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Research Paper

Influence of integrated nutrient management on carbon sequestration and its relationship with productivity of pearlmillet (*Pennisetum glaucum*)-mustard (*Brassica juncea*) cropping sequence

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ABSTRACT

A field experiment was conducted from rainy (*kharif*) season of 2010–11 to winter (*rabi*) season of 2011–12 under pearlmillet [*Pennisetum glaucum* (L.) R. Br. emend. stuntz]-mustard [*Brassica juncea* (L.) Czernj. Cosson] sequence cropping at Gwalior to evaluate the impact of different levels of N,P and K alone or in combination with farmyard manure (FYM) and/or biofertilizers on total carbon sequestration (TCS_Q) and dynamics of various pools of oxidizable organic carbon in relation to crop productivity. The experiment having 16 fertility treatments with 3 replications was conducted in randomized block design. The highest (0.93 Mg/ha) build up of very labile carbon (C_{VL}) was recorded in 100% recommended dose of NPK + FYM @10 t/ha/year. The treatment 100% RDNPK + FYM @10 t/ha/year + *Azotobacter* + PSB showed regular build up of C_{VL} (0.54 Mg/ha), non-labile carbon (C_{NL}; 0.57 Mg/ha) and maintained labile carbon pool (C_L). Both treatments were dominant contributors (54 and 58%) to active pool (ACT) over the passive pool (PSV) and provided the highest value of active : passive pool ratio (1.35 and 1.17), respectively, over sub-optimal dose, imbalanced fertility treatments and control. The change in less-labile carbon (CL) pool was not identical. Higher contribution to passive pool (PSV) in total organic carbon (TOC) was recorded for the control (80%), followed by imbalanced fertility treatments 100% N alone (70%) and 100% NP (71%). The continuous supply of optimal dose of N,P and K and/or biofertilizers in combination with FYM @10 t/ha/year, and super-optimal dose (150% RDNPK) treatments showed dissolution of carbonates ($CaCO_3$) as soil inorganic carbon (SIC) and regular build up of TOC, crop biomass carbon (CBC) and TCS_Q of system over the control, suboptimal dose and imbalanced fertility treatments. The combined use of optimal dose of chemical fertilizers, FYM @10 t/ha/year and biofertilizers significantly increased seed and straw yields of pearlmillet and mustard, respectively over other fertility treatments and control. The highly significant and positive correlation of total productivity was observed with pearlmillet-equivalent yield, TOC, C_{VL}, C_{LL} and ACT and negative with C_{NL}, while moderately positive significant correlation was observed with C_L and negative with PSV and SIC.

Key words: Crop productivity, Carbon sequestration, Integrated nutrient management, Oxidizable organic carbon fractions

Carbon sequestration is a process through which agricultural practices remove carbon dioxide (CO_2) from the atmosphere into a form that does not affect atmospheric chemistry (Lal, 2004a). Carbon sequestration in agricultural soils is frequently promoted as a practical solution to slow down the rate of increase of CO_2 in the atmosphere. A natural way to trap atmospheric CO_2 is by photosynthesis, where carbon dioxide is absorbed by plants and turned into carbon compounds, stored or fixed C as Soil organic carbon (SOC) (Walker *et al*., 2011).

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The SOC pool in soils of India is 2.2% of the world pool for 1 m depth and 2.6% for 2 m depth. Potential of soil C sequestration in India is estimated 6 to 7 Tg C/year for adoption of recommended management practices on agricultural soils, and 22 to 26 Tg C/year for secondary carbonates, while total potential of soil C sequestration is 39 to 49 (44 ± 5) Tg C/year (Lal, 2004b).

Information on organic C stocks in agricultural soils is important because of the effects of SOC on climate change and on crop production. The SOC stock at any time reflects the long-term balance between additions of organic C from different sources and its losses through different pathways. Following the adoption of large-scale intensive cropping, this long-term balance was modified since intensive cropping encourages oxidative losses of C due to continued soil disturbance, while it also leads to a large-scale addition of C to the soil through crop residues Majumder *et al*. (2008). This may cause either a net buildup or a net depletion of SOC stock (Cole *et al,*. 1993; Kong *et al*., 2005).

Cropping systems and management practices that ensure return of the greater amounts of crop residue to the soil are expected to cause a net buildup of the SOC stock. A good farming practice can decrease CO_2 evolution from soil into the atmosphere and enhance soil fertility and thus productivity (Lal, 2004b). This is more important in tropical and subtropical region where soils are inherently low in organic C content and production system is fragile (Mandal *et al.,* 2005). In addition to manure and fertilizers, cropping sequence, duration and timings of 'fallowing' etc. can also affect the SOC stocks (Halvorson *et al*., 2002).

Integrated nutrient management helps maintain soil fertility and improve plant nutrient supply at an optimum level for sustaining the desired productivity through optimization of the benefits from all possible sources on a long-term basis. Application of N,P and K either through inorganic fertilizers or through combination with organics such as farmyard manure (FYM) or crop residue or green manure improves the SOC concentration and its sequestration rate (Nayak *et al*., 2012). Use of organic manure and compost enhances the SOC pool more than application of the same amount of nutrients as inorganic fertilizers (Gregorich *et al*., 2001). Long-term application of organic manures increases the SOC pool (Gilley and Risse, 2000), which not only sequesters CO_2 but also enhances productivity of soil (Swarup *et al.,* 2000; Manna *et al.,* 2005).

In India, a series of fertility experiments were started, using both organic and inorganic sources of nutrients, during the late 1960s and early 1970s when fertilizer-responsive high-yielding cultivars of crops were introduced. Productivity analysis, nutrient balance, and soil quality studies were made for some of these experiments (Singh *et al*., 2004; Chaudhury *et al*., 2005; Mandal, 2005; Sharma *et al*., 2005), but no attempt was made to study the impact of continuous cropping using balanced fertilizer with or without organic amendments on the SOC stock and dynamics of its various pools (Majumder *et al.,* 2008). In the present study our objective was to identify the best integrated nutrient management practice for pearlmillet [*Pennisetum glaucum* (L.) R. Br. Emend. Stuntz.]-mustard (*Brassica juncea* (L.) Czernj. Cosson] cropping system on a Typic Ustochrepts located in the hot, humid, sub-tropical region of India that would improve pools of SOC stock, total carbon sequestration of the system and crop productivity.

MATERIALS AND METHODS

A field investigation was carried out during the rainy season (*kharif*) 2010-11 to winter season (*rabi*) 2011-12 as a part of a 14 years old experiment of pearlmillet-mustard (from *kharif* 1997) cropping system at the Instructional Farm, College of Agriculture, Gwalior, (26° 13'N and 76° 10'E with an altitude 197m). The climate site is semi-arid and sub-tropical with extreme hot and dry summers and cold winters; maximum temperature goes up to 45°C during summer and minimum as low as 2.8°C during winter. The mean annual rainfall of area is 700–800 mm. The experiment was carried out in randomized block design with 3 replications, comprising 16 fertility management practices, viz. control (no fertilizer/manure), 50% RDNPK, 75% RDNPK, 100% RDNPK, 150% RDNPK, 100% NP, 100% N, RDNPK 100% RDNPK-S (sulphur free), 50% RDNPK + *Azotobacter* (@ 10 g/kg seed), 75% RDNPK + *Azotobacter*, 100% RDNPK + *Azotobacter*, 100% RDNPK + *Azotobacter* + phosphate solubilizing bacteria (PSB), 50% RDNPK + farmyard manure (FYM) @ 10 t/ha/year, 75% RDNPK + FYM @ 10 t/ha/year, 100% RDNPK + FYM @ 10 t/ha/year, 100% RDNPK + FYM @ 10 t/ha/year + *Azotobacter* + PSB respectively. Area of single plot was 5m × 3m and total experimental area was 1,024.7 m^2.

The recommended dose (RD NPK) for pearlmillet was 80:40:20 kg N, P_2O_5 and K_2O/ha and for mustard 100:60:40 kg N, P_2O_5 and K_2O/ha. Half of the nitrogen was applied in the form of urea as a basal dose and remaining was top-dressed after first irrigation at 30 days after sowing (DAS) for both crops. Full dose of phosphorus and potash were applied as single superphosphate and muriate of potash, respectively, at the time of sowing. In treatment 100% RDNPK-S (sulphur free), P was added as *diammonium* phosphate (DAP) to make it sulphur-free treatment. As per treatment, FYM containing 0.5% N, 0.25% P and 0.5% K was added @10t/ha/year before sowing of *kharif* crop. In inoculation treatments, seeds were treated with *Azotobacter* and PSB both @ 10 g/kg/ha seed. Pearlmillet 'JBV 3' was sown (seed rate 5 kg/ha) during the middle of July and harvested in the second week of October and mustard 'Pusa Bold' was sown (seed rate 5 kg/ha) during the first to second week of November and harvested at the end of April each year. The soil samples were collected from 0–15, 15–30, 30–60 and 60–100 cm depth (total 1 m) with the help of screw and tube augers at the beginning before sowing of pearlmillet (first crop, *kharif* 2010–11) and after the harvest of mustard (fourth crop, *rabi* 2011–12) to study the impact of various fertility treatment on soil organic and inorganic carbon.

Soil samples were analyzed for oxidizable organic carbon fractions by modified Walkley and Black (1934) method as described by Chan *et al.* (2001), which allows the separation of total C into four pools, viz. Pool I (C_{VL} very labile); pool II: (C_L labile); pool III (C_{LL} less labile); pool IV: (C_{NL} non labile). The pool I and II together represent the active pool, while pool III and pool IV together constitute the passive pool of organic C in soils.

Total soil organic carbon (TOC) stock was calculated by as per Lal *et al.* (1998). For soil inorganic carbon (SIC), the same steps were followed using 12 parts of C present in $CaCO_3$ values (Bhattacharyya *et al.,* 2008).

The carbon content of vegetation can be estimated by simply taking a fraction of biomass (Magnussen and Reed, 2004). The total carbon sequestration (accumulated) (TCS_Q) in the system was calculated by estimating total amount of C accumulated in the biomass during two years (2010–11 to 2011–12) of study period and adding the change in TOC and SIC to it. The seed and straw yield data were analyzed treatment-wise for pearlmillet and mustard during both the years.

RESULTS AND DISCUSSION

Oxidizable organic carbon fractions

At the end of experiment (*rabi* 2011–12) the organic carbon fractions ($C_{VL,}$ $C_{L,}$ $C_{LL,}$ and C_{NL}) and their distribution (Table 1) in soil at 1.0 m soil depth revealed that, there were losses of carbon from all fractions with only a few exceptions. It may be ascribed to high temperature in the sub-tropical region (Bhattacharyya *et al*., 2004; Swarup *et al*., 2000).

Very labile carbon (C_{VL})

The very labile carbon content in 1 m soil depth ranged between 3.2 and 14.6 and 2.7 to 15.2 Mg/ha at initial and final period of study. The fertility treatments containing various levels of N,P and K in combination with FYM, viz. 50% RDNPK + FYM, 75% RDNPK + FYM, 100% RDNPK + FYM and 100% RDNPK + FYM + *Azotobacter* + PSB showed the regular build up of, over the same level of N,P and K alone by 40% over 50% RDNPK, 49% over 75% RDNPK), 39% (100% RDNPK) and 67% over 100% RDNPK-S). Similarly, the increase in for NPK in combination with *Azotobacter* was 15% over 50% RDNPK, 25% over 75% RDNPK, 38% over 100% RDNPK: a the increase in C_{VL} with 100% RDNPK + *Azotobacter* + PSB over 100% RDNPK was 47%. High content of polysaccharides (cellulose and hemicelluloses) in FYM could be responsible for the production of higher amounts of very labile fraction (C_{VL}) of TOC Majumder *et al*. (2008).

The treatments receiving 100% RDNPK + FYM @10 t/ha/year showed maximum build up of C_{VL} factor by 0.93 Mg/ha during 2 years, whereas build up was 0.80 Mg/ha in 100% RDNPK + *Azotobacter* and 0.65 Mg/ha in 150% RDNPK. The sub-optimal fertility dose 50% RDNPK, 75% RDNPK and imbalanced fertility treatments 100% N, 100% NP and control plot showed poor contribution of C_{VL} factor due to lower production of biomass due to imbalanced fertilizer supply and unavailability of organic amendment.

Labile carbon (C_L)

The share of C_L was lower in total organic carbon than to C_{LL} fraction under all fertility treatments. The highest contribution of C_L fraction (10.8 Mg/ha) was recorded under 100% RDNPK + FYM @ 10 t/ha/year + *Azotobacter* + PSB, followed by 9.6 Mg/ha in 100% RDNPK + FYM @ 10 t/ha/year, 9.0 in 75% RDNPK + FYM @ 10 t/ha/year 7.7 Mg/ha in 150% RDNPK, 7.5 Mg/ha in 100% RDNPK + *Azotobacter* + PSB, 6.8 Mg/ha in 100% RDNPK + *Azotobacter* and 6.9 Mg/ha in 100% RDNPK at the initial study periods and regular decrease was recorded under all fertility treatments at the end of study, except 100% RDNPK + FYM + *Azotobacter* + PSB did not show any changes with respect to time. The lower most value was found in control plot (2.3), followed by imbalanced fertility treatments of 100% N (4.2), 100% NP (4.4) and sub-optimal dose fertility treatments 50% RDNPK (4.5) and 50% RDNPK +*Azotobacter* (5.0 Mg/ha) at the end of study period.

Less labile carbon (C_{LL})

The contribution of C_{LL} pool was lower than the other pools (C_{VL}, C_L and C_{NL}) of organic carbon and amount varied with respect to fertility treatment. The maximum values of C_{LL} fraction was 10.5 recorded in 100% RDNPK + FYM + *Azotobacter* + PSB fallowed by 8.9, 7.9, 7.3 7.2 and 6.8 Mg/ha were with 100% RDNPK + FYM, 75% RDNPK + FYM, 100% RDNPK + *Azotobacter* + PSB, 150% RDNPK and 100% RDNPK + *Azotobacter*, respectively, at the initial period of study. The decrease was observed under most of fertility treatments towards the end of study, but control plot showed build up of less labile carbon to 0.24 Mg/ha and 75% RDNPK+*Azotobacter* 0.22 Mg/ha from initial to final period of study, which was not much identical.

Non-labile carbon (C_{NL})

Contribution of C_{NL} fraction was higher in total soil organic carbon of all treatments and amount varied from levels of fertility. The highest value of 21.2 was recorded in 100% N alone treatment over all fertility treatments, followed by 20.6 in 100% NP, 20.0 in control plot and 17.8 Mg/ha in 50% RDNPK treated plot at the initial period of study but regular decrease was observed at the end of study period (Table 1). This may be due to imbalanced fertility treatments or continuous cultivation without supply of fertilizer or organics and less biomass production which increase the losses of non-labile carbon fraction of TOC. Whereas build up of non-labile carbon at the end of study over the initial value (2010–11) was recorded in treatment receiving 100% RDNPK + FYM @ 10 t/ha/year + *Azotobacter* + PSB, being maximum build up by 7%. This result showed that not only very labile carbon pool (C_{VL}) but also non-labile carbon pool (C_{NL}) of soil could be maintained by optimal dose of fertilizer in combination with FYM and biofertilizers. Tian *et al.* (1992) stated that the maximum effect of RDNPK + FYM on less labile/non-labile fraction may be attributed to the higher lignin and polyphenol content of FYM that could lead to formation of more stable complex with protein of plant origin and thus made FYM-C more resistant to decomposition. Similarly, the regular build up of C_{NL} by 4% in both 100% RDNPK + *Azotobacter* and 100% RDNPK + *Azotobacter* + PSB treatments and 3% in 150% RDNPK were recorded at the end of study.

Active (ACT) and passive pool (PSV)

Sixteen fertility treatments showed that the contribution of active pool in TOC was between 20 and 58%, while that of the passive pool was from 42 and 80% for 1.0 m (Table 2) soil depth at the end of study period.

The treatment 100% RDNPK + FYM @ 10 t/ha/year + *Azotobacter* + PSB and 100% RDNPK + FYM @ 10 t/ha/year were dominant contributors of active pool over the passive pool by contributing 58% (26.0 Mg/ha) and 54% (22.6 Mg/ha) of TOC respectively. The control plot recorded the lowest value of 5.6 to 5.0 Mg/ha, followed by treatment 100% N alone (9.8 to 9.6 Mg/ha) and 50% RDNPK (10.4 to 9.8 Mg/ha) at initial and final period of study respectively. This may be ascribed to low residue return to soil in the form of crop biomass and also to the unavailability of FYM as an external organic amendment. The active pool of sub optimal fertility treatments receiving FYM, i.e. 50% RDNPK + FYM @ 10 t/ha/year (14.0 Mg/ha) and 75% RDNPK + FYM @ 10 t/ha/year (18.5 Mg/ha) showed better response over the same level of chemical fertilizer alone (50% RDNPK by 9.8 and 75% RDNPK by 12.2 Mg/ha) and in combination with biofertilizers treated plots (50% RDNPK + *Azotobacter* by 11.7 and 75% RDNPK + *Azotobacter* by 14.3 Mg/ha) and remained almost stable at the end of study. The results showed that as the fertility level decreased from optimal to sub-optimal the value of active pool also decreased.

For all the fertility treatments passive pool remained dominant over active pool except 100% RDNPK + FYM @ 10 t/ha/year + *Azotobacter* + PSB and 100% RDNPK + FYM @ 10 t/ha/year. The higher contribution of passive pool (Table 2) in TOC was recorded in the control (80%), followed by imbalanced fertility treatments 100% N alone (70%) and 100% NP (71%) at the end of study. The sub-

Table 1. Oxidizable organic carbon fractions (Mg/ha) affected by integrated nutrient management (2010–2012)

	Soil depth 1.0 m									
	Initial (2010)					Final (2012)				
Treatment	SOC	C_{VL}	C_L	C_{LL}	C_{NL}	SOC	C_{VL}	C_L	C_{LL}	C_{NL}
Control	26.6	3.2	2.3	1.1	20.0	25.4	2.7	2.3	1.3	19.1
50% RDNPK	32.2	5.8	4.6	4.0	17.8	31.5	5.3	4.5	4.0	17.7
75% RDNPK	34.3	6.5	6.1	4.5	17.2	33.5	6.3	5.9	4.4	16.9
100% RDNPK	35.3	7.5	6.9	6.3	14.5	35.1	7.9	6.5	6.4	14.3
150% RDNPK	37.2	10.1	7.7	7.2	12.2	37.8	10.8	7.5	7.0	12.5
100% NP	35.0	6.1	4.6	3.7	20.6	34.0	5.9	4.4	3.9	19.8
100% N	34.5	5.6	4.2	3.4	21.2	33.5	5.4	4.2	3.5	20.5
100% RDNPK-S	35.3	7.1	6.5	5.7	15.9	35.3	7.6	6.1	5.8	15.9
50% RDNPK + AZO	33.3	6.7	5.2	4.2	17.2	32.8	6.7	5.0	4.0	17.0
75% RDNPK + AZO	34.7	7.7	7.2	6.1	13.7	34.7	7.8	6.6	6.3	14.0
100% RDNPK + AZO	35.4	9.0	6.8	6.8	12.7	36.2	9.8	6.4	6.7	13.3
100% RDNPK + AZO + PSB	36.3	9.8	7.5	7.3	11.9	37.1	10.3	7.3	7.2	12.3
50% RDNPK + FYM	34.6	7.4	6.6	4.4	16.2	34.0	7.7	6.3	4.4	15.6
75% RDNPK + FYM	38.3	9.5	9.0	7.9	11.8	38.0	9.7	8.8	7.9	11.7
100% RDNPK + FYM	41.4	12.7	9.6	8.9	10.2	42.0	13.6	9.0	8.9	10.5
100% RDNPK + FYM + AZO + PSB	44.3	14.6	10.8	10.5	8.3	45.2	15.2	10.8	10.3	8.9
SEm±	1.10	0.1	0.3	0.4	1.1	0.84	0.3	0.5	0.5	0.8
CD (P=0.05)	3.19	0.2	0.8	1.2	3.3	2.41	0.8	1.4	1.4	2.4

SOC, Soil organic carbon; C_{VL}, vary labile carbon; C_L, labile carbon; C_{LL}, less labile carbon; C_{NL}, non-labile carbon; AZO, *Azotobacter*; PSB, phosphate-solubilizing bacteria optimal dose fertility treatments (50% RDNPK, 75% RDNPK, 50% RDNPK + *Azotobacter*) had maximum value of passive pool over that of active pool at initial period of study than other fertility treatments except imbalanced fertility treatments, but showed declined trend with respect to time. Whereas optimal dose of fertilizer in combination with FYM or biofertilizers and super-optimal fertility dose treatment showed regular build up of passive pool at the end of study. Manna *et al*. (2005) reported that application of N,P and K fertilizer, either alone or in combination with FYM maintained active and slow-release pools of C, sequestered C and improved soil quality and productivity.

Ratio of active to passive pool of carbon

The ratio of active to passive pool of carbon (Table 2) ranged from 0.26 to 1.35 at initial stage of study, while at the end of experiment it was 0.24 to 1.35 (1.0 m). This ratio was highest for treatments 100% RDNPK + FYM @ 10 t/ha/year + *Azotobacter* + PSB (1.35), followed by 100% RDNPK + FYM @ 10 t/ha/year (1.17), 75% RDNPK + FYM @ 10 t/ha/year (0.95), 150% RDNPK (0.94) and 100% RDNPK+ *Azotobacter* +PSB (0.91). The ratio having value more than 1 indicated that active pool was always higher than passive pool. Similarly, ratio was very narrow in case of unfertilized control (0.2) and 100% N alone (0.4) treatments, where passive pool remained dominant.

Total soil organic carbon (SOC)

Continuous cropping without use of N,P and K fertilizer or organics caused a net decrease in TOC of control plot by –1.3 Mg/ha (from 26.6 to 25.4 Mg/ha) and imbalanced fertility treatments as 100% N (from 34.5 to 33.5 Mg/ha) and 100% NP (35.0 to 34.0 Mg/ha). The cropping with the use of N,P and K fertilizers in combination with FYM/biofertilizers increased the SOC content in 100% RDNPK + FYM @ 10 t/ha/year + *Azotobacter* + PSB by 59% , 23% and 21% over 150% RDNPK, 100% RDNPK+ *Azotobacter* and 100% RDNPK + *Azotobacter* + PSB, respectively, under the difference between 2 years of study period. These findings confirm those of Gregorich *et al*. (2001) who observed that use of organic manure and compost enhances the SOC pool more than application of the same amount of nutrients as inorganic fertilizers. Similarly the adequate supply of nutrients in soil and long-term manure application can enhance biomass production and TOC content (Gilley and Risse, 2000).

The continuous supply of chemical fertilizer under long-term fertility experiment showed the build up of total soil organic carbon in sub optimal dose fertility treatments by 19% (50% RDNPK), 23% (50% RDNPK + *Azotobacter*), 25% (50% RDNPK + FYM), 24% (75% RDNPK) and 27% (75% RDNPK + *Azotobacter*) over the control at the end of study, but their response was poor over optimal dose of fertility treatments alone or in com-

Table 2. Active, passive pool, total organic carbon (Mg/ha) and active to passive pool ratio as affected by integrated nutrient management (2010–2012)

Treatment	Initial (2010)			Final (2012)		
	ACT	PSV	A:P	ACT	PSV	A:P
Control	5.6	21.0	0.26	5.0	20.4	0.24
50% RDNPK	10.4	21.8	0.48	9.8	21.6	0.46
75% RDNPK	12.6	21.7	0.58	12.2	21.3	0.57
100% RDNPK	14.5	20.8	0.70	14.4	20.7	0.69
150% RDNPK	17.9	19.4	0.92	18.3	19.5	0.94
100% NP	10.6	24.3	0.44	10.3	23.7	0.44
100% N	9.8	24.6	0.40	9.6	23.9	0.40
100% RDNPK-S	13.7	21.6	0.63	13.6	21.7	0.63
50% RDNPK + AZO	11.9	21.4	0.55	11.7	21.0	0.56
75% RDNPK + AZO	14.9	19.8	0.75	14.4	20.3	0.71
100% RDNPK + AZO	15.9	19.5	0.81	16.2	19.9	0.81
100% RDNPK + AZO + PSB	17.2	19.1	0.90	17.6	19.5	0.91
50% RDNPK + FYM	14.0	20.6	0.68	14.0	20.0	0.70
75% RDNPK + FYM	18.6	19.7	0.94	18.5	19.5	0.95
100% RDNPK + FYM	22.3	19.1	1.17	22.6	19.4	1.17
100% RDNPK + FYM + AZO + PSB	25.4	18.8	1.35	26.0	19.2	1.35
SEm±	0.2	1.2		0.4	0.9	
CD(P=0.05)	0.7	3.4		1.2	2.5	

ACT, active pool; PSV, passive pool; A:P, active to passive pool ratio; AZO, *Azotobacter*; PSB, phosphate-solubilizing bacteria bination with FYM or biofertilizers. It may be due to poor supply of nutrients in the form of imbalanced fertilizer which affect the crop growth, less biomass production and indirectly less residue return to the soil.

Soil inorganic carbon (SIC)

The soil of experimental area was slightly calcareous. Sixteen fertility treatments showed continuous increase of soil inorganic carbon (SIC) and ranged from 27.0 to 32.0 at initial and from 27.9 to 33.3 Mg/ha at the end of study, period. But all the fertility treatments showed lower values of SIC in the form of $CaCO_3$ compared with the control (32.0 to 33.3 Mg/ha). It could be due to dissolution of carbonates by the continuous supply of chemical fertilizers alone or in combination with FYM. However, the changes at the end of study period were not identical with respect to treatments. Slight increase in value under most of treatments could be due to aridity in the climate during summer, which led to precipitation of carbonate from lower depth of soil profile to surface soil and imbalanced fertilizer application has been postulated for the formation of pedogenic calcium carbonate with the concomitant development of sodicity and/or salinity. These findings are in line with those of Bhattacharyya *et al.* (2000) and Sahrawat (2003).

Crop biomass carbon

Crop biomass carbon (CBC) at the initial period of study, i.e. before sowing of *kharif* crop (pearmlillet 2010–11) was considered as nil and it was increased with cultivation of each crop (Table 3). The CBC at the end of study was estimated by its addition value of 4 crops estimated in 2010–11 (*kharif* pearlmillet + *rabi* mustard) and 2011–12 (*kharif* pearlmillet + *rabi* mustard). The share of CBC was very prominent compared to TOC and SIC because there were only gains due to biomass production but difference among treatments was quite noticeable. The CBC recorded from different treatments showed that the plots supplied with 100% RDNPK +FYM @ 10 t/ha/year + *Azotobacter* + PSB, 100% RDNPK + FYM @ 10 t/ha/year, super-optimal dose, i.e. 150% RDNPK and treatment receiving 100% RDNPK + *Azotobacter* + PSB contributed statistically significant and comparatively higher content of CBC by 23.6, 22.4, 21.8 and 21.6 Mg/ha, respectively, under total sequestered carbon. The lowermost CBC value of 12.2 Mg/ha was recorded under the control plot, followed by 16.4 in 100% N alone and 16.8 in 50% RDNPK treated plot at the end of study period. The beneficial effect of seed inoculation by *Azotobacter* and PSB and application of FYM was clearly noticed for CBC and content was higher over the same level of fertilizer alone treatments.

Total carbon sequestration of the system (TCS_Q)

Total carbon sequestered by the system was computed on the basis of changes in active and passive pools of TOC, SIC and contribution of crop biomass during two years of study period and it was between 58.6 and 72.1

Table 3. Total carbon sequestration (Mg/ha) of the system affected by integrated nutrient management (2010–2012)

Treatment	Initial (2010)				Final (2012)				Net value (+/-)			
	TOC	SIC	CBC	TCSQ	TOC	SIC	CBC	TCSQ	TOC	SIC	CBC	TCSQ
Control	26.6	32.0	-Nil-	58.6	25.4	33.3	12.2	70.8	–1.3	1.3	12.2	12.2
50% NP	32.2	30.1	-Nil-	62.3	31.5	30.9	16.7	79.1	–0.8	0.8	16.7	16.8
75% RDNPK	34.3	29.7	-Nil-	64.1	33.5	30.6	18.3	82.3	–0.8	0.8	18.3	18.3
100% RDNPK	35.3	29.7	-Nil-	65.1	35.1	30.6	19.9	85.7	–0.2	0.9	19.9	20.6
150% RDNPK	37.2	28.9	-Nil-	66.1	37.8	29.7	21.8	89.3	0.6	0.8	21.8	23.2
100% NP	35.0	27.4	-Nil-	62.4	34.0	28.2	18.1	80.3	–0.9	0.7	18.1	17.9
100% N	34.5	27.0	-Nil-	61.5	33.5	27.9	16.5	77.8	–1.0	0.9	16.5	16.4
100% RDNPK-S	35.3	27.8	-Nil-	63.0	35.3	28.1	19.1	82.5	0.0	0.3	19.1	19.5
50% RDNPK + AZO	33.3	28.7	-Nil-	61.9	32.8	29.0	17.8	79.5	–0.5	0.3	17.8	17.6
75% RDNPK + AZO	34.7	29.5	-Nil-	64.3	34.7	29.8	19.3	83.8	–0.1	0.3	19.3	19.5
100% RDNPK + AZO	35.4	29.7	-Nil-	65.1	36.2	30.2	21.1	87.4	0.8	0.5	21.1	22.3
100% RDNPK + AZO + PSB	36.3	28.8	-Nil-	65.2	37.1	29.3	21.6	88.0	0.8	0.5	21.6	22.9
50% RDNPK + FYM	34.6	28.2	-Nil-	62.8	34.0	29.0	18.6	81.6	–0.6	0.8	18.6	18.8
75% RDNPK + FYM	38.3	26.1	-Nil-	64.4	38.0	26.8	20.4	85.3	–0.2	0.7	20.4	20.9
100% RDNPK + FYM	41.4	28.1	-Nil-	69.5	42.0	29.1	22.4	93.4	0.6	0.9	22.4	23.9
100% RDNPK + FYM + AZO + PSB	44.3	27.8	-	72.1	45.2	28.4	23.6	97.2	0.9	0.6	23.6	25.1
SEm±	1.10	0.05	-	1.10	0.84	0.06	0.37	0.88				
CD (P=0.05)	3.19	0.15	-	3.17	2.41	0.17	1.07	2.55				

TOC, total organic carbon; SIC, soil inorganic carbon; CBC, crop biomass carbon; TCS_Q: total carbon sequestration; AZO, *Azotobacter*; PSB, phosphate-solubilizing bacteria; D/B, decrease or buildup and 70.8 and 97.2 Mg/ha at initial and final period of experiment respectively. The pearlmillet–mustard cropping system indicated that there was always gain in value of total carbon sequestration (TCS_Q) at the end of study period compared to initial period (Table 3), and it was very prominent build up recorded during 2 years of study in 100% RDNPK + FYM @ 10 t/ha/year + *Azotobacter* + PSB (25.1 Mg/ha), 100% RDNPK + FYM @ 10 t/ha/year (23.9 Mg/ha), 150% RDNPK (23.2 Mg/ha), 100% RDNPK + *Azotobacter* + PSB (22.9 Mg/ha) and 100% RDNPK + *Azotobacter* (22.3 Mg/ha). All these treatments showed higher build up of TCS_Q over other fertility treatments and control, may be the result of higher biomass production through the application optimal dose of fertilizer in combination with FYM or biofertilizers and super-optimal dose of chemical fertilizers which also led to an additional build up of SOC. Major contribution in carbon sequestration was made by biomass production rather than changes in SOC pools which were slowly changed. The data indicated that even if a small portion of biomass could be recycled to soil then only crop production itself can enrich SOC content and stop its further deterioration. Lal (2004) summarized the results of a number of studies and concluded that improved fertility management can enhance the SOC content at the rate of 0.05 to 0.15 Mg/ha/year to the soil through only crop roots.

Crop productivity

Different fertility treatments significantly affected yield of pearlmillet and mustard. The pooled (2010–12) grain and straw yield of crops varied between 1.8 and 4.0 t/ha and 4.4 and 8.8 t/ha for pearlmillet and 1.2 and 2.1 t/ha and 3.5 and 7.0 t/ha for mustard (Table 4). The continuous cycle of this cropping sequence with long-term fertility treatments indicated that integrated use of all sources of nutrients (100% RDNPK + FYM @ 10 t/ha/year + *Azotobacter* + PSB) enhanced seed and straw yields of pearlmillet by 121 and 100% and that of mustard by 76 and 96%, respectively, over the control and chemical fertilizer alone (100% RDNPK by 18 and 19; 14 and 15% and 100% RDNPK-S by 18 and 24; 23 and 24%). In addition to major nutrients, availability of micronutrients as well as other benefits rendered by farmyard manure might have helped in improvement of yield. The results are in conformity with those with Satyajeet Nanwal (2007) and Parihar *et al*. (2009).

The higher percent increase of seed (8 and 11%) and straw yield (8 and 5%) under 150% RDNPK followed by 100% RDNPK + *Azotobacter* + PSB (7 and 7%; 10 and 6%) and 100% RDNPK+ *Azotobacter* (5 and 5%; 5 and 2%) was recorded over 100% RDNPK alone for pearlmillet and mustard, respectively. This increase in yields might be ascribed to supply of supper-optimal fertility dose and to additional advantages provided by biofertilizers with seed inoculation of *Azotobacter* and PSB having ability to produce growth substances and antifungal substances in addition to the contribution of atmospheric nitrogen made available to plant Mishra *et al.*

Table 4. Grain and straw yield (t/ ha) as affected by integrated nutrient management in pearlmillet and mustard (2010–2012)

	Grain yield (t/ha)						Straw yield (t/ha)					
	Pearlmillet			Mustard			Pearlmillet			Mustard		
Treatment	2010	2011	Pooled	2011	2012	Pooled	2010	2011	Pooled	2011	2012	Pooled
Control	1.8	1.8	1.8	1.2	1.1	1.2	4.5	4.3	4.4	3.5	3.6	3.5
50% RDNPK	2.9	2.7	2.8	1.7	1.5	1.6	6.0	5.8	5.9	5.1	5.1	5.1
75% RDNPK	3.2	3.0	3.1	1.9	1.5	1.7	6.6	6.4	6.5	5.7	5.6	5.6
100% RDNPK	3.5	3.3	3.4	2.0	1.6	1.8	7.5	7.2	7.4	6.2	5.9	6.0
150% RDNPK	3.8	3.6	3.7	2.2	1.7	2.0	8.4	8.0	8.2	6.3	6.3	6.3
100% NP	3.5	3.3	3.4	1.8	1.5	1.6	6.5	6.2	6.3	5.7	5.4	5.6
100% N	3.0	2.8	2.9	1.5	1.5	1.5	5.8	5.5	5.6	5.4	5.3	5.4
100% RDNPK-S	3.4	3.3	3.4	1.8	1.6	1.7	7.2	6.9	7.1	5.7	5.6	5.6
50% RDNPK + AZO	3.2	3.0	3.1	1.8	1.5	1.6	6.6	6.4	6.5	5.2	5.3	5.3
75% RDNPK + AZO	3.3	3.1	3.2	1.9	1.5	1.7	7.3	7.0	7.1	6.0	5.6	5.8
100% RDNPK + AZO	3.6	3.5	3.5	2.0	1.7	1.9	7.9	7.6	7.8	6.1	6.3	6.2
100% RDNPK + AZO + PSB	3.7	3.5	3.6	2.1	1.8	2.0	8.0	7.7	7.9	6.3	6.5	6.4
50% RDNPK + FYM	3.3	3.1	3.2	1.9	1.4	1.7	6.6	6.4	6.5	5.9	5.9	5.9
75% RDNPK + FYM	3.4	3.2	3.3	2.0	1.6	1.8	7.7	7.5	7.6	6.4	6.2	6.3
100% RDNPK + FYM	3.7	3.5	3.6	2.2	1.8	2.0	8.6	8.3	8.5	6.6	6.6	6.6
100% RDNPK + FYM + AZO + PSB	4.1	3.9	4.0	2.2	1.9	2.1	9.0	8.6	8.8	7.0	6.9	7.0
SEm±	0.10	0.09	0.01	0.35	0.08	0.03	0.35	0.33	0.38	0.09	0.28	0.08
CD (P=0.05)	0.28	0.27	0.03	1.01	0.96	0.08	1.01	0.96	1.16	0.26	0.82	0.25

(2008). The application of 100% N alone and 100% NP and sub-optimal dose of fertility (50% RDNPK, 75% RDNPK) treatment recorded significantly higher yield than the control for pearlmillet and mustard, but response was poor over the optimal dose of fertility.

Relationship of crop productivity with carbon fractions

Simple correlation coefficients obtained between crop productivity with different forms of carbon are presented in Table 5. The association of total productivity (TP) as seed yield of pearlmillet + mustard was highly positive and significant with pearlmillet-equivalent yield (PEY, i.e. system productivity) (r = 0.899**), TOC (r = 0.754**), C_{VL} (r = 0.830**), C_{LL} (r = 0.772 **) and ACT (r = 0.817**), whereas moderately positive significant correlation was observed with C_L (r = 0.663 **). The highly negative and significant correlation of TP was found with C_{NL} (r = –0.762**), whereas moderately negative and significant correlation was found with passive pool of organic carbon (PSV) (r = –0.592**) and soil inorganic carbon (SIC) (r = –0.734**). This indicated that total productivity of pearlmilet–mustard cropping was enhanced and control by different carbon fractions, TOC and SIC.

The linear relationship of crop productivity and system productivity (PEY) with soil organic carbon for 0–15 cm plough layer (Figs. 1, 2 and 3) showed that the crop productivity (pearlmillet + mustard) as seed yield and straw yield were affected by total soil organic carbon and increased at the rate of 0.382 t/ha (TOC = –0.753 + 0.382 seed yield; R^2 = 0.568) and 1.065 t/ha (TOC = –2.676 + 1.065 straw yield; R^2 = 0.603), respectively, with 1 Mg/ha increase in soil organic carbon. The pearlmillet-equivalent yield, i.e. system productivity is also affected by TOC and increased at the rate of 1.129 t/ha (TOC = –2.015 + 1.129 pearlmillet-equivalent yield; R^2 = 0.542) with 1 Mg/ha increase in soil organic carbon during the study period.

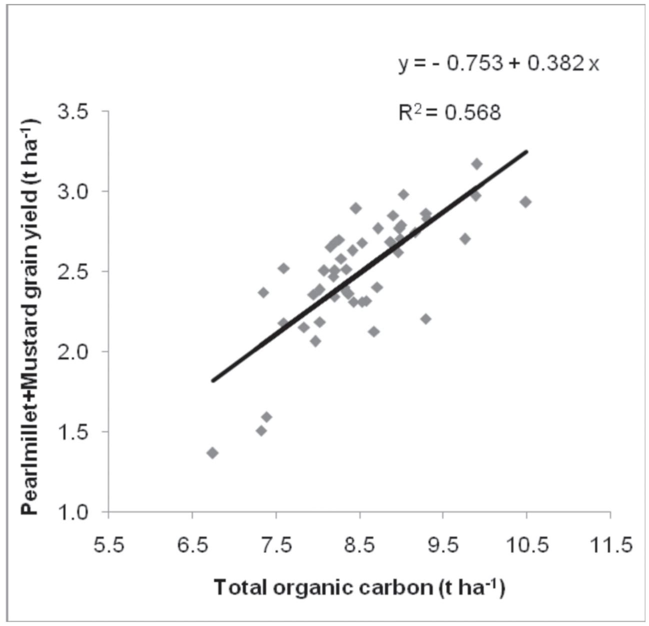

Fig. 1. Relationship between seed yield of pearlmillet and mustard and total organic carbon (TOC) stocks in 0–15 cm during 2010–11.

Integrated use of optimal dose of chemical fertilizers in combination with farmyard manure @ 10 t/ha/year and biofertilizers under pearlmillet–mustard cropping sequence significantly improved not only vary labile (C_{VL}) but also maintained non-labile (C_{NL}) carbon pool. Similarly, it remained dominant contributor for active pool over passive pool of organic carbon, increased soil organic carbon, crop biomass carbon and total carbon sequestration of the system over unfertilized control, imbalanced fertility treatments and sub-optimal fertility dose treatments alone. But share of crop biomass carbon is very prominent in total carbon sequestration of the system (TCS_Q) as compared to total organic carbon (TOC) and soil inorganic carbon (SIC). The combined use of chemical fertilizer, farmyard

Table 5. Correlation matrix between soil organic carbon fractions, inorganic carbon and total grain productivity (pearlmillet-mustard) in 2010–12

	TP	PEY	TOC	C_{VL}	C_L	C_{LL}	C_{NL}	ACT	PSV	SIC
TP	1									
PEY	0.899**	1								
TOC	0.754**	0.777**	1							
C_{VL}	0.830**	0.811**	0.881**	1						
C_L	0.663**	0.770**	0.830**	0.730**	1					
C_{LL}	0.772**	0.861**	0.812**	0.785**	0.866**	1				
C_{NL}	-0.762**	-0.835**	-0.686**	-0.821**	-0.847**	-0.914**	1			
ACT	0.817**	0.851**	0.923**	0.955**	0.900**	0.876**	-0.891**	1		
PSV	-0.592**	-0.632**	-0.402*	-0.691**	-0.652**	-0.629**	0.890**	-0.724**	1	
SIC	-0.734**	-0.771**	-0.739**	-0.801**	-0.693**	-0.738**	0.749**	-0.812**	0.607**	1

**P= 0.01; TP, total productivity; PEY, pearlmillet equivalent yield; TOC, total organic carbon; C_{VL}, very liable carbon; C_L, liable carbon; C_{LL}, less liable carbon; C_{NL}, non-liable carbon; ACT, active pool; PSV, passive pool; SIC, soil inorganic carbon

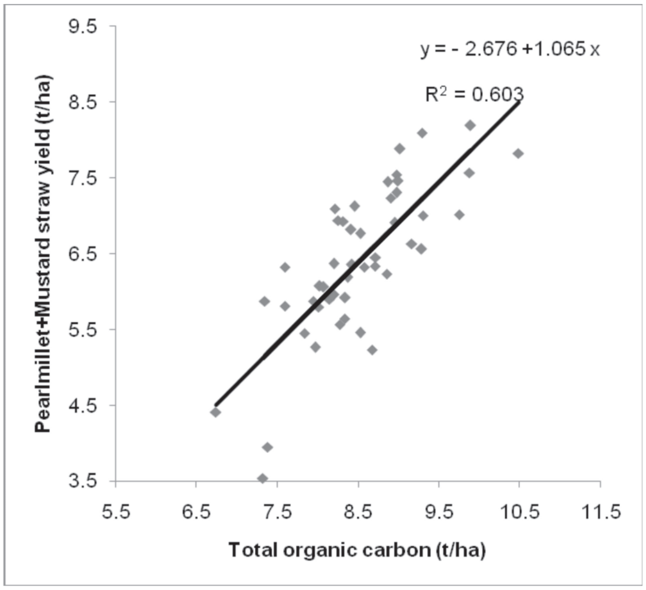

Fig. 2. Relationship between straw yield of pearlmillet and mustard and total organic carbon (TOC) stocks in 0–15 cm during 2010–11.

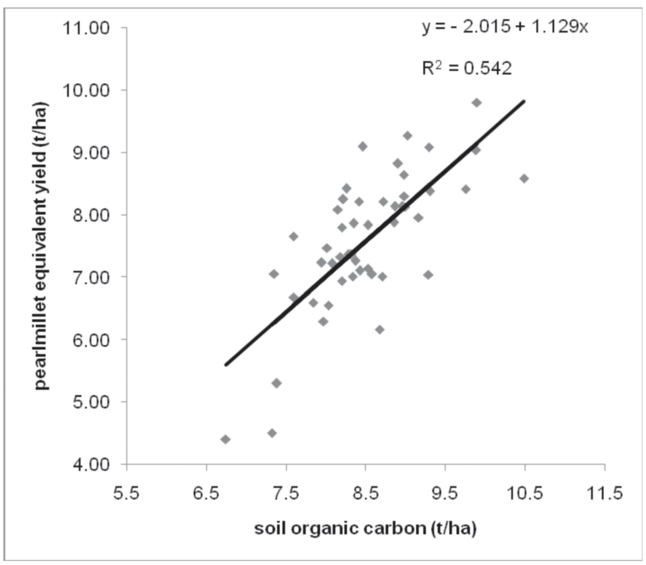

Fig. 3. Relationship between system productivity (pearlmillet equivalent yield) and total organic carbon (TOC) stocks in 0–15 cm during 2010–11.

manure and biofertilizers increased the productivity of both crops over unfertilized control and other fertility treatments. The productivity of the system was significantly related with carbon fractions and soil organic carbon. Thus, the application of chemical fertilizer in combination with organic manure and biofertilizers was most suitable practice for the continuous pearlmillet–mustard sequence cropping in the semi-arid region of Madhya Pradesh. However, the results are not much identical for exceptions under the 2 years of study period but the difference between treatments may be due to 14 years (1997) of long-term fertility experiment and annual variations in seasons.

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