increased buildup of C in the acid non-hydrolysable fraction (66% and 103%) in comparison to NPK alone despite no change of concentration in the slow pool. This trend suggests that C stability (resistant fraction) in soil is the function of the quantity and quality of clay (1:1 or 2:1) and that of the added C (C:N ratio). Thus, the data reported herein support the conclusion that the concentration of resistant C (C sequestration) in light-textured soil could be increased by the application of NPK + FYM at the recommended rate for site specific condition on a long-term basis (Jenkinson et al., 1990).

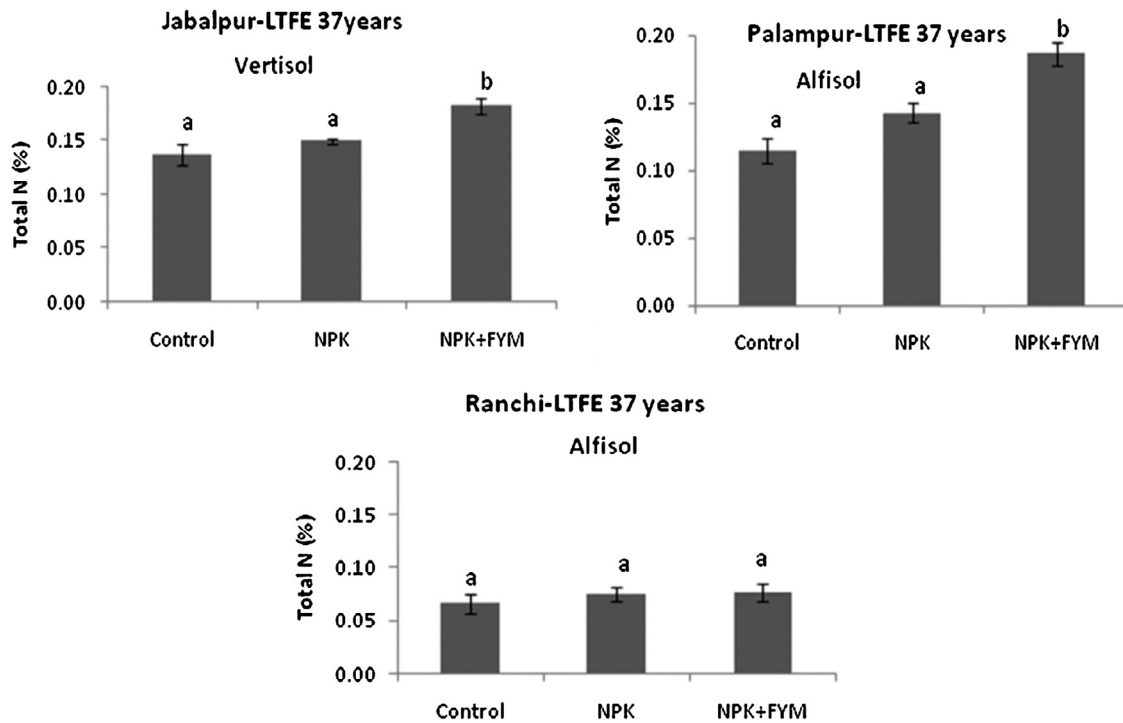


Fig. 3. Changes in total N content of soil under long-term chemical fertilization and manuring treatments (bar indicates standard error of mean, means followed by the same letter under a particular soil type is not different at 0.05 probability level using Student Newman Keuls test).

3.4. Effect of long-term fertilization and manuring on soil N dynamics

Soil TN concentration increased with NPK + FYM treatment at all sites in comparison to that of control (Fig. 3). However, there are no significant differences in TN concentration among control and NPK treatments at any of the sites. The TN concentration of soils across all sites ranged from 0.07% to 0.19% and the highest concentration was observed for the soils at Palampur and Jabalpur sites, and the lowest for Ranchi site. Application of NPK + FYM increased TN concentration by 28% and 72% over the control at Jabalpur and Palampur, respectively. There was no significant difference in TN concentration among NPK + FYM and control treatments in soil at the Ranchi site (Fig. 3). On the whole, TN concentration increased linearly with increase in concentration of SOC (Fig. 4;  $R^2 = 0.77$ ,  $p = 0.01$ ). The degree of correlation between SOC and available N was low (Fig. 5a;  $R^2 = 0.12$ ) but with a higher correlation between acid-hydrolysable C ( $C_a + C_s$ ) and available N concentration (Fig. 5b;  $R^2 = 0.64$ ,  $p = 0.01$ ). Thus, long-term use of chemical fertilizers and

manure can significantly enhance the C concentration in the stable pool, while also reducing significantly proportion of C in the acid-hydrolysable pool. These data have strong practical implication in terms of the available N concentration in soil. While SOC

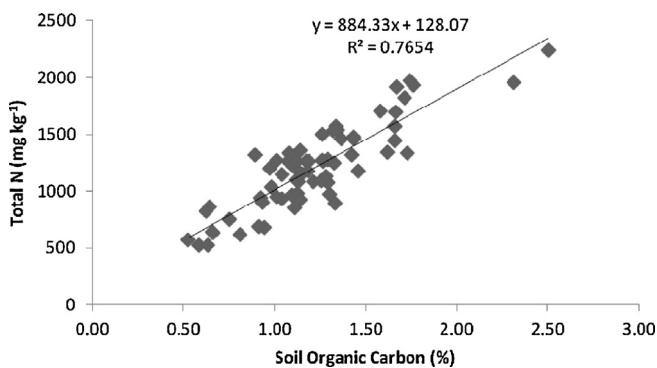


Fig. 4. Relationship between total organic carbon and nitrogen ( $N = 66$ , inclusive of all sites).

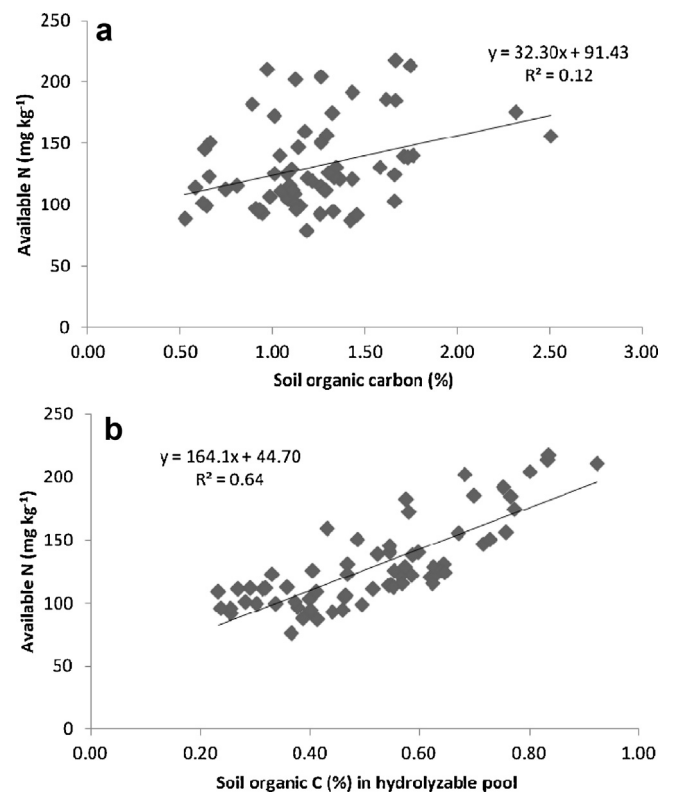


Fig. 5. (a) Relationship between available N and total organic carbon (b) relationship between available N and soil carbon in acid-hydrolysable pool ( $N = 66$ , inclusive of all sites).

concentration of Vertisol are considerably higher than those of the Alfisols because of the higher silt+clay contents, yet the availability of N is much lower in Vertisols probably because of a higher concentration of non-hydrolysable C. Such a response can aggravate N deficiency despite having higher total N reserve in Vertisols than those in Alfisols. Therefore, the C concentration of acid-hydrolysable pool (mineralizable C) could be used as a tool to predict N availability to crops in these soils. The data reported herein show that relatively higher amount of C in the acid-hydrolysable pool (active + slow pool) in an Alfisol (Palampur), may limit the buildup of C in a stable pool of SOC.

#### 4. Conclusions

The data presented support the following conclusions:

- (1) Long-term use of NPK and NPK + FYM affected soil C concentration and N availability.
- (2) Data presented on soil C pools using the double decomposition model suggest that long-term application of NPK + FYM increased the proportion of C in the acid non-hydrolysable fraction (acid non-hydrolysable C) irrespective of the soil type.
- (3) Application of NPK + FYM significantly enhanced C concentration in the stable pool and TN concentrations.
- (4) Concentration of available N depends on the amount of C in the acid-hydrolysable pool rather than on the SOC pool.
- (5) Thus, acid-hydrolysable pool (mineralizable C) may be used as a tool to predict plant available N in these soils.

#### References

- Banger, K., Kukul, S.S., Toor, G., Sudhir, K., Hanumanthraju, T.H., 2009. Impact of long-term additions of chemical fertilizers and farm yard manure on carbon and nitrogen sequestration under rice-cowpea cropping system in semi-arid tropics. *Plant Soil* 318, 27–35.
- Belay-Tedla, A., Zhou, X.H., Su, B., Wan, S.Q., Luo, Y.Q., 2009. Labile, recalcitrant and microbial carbon and nitrogen pools of a tall grass prairie soil in the US Great Plains subjected to experimental warming and clipping. *Soil Biol. Biochem.* 41, 110–116.
- Bharadwaj, V., Omanwar, P.K., 1994. Long-term effects of continuous rotational cropping and fertilization on crop yields and soil properties II. Effects on EC, pH, organic matter and available nutrients of soil. *J. Indian Soc. Soil Sci.* 42, 387–392.
- Black, C.A., 1965. *Methods of Soil Analysis*. American Society of Agronomy, Madison, WI.
- Chander, K., Goyal, S., Mundra, M.C., Kapoor, K.K., 1997. Organic matter, microbial biomass and enzyme activity of soils under different crop rotations in the tropics. *Biol. Fertil. Soils* 24, 306–310.
- Dungait, J.A.J., Hopkins, D.W., Gregory, A.S., Whitmore, A.P., 2012. Soil organic matter turnover is governed by accessibility not recalcitrance. *Glob. Change Biol.* 18, 1781–1796.
- Fontaine, S., Bardoux, G., Abbadie, L., Mariotti, A., 2004. Carbon input to soil may decrease soil carbon stability. *Ecol. Lett.* 7, 314–320.
- Fontaine, S., Barot, S., Barre, P., Bdioui, N., Mary, B., Rumpel, C., 2007. Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature* 450, 277–281.
- Franzuebbers, A.J., Stuedemann, J.A., 2002. Particulate and non-particulate fractions of soil organic carbon under pastures in the Southern Piedmont USA. *Environ. Pollut.* 116, S53–S62.
- Hassink, J., Whitmore, A.P., 1997. A model of the physical protection of organic matter in soils. *Soil Sci. Soc. Am. J.* 61, 131–139.
- Hati, K.M., Swarup, A., Mishra, B., Manna, M.C., Wanjari, R.H., Mandal, K.G., Misra, A.K., 2008. Impact of long-term application of fertilizer, manure and lime under intensive cropping on physical properties and organic carbon content of an Alfisol. *Geoderma* 148, 173–179.
- Jagadamma, S., Lal, R., Hoefft, R.G., Nafziger, E., Adee, E.A., 2007. Nitrogen fertilization and cropping system impacts on soil properties and their relationship to crop yield in the central corn belt, USA. *Soil Till. Res.* 98, 120–129.
- Jenkinson, D.S., Andrew, S.P.S., Lynch, J.M., Goss, M.J., Tinker, P.B., 1990. The turnover of organic carbon and nitrogen in soil. *Phil. Trans. R. Soc. Lond.* 329, 361–368.
- Jha, P., Mohapatra, K.P., Dubey, S.K., 2010. Impact of land use on physico-chemical and hydrological properties of ustifluent soils in riparian zone of river Yamuna, India. *Agrofor. Syst.* 80, 437–445.
- Jha, P., Garg, N., Lakaria, B.L., Biswas, A.K., Rao, A.S., 2012. Soil and residue carbon mineralization as affected by soil aggregate size. *Soil Till. Res.* 121, 57–62.
- Jha, P., Biswas, A.K., Lakaria, B.L., Saha, R., Singh, M., Rao, A.S., 2014. Predicting total organic carbon content of soils from Walkley and Black analysis. *Commun. Soil Sci. Plant Anal.*, <http://dx.doi.org/10.1080/00103624.2013.874023>.
- Johnson, J.M.F., Allmaras, R.R., Reicosky, D.C., 2006. Estimating source carbon from crop residues roots and rhizodeposits using the national grain-yield database. *Agron. J.* 98, 622–636.
- Kundu, S., Bhattacharya, R., Prakash, V., Ghosh, B.N., Gupta, H.S., 2007. Carbon sequestration and relationship between carbon addition and storage under rain-fed soybean-wheat rotation in a sandy loam soil of the Indian Himalayas. *Soil Till. Res.* 92, 87–95.
- Leavitt, S.W., Follett, R.F., Paul, E.A., 1996. Estimation of slow- and fast-cycling soil organic carbon pools from 6N HCl hydrolysis. *Radiocarbon* 38, 231–239.
- Mfilinge, P.L., Atta, N., Tsuchiya, M., 2002. Nutrient dynamics and leaf litter decomposition in a subtropical mangrove forest at Oura Bay, Okinawa, Japan. *Trees* 16, 172–180.
- Mulvaney, R.L., Khan, S.A., Ellsworth, T.R., 2009. Synthetic nitrogen fertilizers deplete soil nitrogen: a global dilemma for sustainable cereal production. *J. Environ. Qual.* 38, 2295–2314.
- Neff, J.C., Townsend, A.R., Gleixner, G., Lehman, S.J., Turnbull, J., Bowman, W.D., 2002. Variable effects of nitrogen additions on the stability and turnover of soil carbon. *Nature* 419, 915–917.
- Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. In: Page, A.L., et al. (Eds.), *Methods of Soil Analysis*, Part 2, 2nd ed. American Society of Agronomy, Inc., Madison, WI, Agronomy, 9, 961–1010.
- Paul, E.A., Follett, R.F., Leavitt, S.W., Halvorson, A., Peterson, G.A., Lyon, D.J., 1997. Radiocarbon dating for determination of soil organic matter pool sizes and dynamics. *Soil Sci. Soc. Am. J.* 61, 1058–1067.
- Paul, E.A., Harris, D., Collins, H.P., Schulthess, U., Robertson, G.P., 1999. Evolution of CO<sub>2</sub> and soil carbon dynamics in biologically managed, row-crop agroecosystems. *Appl. Soil Ecol.* 11, 53–65.
- Paul, E.A., Collins, H.P., Leavitt, S.W., 2001. Dynamics of resistant soil carbon of mid-western agricultural soils measured by naturally occurring C-14 abundance. *Geoderma* 104, 239–256.
- Paustian, K., Collins, H.P., Paul, E.A., 1997. Management controls on soil carbon. In: Paul, E.A., Paustian, K., Elliott, E.T., Cole, C.V. (Eds.), *Soil Organic Matter in Temperate Agroecosystems: Long-term Experiments in North America*. CRC Press, Boca Raton, FL, pp. 15–49.
- Reay, D., Sabine, C., Smith, P., Hymus, G., 2007. Spring-time for sinks. *Nature* 446, 727–728.
- Rovira, P., Vallejo, V.R., 2007. Labile, recalcitrant, and inert organic matter in Mediterranean forest soils. *Soil Biol. Biochem.* 39, 202–215.
- Schjonning, P., Christensen, B.T., Carstensen, B., 1994. Physical and chemical properties of a sandy loam receiving animal manure, mineral fertilizer or no fertilizer for 90 years. *Eur. J. Soil Sci.*, 257–268.
- Silveira, M.L., Comerford, N.B., Reddy, K.R., Cooper, W.T., El-Rifai, H., 2008. Characterization of soil organic carbon pools by acid hydrolysis. *Geoderma* 144, 405–414.
- Singh, K.P., Suman, A., Singh, P.N., Lal, M., 2007. Yield and soil nutrient balance of a sugarcane plant-rato on system with convention a land organic nutrient management in sub-tropical India. *Nutr. Cycl. Agroecosyst.* 79, 209–219.
- Six, J., Conant, R.T., Paul, E.A., Pautain, K., 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant Soil* 241, 155–176.
- Soil Survey Staff, 2010. *Keys to Soil Taxonomy*, 11th ed. USDA-Natural Resources Conservation Service, Washington, DC.
- Subbiah, B.V., Asija, G.L., 1956. A rapid procedure for estimation of available nitrogen in soils. *Curr. Sci.* 25, 259–260.
- Swanston, C., Homann, P.S., Caldwell, B., Myrold, D.D., Ganio, L., Sollins, P., 2004. Long-term effects of elevated nitrogen on forest soil organic matter stability. *Biogeochemistry* 70, 227–250.
- Trumbore, S.E., Chadwick, O.A., Amundson, R., 1996. Rapid exchange between soil carbon and atmospheric carbon dioxide driven by temperature change. *Science* 272, 393–396.
- von Lütow, M., Kögel-Knabner, I., Ludwig, B., Matzner, E., Flessa, H., Ekschmitt, K., Guggenberger, G., Marschner, B., Kalbitz, K., 2008. Stabilization mechanisms of organic matter in four temperate soils: development and application of a conceptual model. *J. Plant Nutr. Soil Sci.* 171, 111–124.
- Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining organic carbon in soils: effect of variations in digestion conditions and of inorganic soil constituents. *Soil Sci.* 63, 251–263.
- Zinn, Y.L., Lal, R., Bigham, J.M., Resck, D.V.S., 2007a. Edaphic controls on soil organic carbon retention in the Brazilian cerrado: texture and mineralogy. *Soil Sci. Soc. Am. J.* 71, 1204–1214.
- Zinn, Y.L., Lal, R., Bigham, J.M., Resck, D.V.S., 2007b. Edaphic controls on soil organic carbon retention in the Brazilian cerrado: soil structure. *Soil Sci. Soc. Am. J.* 71, 1215–1224.