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Soil Carbon Dioxide Emissions from Sorghum–Sunflower Rotation in Rainfed Semi-arid Tropical Alfisols: Effects of Fertilization Rate and Legume Biomass Incorporation

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*The long-term effects of plant legume [horse gram (*Macrotyloma uniflorum*)] biomass incorporations were assessed in terms of carbon dioxide (CO_2) emissions, soil quality parameters, and climatically influenced soil parameters in a dryland Alfisol under varying soil fertility conditions. Six selected treatments consisted of off-season legume incorporation (I) and no incorporation / fallow (F), each under three varying nitrogen and phosphorus fertilizer levels (viz., N_0P_0, $N_{25}P_{30}$, and $N_{50}P_{30}$). Soil moisture, soil temperature, soil surface carbon dioxide emission, soil dehydrogenases, and microbial biomass carbon (MBC) were monitored at three different crop situations [viz., Kharif period (KP), legume/fallow period (LP), and no crop period (NP)] at 14 different periods of the year. Incorporation practices resulted in greater rates of CO_2 emission over fallow conditions during the Kharif and legume periods, whereas the emission rate was greater in fallow soils during the end of the legume and no crop periods. The increased rates of fertilizer doses also significantly increased the soil CO_2 flux during the majority of the measurements. Beneficial effects of incorporation practices were observed in terms of high soil moisture (5–11%), low soil temperature (3–7%), and high content of MBC over without incorporations. Correlation studies indicated that the soil property MBC was found to be the greatest significant variable with CO_2 emission in all the fertilizer treatments under biomass-incorporated soils. These results indicated the undesirable (in terms of CO_2 fluxes) and desirable (soil biological and other parameters) effects of legume biomass incorporation and fertilizer application and their significance in improving soil quality and greenhouse gas (GHG) emissions in dryland Alfisols of semi-arid tropics.*

Keywords Fertilizer effects, legume biomass incorporation, SAT alfisols, soil carbon dioxide emission, soil quality

Introduction

Alfisols are the third most important soil order in the world, covering about 13.1% of the world land area (Anonymous 2002). These soils are most abundant in semi-arid tropics

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(SAT) (Kampen and Burford 1980). About 62% of the Alfisols in SAT are located in West Africa and India. These soils suffer on account of several quality constraints including a miserably low amount of organic carbon (C), poor fertility, textural and structural infirmities, low water-retention capacity, crust formation, and hard-setting tendencies.

Among all these constraints, low organic C is one of the major limitations that ultimately results in poor quality (functional capacity) of these soils. These soil-quality-related constraints result in critically low yields of rainfed crops. The predominant reasons for low organic C in these soils could be (i) loss of organic matter with runoff water from the sloped lands, (ii) temperature-mediated fast oxidation of organic C entrapped in soil aggregates, and (iii) low levels of fertilizer application leading to little above- and below-ground biomass contribution and little or no advertent recycling of crop residues back to soil because of competing demand for fodder.

It is well established that quality of agricultural soils is largely a function of soil organic matter (Franzluebbers et al. 1998). To improve the soil organic-matter status in dryland regions, it is of paramount importance to keep track of organic-matter additions through proper soil and crop management practices and there is a need to monitor the organic C losses as carbon dioxide (CO_2) emissions. Barber and Navarro (1994) reported that although the legume cover crops have large biomass production and turnover, they are not likely to increase the soil organic-matter content. Among various measures to improve the soil organic carbon (SOC), growing of a legume crop with the residual moisture after harvest of Kharif main crop and incorporating the biomass in the top soil was quite effective in improving the yield of the next Kharif crop and soil fertility in the long run (Venkateswarlu et al. 2007).

No doubt, the fate of soil C accrued by management practices such as a growing legume crop with differential residual fertility situations and incorporating its biomass in soil or virtually practicing in situ green manuring may help improve several soil quality parameters. At the same time, such management practices may also influence the CO_2 emission rates, which is a matter of great concern during the present times, when the agriculture as a whole is being labeled as one of the important culprits for greenhouse gases and global warming. It has been understood that the loss of sequestered carbon (C) as gaseous carbon dioxide to the atmosphere during different seasons of the year depends on differential pattern of C decomposition as influenced by soil and climatic variables. Soil moisture and temperature conditions in drylands vary widely because of the erratic distribution of annual rainfall during crop and fallow periods, and there is an acute need to quantify them to know their influence on carbon dioxide flux. The level of organic C in any given soil is governed by climatic conditions influencing soil microbial biomass and enzyme activity. The decomposition of C in soils involves the mineralization of labile C fractions by decomposer organisms, and the knowledge of their metabolic activity during different seasons of the year is essential to understand the dynamics of soil C and its release to atmosphere as carbon dioxide. Hence, the quantitative assessment of predominant biological indicators of soil quality (viz., microbial biomass carbon and enzyme activities such as dehydrogenases) in relation to the negative consequences such as greater CO_2 fluxes will provide a more sensitive indication over a simple measurement of organic C, especially when the change has to be observed at short time intervals (Campbell et al. 1992; Mele and Carter 1993; Powlson, Brookes, and Christensen 1987; Sparling 1992). Also, fertilization is the primary means of improving plant productivity and crop yield, and addition of fertilizer nitrogen (N) and phosphorus (P) improves aboveground and root biomass. Hence, an increase in soil organic C can be expected over a long-term period, which may also influence the pattern of CO_2 evolution and directly and indirectly contribute to increase the volume of greenhouse gases, leading to negative impacts in terms of climate change. However, researchers have given different views on this subject. Recent research reports suggested that the soil organic-matter (SOM) content of agricultural soils will be reduced by excessive application of nitrogenous fertilizers (Cvetkov et al. 2010; Seremestic et al. 2009). Duxbury (1995) opined that agricultural practices result in significant release of carbon dioxide to the atmosphere. Schlesinger (2000) reported that the rate of accumulation of SOM is often greater on fertilized fields, but the resulting carbon dioxide emission is seldom assessed in fields receiving inorganic fertilization. Qiang, Yuan, and Gao (2004) reported that in wheat–corn cropping, the soil respiration was increased by the residue incorporation, and the impact was more apparent when the incorporated residue level was doubled. The soil microbial biomass was also increased by the residue incorporation. They concluded that residue incorporation can be suggested as a measure to increase the soil fertility, but doubling the amount of residue incorporation seems not necessary as it may enhance CO_2 emission. In recent research, Montoya-Gonzales et al. (2009) commented that incorporation of crop residues instead of burning can help reduce the CO_2 emissions by a factor of 1.2.

A majority of the studies on legume biomass incorporation and its effect on soil health is focused on improved soil properties, especially N dynamics, turnover of legume residue N in soil, interactions between legume residue N and soil N, and transfer of N from legume residues to subsequent nonlegumes. The information pertaining to assessment of legume-biomass-incorporated soils in terms of periodical changes in soil quality, especially biological indicators and CO_2 emissions in rainfed semi-arid tropics, was scarce in scientific literature. Thus, keeping in view the growing concern about climate change threats due to the increasing levels of greenhouse gases through agricultural and crop husbandry practices, we felt it was essential to keep a strict watch on periodical monitoring of CO_2 emission, beside monitoring the impact of legume biomass incorporation on predominant biological soil quality indicators and other soil parameters such as soil moisture and temperature during cropped, post-rainy, and fallow seasons in one of the important crop rotations (viz., sorghum–sunflower) of dryland Alfisol. Thus, this study was taken up under the National Agricultural Technology Program (NATP) of the Indian Council of Agricultural Research (ICAR) supported by the World Bank with these specific objectives: (i) to determine the influence of legume biomass grown with varying fertilizer levels and its in situ incorporation on periodical CO_2 emissions, predominant biological soil quality indicators, and climatically influenced soil parameters and (ii) to establish the relationships among CO_2 emission, biological soil quality indicators, and climatically influenced soil parameters in rainfed semi-arid tropical Alfisols.

Materials and Methods

Location and Other Experimental Details

This study was conducted in an ongoing long-term experiment focusing on measuring the effect of legume biomass incorporation and fertilization on CO_2 emissions and influence on biological soil quality indicators in a sorghum–sunflower system. The long-term study was initiated during 1994 and continued until 2004 in a Typic Rhodustalf soil at Gunegal Research Farm (longitude 78° 40′ E and latitude 17° 6′ N, 542 m above sea level) of the Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad. Climatically, this region falls under the category semi-arid tropics with unimodel average annual rainfall of 738 mm. About 70% of this rainfall occurs during June–September, which is the main crop-growing period and is termed as monsoon or Kharif season. The remaining about 30%

of rainfall occurs during October–May, which is not adequate for growing a second crop, that is, during postmonsoon or Rabi season (October–December) under rainfed conditions in these Alfisols. However, to capitalize on this 30% rainfall, short-duration legumes, such as horse gram, a pulse legume (*Macrotyloma uniflorum*) crop can be raised, which may end up in biomass or both grain and biomass depending upon the rainfall quantum and its distribution. The detailed information about the experimental site, climatic conditions, sorghum (variety SPV-462, *sorghum bicolor*) / sunflower (variety Mordern, *Helianthus annus*) cropping system and method, and incorporation schedule of biomass grown as off-season horsegram (*Macrotyloma uniflorum*) crop have been given in detail elsewhere (Venkateswarlu et al. 2007). In brief, the experimental soils were acidic, nonsaline, low in organic C (0.27%) and available N, and medium in available P and K. The information on some of the predominant soil parameters is presented in Table 1. The long-term ongoing experiment was sorghum–sunflower rotation at site I (clay content 21%) and sunflower–sorghum rotation at site II (clay content 16%) at the same farm during the Kharif seasons (June to September, may extend to October). As these Alfisol soils slightly vary spatially in their clay content, two sites were taken for the field experiment for more confirmed results. At each of the site, treatments had two main plots (with and without biomass incorporation) and five N and P (P_2O_5) combinations (viz., N_0P_0, $N_{25}P_0$, N_0P_{30}, $N_{25}P_{30}$, and $N_{50}P_{30}$ kg ha^{-1}) as subplots with three replications. Thus, the total number of plots was as follows: 2 (main plots) × 5 (fertilizer combinations) × 3 (replications) = 30. Each subplot was $40 \times 40\ m^2/30 = 53.33\ m^2$ in area. These fertilizer treatments were applied to sorghum and sunflower crops in rotation each year [yearly rotation: 1 year sorghum (Kharif) and 1 year sunflower (Kharif)]. After the harvest of Kharif crops every year at both the sites, in one of the two main plots horse gram (*Macrotyloma uniflorum*) was grown up to the flowering stage only and was incorporated in the soil, and other main plots remained fallow. During

Table 1
Physicochemical properties of soil in the experimental site

Characteristics	Description/value
Soil order	Alfisol
Soil series	Gunegal
Sand (g kg^{-1} soil)	720
Silt (g kg^{-1} soil)	30
Clay (g kg^{-1} soil)	250
Texture	Sandy clay loam
Bulk density (Mg m^{-3})	1.5
Moisture at 0.033 Mpa (% w/w)	9.4
Moisture at 1.50 Mpa (% w/w)	2.6
Available water capacity (% w/w)	6.8
Porosity (%)	37
Maximum water-holding capacity (%)	41
pH (soil/water, 1:2)	6.3
EC (dSm^{-1})	0.05
Organic carbon (g kg^{-1})	2.7
Available N (0.32% $KMnO_4$-oxidisable N) (g kg^{-1})	0.14
Available P (0.5 M $NaHCO_3$-extractable) (g kg^{-1})	0.004
Available K (g kg^{-1})	0.043

2003, the biomass yield of horsegram was 0.89 t ha^{-1} (dry-weight basis). The horse gram biomass was incorporated by using tractor-drawn disc plow following conventional tillage up to 15 cm deep. The overall design followed in this long-term study was split plot. The fertilizer sources were urea and superphosphate.

For present study of monitoring of CO_2, only one site (site I) was chosen. During the year of the study (2003), the annual rainfall was 870 mm and during the Kharif season (June–September) it was 708 mm. During Rabi season (October–December), the rainfall (162 mm) occurred only during October and first fortnight of November. In this study, among the five fertilizer treatments, three representative treatments in each of the fallow (F) and incorporated (I) plots N_0P_0, $N_{25}P_{30}$, and $N_{50}P_{30}$ (kg ha^{-1}) (the recommended dose of fertilizer) were adopted. In this case, sorghum was sown on 15 June 2003 [Julian date (JD) 166] and harvested on 1 October (JD 274). Horsegram was sown on 9 October (JD 283) and incorporated into soil to determine the effects of incorporation and fertilizer application on yield of crop grown during 2004. In this study, all the field and soil measurements were taken five times during the main crop Kharif period (KP) (June to September), four times during legume crop period (LP) (October to December), and five times during the no crop period (NP) (January to May 2004).

Monitoring Soil Surface CO_2 Emissions

Soil surface carbon dioxide emissions were measured on 9 June (before sowing, JD 160), 29 July (JD 210), 18 August (JD 230), 22 September (JD 265), 1 October (JD 274), 9 October (JD 282), 24 October (JD 297), 11 November (315), 25 November (JD 329), 3 January (JD 3), 26 February (JD 57), 9 April (JD 99), 7 May (JD 127), and 24 May (JD 144) in 2003–4 when the sorghum crop was in the field. The rate of soil surface carbon dioxide evolution was measured with a portable closed, dynamic chamber EGM-4 with SRC-4 (PP Systems, UK). While recording the observations, slight modifications were made in the instrument assembly to facilitate the soil collars to fit with a perfect seal. Soil collars made up of PVC (poly vinyl carbonate) 10 cm in diameter and 4.5 cm long were inserted 2.5 cm deep into the soil along the row in such a way that they were 3 cm away from crop plant. Once inserted, the collars were allowed to rest in place throughout the study period. The measurement area was maintained weed free throughout the experiment. Five measurements were made from each plot and averaged in each replication. The measurements were made between 9.00 am and 1.00 pm to avoid diurnal fluctuations in soil temperature. No measurements were performed within 3 days of each rainfall event.

Soil Temperature and Moisture Measurements

Surface soil temperature and volumetric soil moisture content at 0–0.15 m deep were measured with a portable STP-1 probe (PP systems, UK) and TDR profile soil moisture probe (TRIME-FM GmbH, Germany), respectively. The probes were inserted adjacent to the soil collars at the time of each soil C flux measurement.

Soil Sampling, Processing, and Analysis

Soil samples (0–0.15 m deep) were collected at each measurement close to the collar area and analyzed for various chemical and biological properties. A composite soil sample was made from samples collected at five spots in each replication. A representative portion of each soil sample was air dried, powdered, and passed through 0.2-mm sieve for the determination of organic C (OC) by the Walkley and Black method (Jackson 1967) during three representative periods: before sowing, after harvest, and in May 2004. Biological properties such as microbial biomass carbon (MBC) and dehydrogenase activity (DHA) were measured in freshly collected samples. The MBC was measured by the chloroform fumigation and extraction method (Bremner and Van Kessel 1990) and dehydrogenase activity by the tri-phenyl formazon procedure (TPF) (Klein, Loh, and Goulding 1971). The ratio of soil MBC to soil OC was expressed in percentages for the three representative stages (June, October, and May).

Data Analysis

Analysis of variance (ANOVA) and linear correlation were performed to test for significant treatment differences between measured variables (Snedecor and Cochran 1989). The effects of each variable among the different stages were studied with a three-way factorial analysis. The least significant difference (LSD) procedure was used to test significance between treatment means. Regression analysis was done in all the treatments between soil C flux and all the studied soil properties to determine their relationships.

Results and Discussion

Effect of Fertilizer Application and Biomass Incorporation Practices on Soil Carbon Dioxide Emission

The phenomenon of soil C loss as gaseous CO_2 to the atmosphere occurs throughout the year as a result of the activity of roots and soil organisms, and the intensity of loss varies with climate, crop, and soil conditions prevalent during different seasons of the year. Values of CO_2 emission rate during the five sampling stages of KP ranged from 37 mg CO_2 m^{-2} h^{-1} in IN_0P_0 at JD 160 to 507 mg CO_2 m^{-2} h^{-1} in $FN_{50}P_{30}$ at JD 210 (Figure 1). Emission rate increased and attained maximum during JD 210 and decreased thereafter. It is reported that rainfall influences soil moisture content and temperature, and both of these factors play roles in controlling soil surface CO_2 emission (Curtin et al. 2000; Parkin and Kaspar 2003). The percentage increase as a result of main effects of incorporation over fallow was 38% and that of fertilizer dose of $N_{50}P_{30}$ over N_0P_0 was 38%. During JD 160, significant effects of interaction were observed, and the rate of CO_2 flux at this stage increased with increasing fertility levels under both incorporated and fallow plots. During JD 210, the overall mean emission rate was 125% greater than JD 160. The rates of emission were 467 and 507 mg CO_2 m^{-2} h^{-1} corresponding to $FN_{25}P_{30}$ and $FN_{50}P_{30}$ treatments. The ratio of MBC to SOC was also found to be high in JD 210 under incorporated treatments under all fertilizer levels, which supports the reasons for high CO_2 emission at JD 210 (Table 2). In sorghum, the application of fertilizer N was made during 30 and 60 days after sowing (DAS), and probably the increased vegetative growth might have contributed to more release of CO_2. In general, during the Kharif period, the fertilizer level $N_{50}P_{30}$ under incorporation increased the CO_2 flux during JD 160, 210, and 230, whereas in fallow, this treatment resulted in increased rate of emission in all the five sampling periods. The magnitude of emission as a result of fertilizer addition was greater in fallow than in biomass incorporation during JD 210, 265, and 274. In the oxidative conversion of organic inputs to humus by soil microorganisms, 80–90% of aboveground C and 50–80% of belowground C is lost as CO_2 to the atmosphere (Nye and Greenland 1960). The share of crop roots in contributing to the total amount of CO_2 release was found to be 45–58% in annual crops.

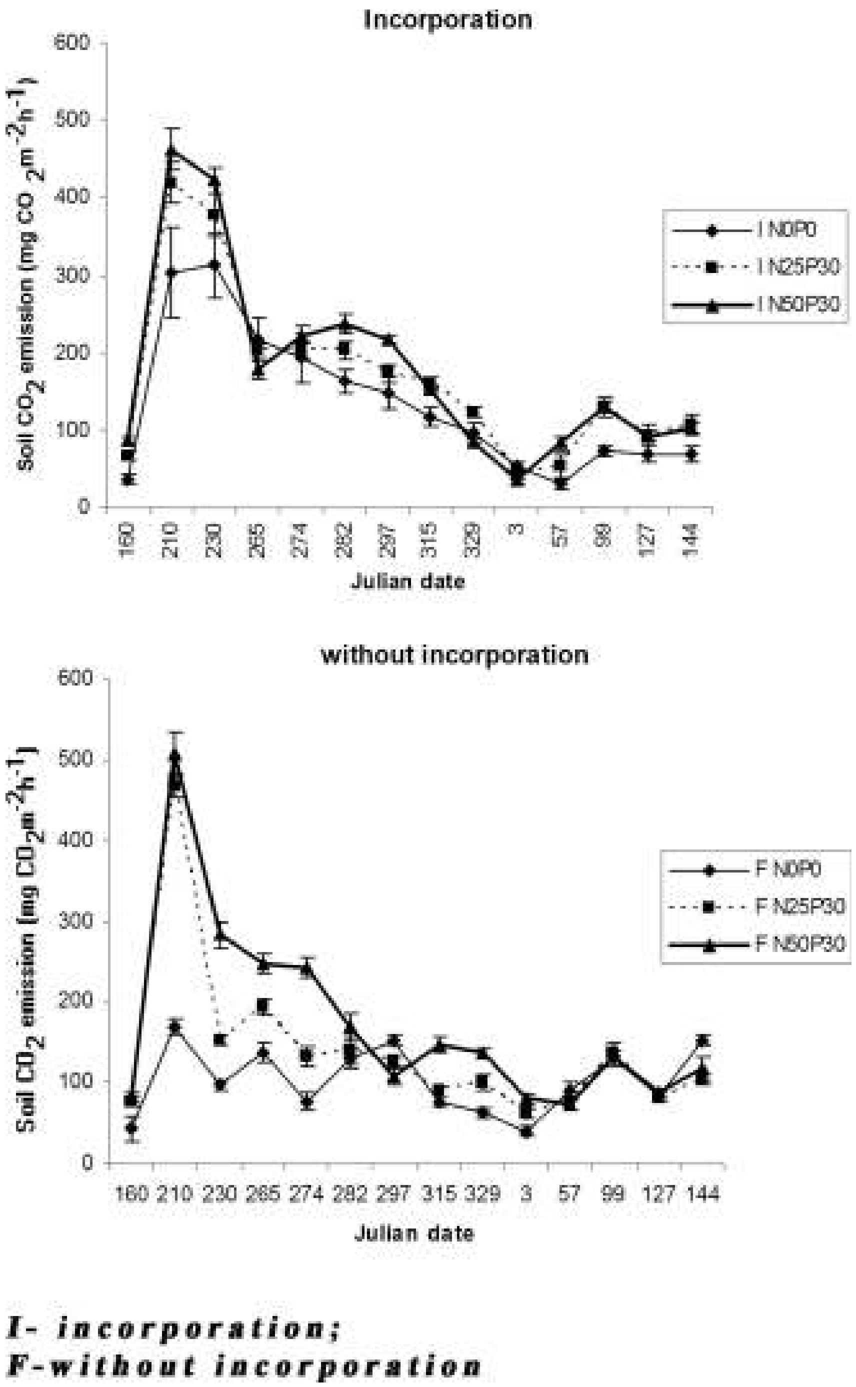


Figure 1. Effects of fertilizer levels in treatments with and without incorporation on soil CO_2 emission under different crop conditions at different periods. Data are means ± standard deviation.

Table 2

Effects of biomass incorporation and fertilizer application on MBC/SOC (%) ratio at three different periods of study

	JD 210		JD 300		JD 127	
Treatment	I	F	I	F	I	F
N_0P_0	5.9	3.4	2.3	3.4	4.1	2.8
$N_{25}P_{30}$	4.6	3.1	4.3	2.9	2.7	3.8
$N_{50}P_{30}$	4.9	4.3	4.5	4.2	2.9	5.3

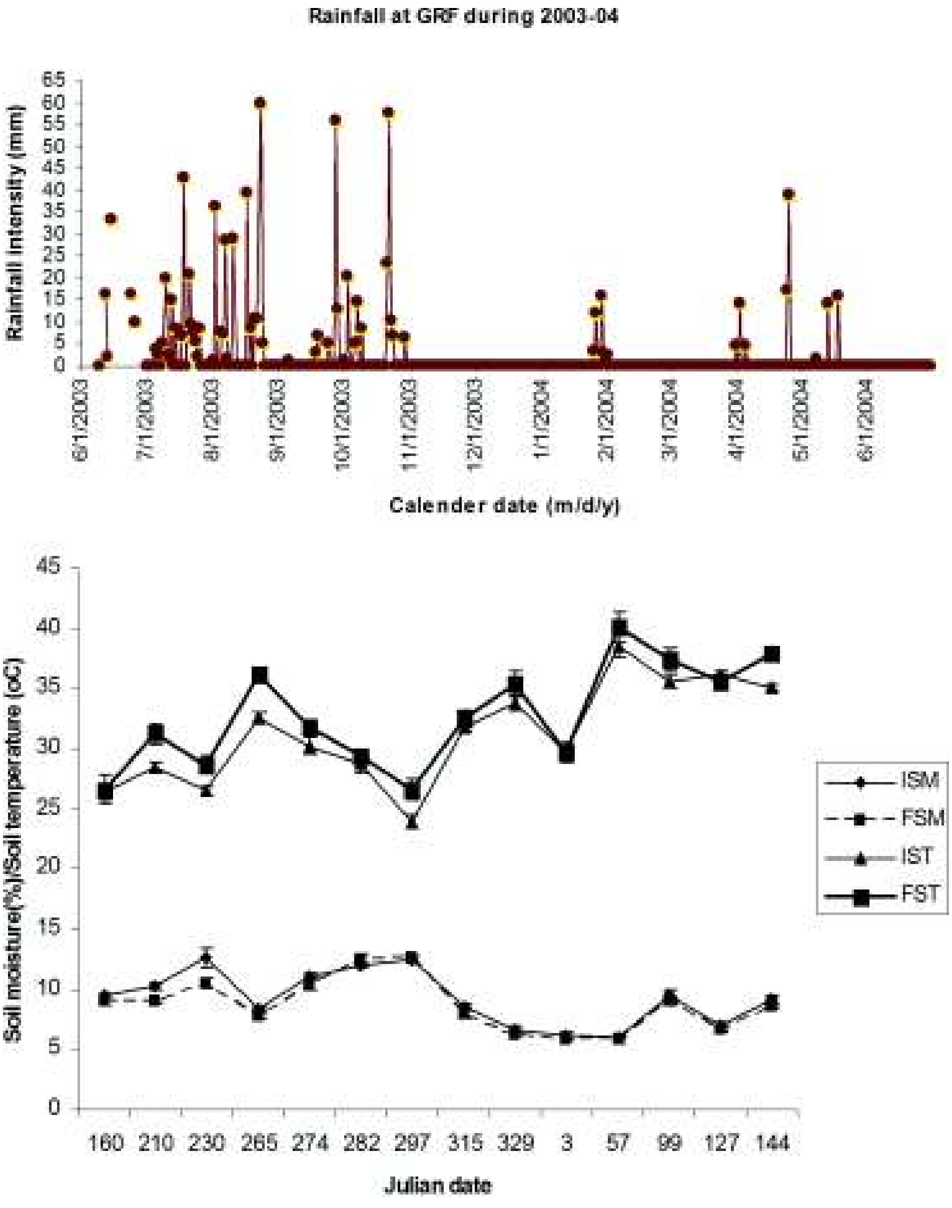
Notes. JD, Juilan date; I, incorporation; and F, fallow.

Among the four sampling dates of the legume period, the rate of emission varied from 63 mg CO_2 m^{-2} h^{-1} in FN_0P_0 in JD 329 to 237 mg CO_2 m^{-2} h^{-1} in $IN_{50}P_{30}$ during JD 282. During this period, the rate of emission decreased with time, and the overall mean indicated that the emission rates were 35% and 65% in I and F plots as compared to Kharif period. Among the treatments, the release was 30% greater in incorporation over fallow, and the emission rates were 18% and 31% greater in $N_{25}P_{30}$ and $N_{50}P_{30}$ over N_0P_0 respectively. During JD 300, the two fertilizer treatments under incorporated soils had high MBC/SOC ratio (Table 2). Incorporation resulted in increased emission as compared to fallow during this period at JD 282, 297, and 315. The influence of increased fertilizer dose in increasing emission rate was also observed, but the release rate was significantly less than in the Kharif period.

During no crop period, the mean CO_2 emission was 26% less than in the legume period. The rate of emission varied from 30 mg CO_2 m^{-2} h^{-1} in IN_0P_0 at JD 57 to 137 mg CO_2 m^{-2} h^{-1} in $FN_{25}P_{30}$ during JD 99. During this period, fallow soils were found to release greater CO_2 as compared to incorporation treatment. The fertilizer dose of $N_{25}P_{30}$ increased the rate of emission as compared to N_0P_0 in incorporated soils only during JD 57, whereas in fallow, this influence was observed during JD 3 only. The interaction was found to be significant during JD 3, 57, and 144. There was no marked influence of fertilizer in other stages. The greater rate of emission in JD 144 was due to better moisture conditions because of rainfall.

Effects of Fertilizer Application and Biomass Incorporation Practices On Soil Moisture and Temperature

Data on the rainfall amount during different cropping situations indicated that Kharif period received 630 mm rainfall, whereas the amounts of rainfall received for legume period and no crop period were 130 and 40 mm respectively (Figure 2). The rate of rainfall directly influenced the magnitude of soil moisture content with significant differences observed between the incorporated and fallow treatments with different fertilizer rates. During the Kharif period, the mean soil moisture content in biomass incorporated soils was 7% greater compared to fallow plots. This trend was noticed during legume period and no crop period, but the percentage difference among I and F plots decreased with time. The greater content of moisture in biomass-incorporated soils could be attributed to greater amount of organic C in these plots. Earlier, Venkateswarlu et al. (2007) established in this experiment that plots where biomass was incorporated had greater OC content than fallow plots. Long-term legume incorporation results in increased SOC (Nambiar 1994), and the



ISM- soil moisture of incorporated soils;
FSM-soil moisture of non incorporated soils;
IST- soil temperature of incorporated soils;
FST-soil temperature of non incorporated soils

Figure 2. Variation in soil moisture and soil temperature in different treatments (color figure available online).

effect of organic-matter adsorption is more pronounced in soils containing less than 25% clay (Sharma et al. 1999). Moreover, because of this effect, the soil physical characteristics such as low bulk density and high water-holding capacity of the incorporated soils might also be responsible for retaining greater soil moisture content (Boparai, Singh, and Sharma

1992; Singh, Nagarajarao, and Sadaphal 1980). Similarly, in the present study, increased fertilizer rates resulted in greater soil moisture and the effect was more pronounced in biomass-incorporated soils than in those without biomass incorporation during all three stages of the study. The average percentages increase in moisture as a result of fertilizer levels (viz., $N_{25}P_{30}$ and $N_{50}P_{30}$) over control (N_0P_0) were 9.4% and 15.6% respectively in incorporated soils, and negligible increase was observed in the case of fallow soils. This effect could be attributed to improvement in soil physical properties and addition of OC through legume biomass incorporation. It has already been established that horsegram biomass incorporation at about 1.5 t on dry biomass basis (at about 75 days of growth) added about 35 kg N ha^{-1} (Sharma et al. 1999). Application of N fertilizers in the long run leads to an improvement in SOC, especially in semi-arid soils (Rasmussen and Rhode 1988).

Soil temperature in the two levels of biomass incorporation varied between 23.9 °C and 40.1 °C during the study period. Except on JDs corresponding to 160, 282, 329, and 3, during the other sampling periods, biomass-incorporated soils had significantly lower soil temperature as compared to fallow soils. Similarly, with increase in fertilizer levels under both incorporation levels (I and F), the soil temperature decreased. Average soil temperature during the Kharif period was 28.8 °C in biomass-incorporated soils and 30.9 °C in fallow soils. Similarly, incorporated soils recorded mean soil temperatures of 29.6 °C and 35.1 °C during legume and no crop periods as compared to fallow soils with 30.9 °C and 36.1 °C. During JD 127, greater soil temperature was observed in incorporation treatments, which could be attributed to low soil moisture content (6.8%). A significant and negative association was observed among these two soil physical variables in all the biomass incorporation and fallow treatments, and the association was of greatest magnitude in N_0P_0 ($r = -0.78$, $P < 0.01$). The decreased soil temperature in the incorporation treatment with different fertilizer rates could have caused by the effects of OC content and vegetative cover.

Soil Dehydrogenases and MBC. Soil enzyme activity is considered as an index of microbial activity as well as soil fertility (Burns 1982). Additions of SOC through biomass incorporation resulted in increased soil Dehydrogenase Activity (DHA) and the increases in the metabolic activity in biomass-incorporated soils as compared to soils of fallow treatment were 63%, 5%, and 90% during the Kharif period, legume period, and no crop period respectively (Table 3). Previous studies indicated the positive relationship of dehydrogenases with that of OC (Barush and Mishra 1984). Significant increases in soil dehydrogenases due to incorporation of N-fixing green manures such as *Sesbania rostrata* has been reported by Kalidurai and Kannaiyan 1989. Microbial activities comprise all biochemical reactions catalyzed by microorganisms in soil, especially the presence of active and intact microbial cells (Alef and Nannipieri 1995), and soil enzymes, especially living-cell-associated enzymes such as dehydrogenases, provide better indications of the metabolic status of the soils. Similarly, increased doses of fertilizers ($N_{25}P_{30}$ and $N_{50}P_{30}$) resulted in increases of 38% and 113% DHA over N_0P_0 during the Kharif period. However, no such increase in DHA was observed during the legume period, whereas increased rate of fertilizers resulted in decreased activity during the no crop period. No significant relationship of soil DHA with that of other soil parameters was observed in the biomass-incorporated treatments, while a significant negative relationship with that of soil moisture was observed in all the three treatments under fallow. The increase in MBC content observed in the case of all the six treatments was in the order of no crop period < legume period < Kharif period. The MBC content was greater in biomass-incorporated

Table 3
Soil dehydrogenase activity (μg TPF g^{-1} h^{-1}) as influenced by different treatments during different periods (crop situations) of the year

	Kharif period			Legume period			No crop period		
	I	F	Mean	I	F	Mean	I	F	Mean
N_0P_0	0.46	0.35	0.40	0.67	0.83	0.75	0.59	1.78	1.18
$N_{25}P_{30}$	0.66	0.44	0.55	0.65	0.59	0.62	0.75	1.37	1.06
$N_{50}P_{30}$	1.12	0.58	0.85	0.55	0.54	0.54	0.76	0.85	0.80
Mean	0.75	0.46		0.62	0.65		0.70	1.33	
LSD	IL	0.006		0.08			0.04		
	FL	0.035		0.04			0.02		
	IL × FL	0.04		0.06			0.03		

Notes. IL, incorporation levels; FL, fertilizer levels; I, incorporation; and F, fallow.

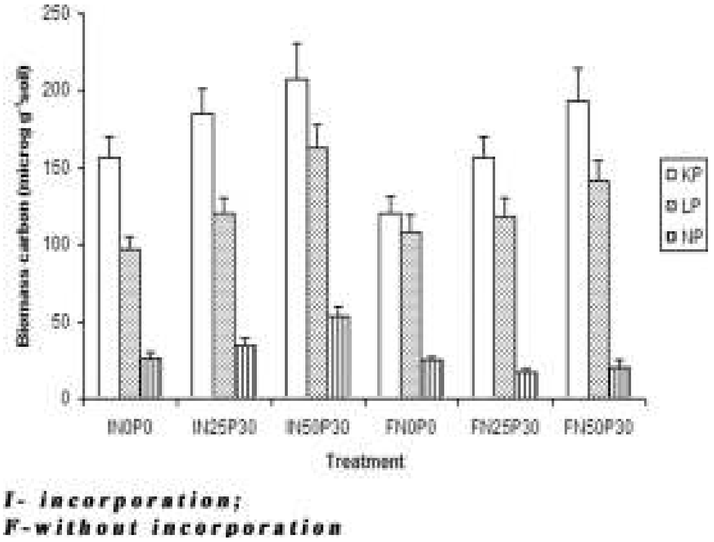


Figure 3. Microbial biomass C content (μg g^{-1}) of soil under different incorporation and fertility levels at different crop conditions and at different periods.

plots compared to fallow conditions, and the addition of fertilizers at increasing rates increased the biomass C content (Figure 3). Significant positive and negative correlations of MBC were observed with soil moisture and soil temperature respectively in all the fertilizer treatments under biomass incorporation and failed to correlate with any other soil variables under fallow condition. It has been proved that changes in microbial biomass as a result of management are sometimes greater than differences in organic matter (Alvarez et al 1995).

Relationships between Carbon Dioxide Emission and Soil Properties. The association of soil moisture with CO_2 emission was positive and significant in all the treatments under

Table 4
Correlations of measured soil variables with soil carbon dioxide emission under different treatments

Parameter	IN_0P_0	$IN_{25}P_{30}$	$IN_{50}P_{30}$	FN_0P_0	$FN_{25}P_{30}$	$FN_{50}P_{30}$
Soil moisture	0.61**	0.63**	0.70**	NS	NS	NS
Soil temperature	–0.50**	–0.44**	–0.49**	NS	NS	NS
MBC	0.88**	0.80**	0.76**	NS	NS	0.53**

**Significant at $P < 0.01$.
Notes. NS, nonsignificant; and MBC, microbial biomass carbon.

biomass incorporations, the magnitude being greater in $N_{50}P_{30}$ (Table 4). In semi-arid climates, moisture was found to be the main controlling factor of soil respiration during crop seasons (Akinremi, McGinn, and McLean 1999). Among the various factors that are highly interrelated and occur through complex processes, identified to affect the release of CO_2 from soils, the moisture and temperature are important and their influence varies with soil texture and substrate quantity and quality (Buchmann 2000). As the C/N ratio of the incorporated biomass was low, decomposition took place quickly, which resulted in fast release of soil CO_2. The relationship of soil temperature was significant and negative with that of soil moisture and carbon dioxide emission. Soil MBC was also positively and significantly correlated, but the extent of correlation decreased with increase in fertilizer levels. The soil properties under fallow conditions failed to establish any correlation with soil CO_2 emission except MBC in $N_{50}P_{30}$. Analysis of regression between average values of CO_2 flux and soil properties (soil moisture, soil temperature, and MBC) in all the six treatments also showed the significant role of MBC in explaining the variation in CO_2 emission in all the fertilizer treatments of biomass-incorporated soils. Both soil moisture and MBC accounted for explaining 90% variations in emission in IN_0P_0 with a high probability level.

Conclusions

This article reports the effects of fertilizer application and legume biomass incorporation practices on CO_2 emission at different seasons of the year and influence on few soil properties through a study carried out in a long-term experiment on annual legume biomass incorporation at varied soil fertility conditions in a dryland Alfisols of semi-arid tropical India. The rate of CO_2 emission significantly differed among the different incorporation and fallow treatments. In general, a greater soil CO_2 flux rate apparently indicates greater biological activity in soil at any given time but is a deleterious process from the view point of loss of organic matter from the soil, which is considered as wealth of soil. This process of CO_2 emission from biomass-treated or untreated agricultural land not only robs the soil of its precious C resource but also jeopardizes the environmental safety by adding to the pool of greenhouse gases in the atmosphere. There is no doubt that the soil ameliorative processes in terms of biomass additions and fertility improvement are needed to improve soil quality in rainfed Alfisols of semi-arid tropics, but these management practices should be performed safely to protect the environment. Therefore, an optimum rate of emission of this greenhouse gas needs to be standardized under specific farming conditions to avoid accelerating the buildup in the atmosphere. In this study, biomass-incorporated soil was found to have greater soil CO_2 flux as compared to fallow soils during the Kharif period and legume periods, when the factors controlling its release exerted the greater influence as compared to dry periods with no crops. Though CO_2 emission sometimes becomes necessary during the process of amelioration of soil with crop residues, fertilizer, and other biosolids, it absolutely must be watched and efforts should be made to minimize the emission, as CO_2 emission always acts as a double edged sword (i.e., results in loss of SOC and harms the atmosphere and environment). To distinguish the beneficial role of biomass incorporation and fertilizer additions with reference to fallow condition exclusively on soil CO_2 emissions, there is a need to comprehensively study the contribution of root and soil respiration, decomposition pattern of different C substrates, rate of SOC accumulation, and SOC movement up to rooting depth of rainfed crops with different rates of biomass additions and the associated soil CO_2 emission from below the tillage layers. Thus, the present study is a brief account on the effects of fertilizer application and legume biomass incorporation on CO_2 emission, important soil quality indicators, and their associated relationships. The results of this study will be useful to the future researchers, land managers, and other related stakeholders.

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