Journal of Agricultural and Crop Research
Vol. 2(2), pp. 32-43, February 2014
ISSN: 2384-731X
Research Paper

Influence of soil fertility management on organic carbon mineralization in irrigated rice

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Accepted 25th January, 2014

Abstract. The measurement of soil carbon dioxide (CO_2) respiration is a means to gauge biological soil fertility. A laboratory incubation experiment was conducted for 14 days under controlled conditions (25°C and moisture content 80% of water holding capacity) to study the influence of cropping system on carbon dioxide emission in the Bagré irrigated rice scheme, Burkina Faso, West Africa.. The production of CO_2-C were studied from both bulk samples and particle size fractions ($F > 50$ µm and $F < 50$ µm) of topsoil from a paddy field under a long-term fertility experiment with different amounts of manure and mineral fertilizers collected at plowing, at early tillering and at rice harvesting. The carbon mineralized as CO_2 evolved was measured every day in the first 7 days and every two days in the following days. The CO_2-C production rate was higher in the early phase of incubation, decreased rapidly then, and tended to stable afterwards. The cumulative amounts of CO_2-C were significantly higher ($p < 0.001$) at harvest compared to tillering and tillage. A combined application of chemical fertilizers and manure increased significantly the cumulative amounts of CO_2-C and the paddy related yield. There were correlation between the total carbon and the fraction $F < 50$ µm ($r = 0.932$, $p < 0.001$) and between the total carbon and the fraction $F>50$ µm ($r = 0.712$, $p < 0.048$). The fine fraction therefore was involved significantly in the process of biodegradation and mineralization of soil organic matter. Thus, rational organic and mineral fertilizer should be undertaken for mitigating the climate change.

Keywords: C mineralization, laboratory incubation, paddy soil, particle size fractions, soil fertility management.

INTRODUCTION

Soil carbon mineralization and the carbon dioxide (CO_2) efflux had important effect on the global carbon cycle and terrestrial ecosystem functioning (Jenkinson et al., 1991; Valentini et al., 2000; IPCC, 2008). Organic matter, as one of the main keys to soil productivity, received global attention recently. In particular, an appropriate management strategy towards carbon sequestration can improve soil productivity and crop production as well as help to reduce carbon dioxide efflux in the atmosphere (Goyal et al., 1999). The enhancement of C sequestration in cropland soil not only improves soil fertility but also mitigates atmosphere CO_2 (Lal, 2004). Any change of soil organic carbon (SOC) stock is balanced between C input and output. Throughout the world, fertilization has been proved to improve C sequestration besides crop yield (Franzluebbers, 2005; Rasmussen et al., 1998) through the return of belowground biomass or direct addition of organic manure, while overuse of fertilization may increase the risk of agriculture non-point environment pollution (Yan et al., 2013). This requests us to seek management strategies of attaining high soil C sequestration efficiency and agricultural sustainability. Thus, the addition of organic materials to agricultural soil (with or without chemical fertilizers) is important for replenishing the annual C losses and for improving both the biological and chemical properties of the soils (Goyal et al., 1999). This can be achieved from the plant biomass that is usually removed from the agricultural field and from the extensive use of animal manure with improved management approaches. Indigenous soil properties contribute largely to C and N mineralization, where soil pH can play a dominant role (Wang et al., 2001). Land use practices have great impact on CO_2 flux from soil surface (Creamer et al., 2013). Soil organic carbon (SOC) is a key indicator of fertility and quality of the arable fields (Abro et al., 2011). It has crucial role in nutrient cycling, improving soil physical, chemical, and biological properties, crop productivity, and reducing greenhouse gases (Bhattacharyya, 2009). The mineralization of paddy soil SOC and its potential response to global warming may be of great concern to the C dynamics of agricultural soil in the context of global climate change. Soil respiration is an important aspect of soil quality and an indicator of soil fertility (Staben et al., 1997). Soil incubations are a more direct approach to quantifying mineralizable soil C than various procedures using chemical extraction or organic compound class analysis (Ahn et al., 2009). However, there has been little information either on the relative dominance of CO_2 production during submerged C mineralization or on the effect of chemical fertilization alone on C mineralization and CO_2 production compared to that of combined application. While chemical fertilizers are increasingly applied in paddy's fields, the effect of chemical fertilizers or combined applications of organic and chemical fertilizers is particularly crucial for predicting the future trend of greenhouse gas (GHGs) emission from paddies and possible approaches to mitigate climatic change by agricultural practices.

The aim of this study is to evaluate the influence of cropping systems on the qualitative evolution of soil organic matter in irrigated rice system, using laboratory incubation, with special reference to the soil fertility management effects on C mineralization, CO_2 evolution and paddy related yield.

MATERIALS AND METHODS

Study site

The study was conducted in the rice plain of Bagré village (11°30' N, 0°25' W) located in the eastern part of Burkina Faso, West Africa. The climate is typical for the agro ecological zone of the Sudan savanna with rainy season occurring from July to October, followed by a cold and dry season from November to February, and a hot dry season from March to June. Average annual rainfall is 850 mm yr^{-1} and minimum air temperature below 15°C occur in the cold dry season, and maximum temperatures above 39°C occur in the hot dry season (BEGE, 2008). Soils at the site are developed in alluvial sediments of Quaternary age. According to FAO classification (FAO, 1988), soils of the irrigated plain (600 ha on the left bank of the Nakanbe river) were classified as Gleysols and dystric Fluvisols (62% of total area). Soil depth was between 0.4 to 1.2 m.

Experiment design

The study was conducted with soil samples from a long-term fertility experiment (LTFE) in the evolution of ″organic matter″ in irrigated rice system. Experimental design was a split plot with two varieties (FKR 19 or "TOX 728-1", FKR 14 or "4418") as main plots and eight different amounts of manure and mineral fertilizers as subplots: **T1**: uncultivated soil (no rice crop and no fertilizer application), (uncultivated), **T2**: no fertilization application (control), **T3**: mineral fertilizer application (fmv), **T4**: manure application (fov), **T5**: manure and mineral fertilizer application (fmv+fov), **T6**: uncultivated soil with organic amendment application (uncultivated+OA), **T7**: organic amendment application (OA), **T8**: organic amendment and mineral fertilizer application (OA+fmv). Each treatment was repeated six times. Mineral fertilizer was applied at the rate of 82 kg N ha^{-1}, 31 kg P ha^{-1}, 30 kg K ha^{-1} as 300 kg "cotton fertilizer" and 100 kg urea ha^{-1}. The "cotton fertilizer" was applied at transplanting and urea in two fractions: 35 % at 21 days after transplanting and 65 % at panicle initiation. Manure was applied at the rate of 6 t ha^{-1} yr^{-1} and organic amendment at the rate of 12 t ha^{-1} yr^{-1}, at ploughing. The elementary plot had an area of 30 m^2 (6 m × 5 m). An adjacent field to the study device, maintained without culture and irrigation was called "fallow" or "reference soil".

Soil samples and analysis

Composite soil samples from four spots at 0 to 0.20 m were taken from each of the plots in three occasions: at plowing, at early tillering and at rice harvesting. The soil sample was air-dried and sieved through a 2 mm sieve. The distribution of samples in the time allowed monitoring soil fertility depending on the type of fertilizer, from tillage to harvest. Collection and analysis of CO_2 evolved was conducted by following a procedure described by Morel et al. (1979) and adapted by Sedogo (1993). This method allows a period of incubation, measures the mineralization of organic matter incorporated into the soil by measuring carbon of carbon dioxide (CO_2-C) generated daily. In one liter of glass jar, 100 g of soil were introduced and brought to a humidity of 80% of water holding capacity "WHC"). A CO_2 trap consisting of 20 ml of sodium hydroxide (NaOH) 0.1 N and a bottle of water to moisten the mixture was placed in each jar which

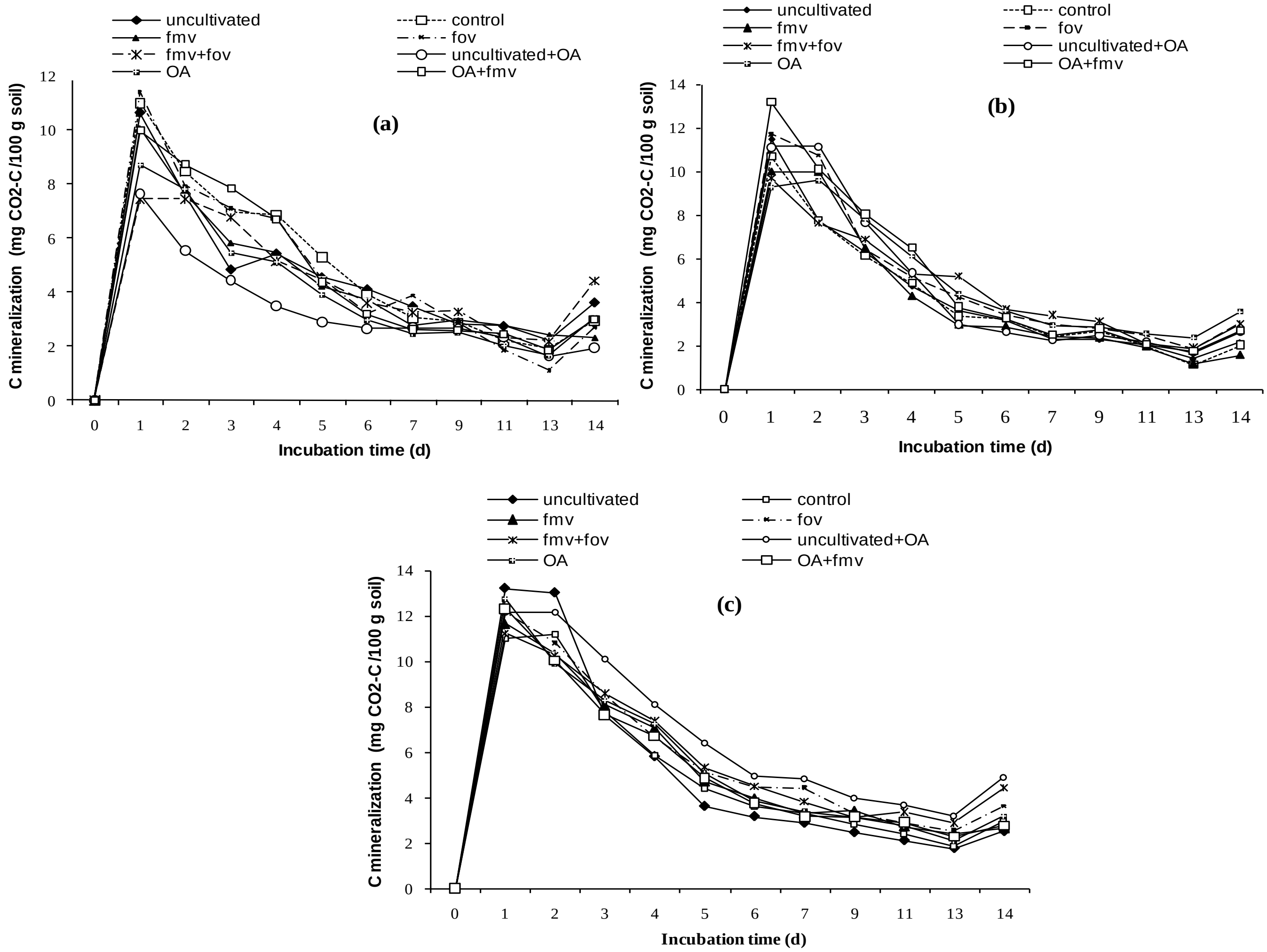

Figure 1. Evolution of daily CO_2-C released in soils at plowing (a); active tillering (b) and harvesting (c).

is then resealed. All bottles thus formed were incubated in an incubator (Thermosi Series SR, France) at a constant temperature of 30°C for 14 days. Each treatment consisted of three replicates, with a series of bottles being used for destructive samplings. The CO_2 released and trapped by NaOH was dosed daily by titration until the seventh day, then every two day until the 14^{th} day with hydrochloric acid (HCl) 0.1 N in the presence of phenolphthalein (color indicator) after prior precipitation of sodium carbonate (Na_2CO_3) with 2 ml of barium chloride ($BaCl_2$) to 3%. All the pots were taken out and opened periodically, aerated for a few minutes, and soil water content was checked and adjusted by weighing then adding distilled water to maintain water levels. A control vial with no soil is included in the incubation to correct for the CO_2 in the jar at the initiation of the incubation. The soil organic carbon was determined by Walkley and Black's titration method (Olsen and Sommers, 1982). The coarse fraction (F > 50 µm) and fine fraction (F < 50 µm) were obtained through dry sieving at 50 µm sieve (Feller, 1979; Sedogo et al., 1994).

The ability to mineralization of total SOC was measured after CO_2-C generated daily and cumulatively. Data were subjected to one way analysis of variance (ANOVA). These data were then subjected to a simultaneous comparison of means by Duncan test when analysis was significant. ANOVA tests and comparison of averages were calculated using a General Linear Model (GLM) implemented in SPSS (SPSS, 2002) software. Tests were conducted with an alpha level of 5%.

RESULTS

Evolution of CO_2-C released

The daily evolution of CO_2-C released showed three main steps in the degradation of organic substrates that corresponded to specific phases of mineralization (Figure 1). The maximum amounts of carbon (9.44 to 11.77 mg CO_2-C) were released on the first day (phase 1) for all treatments and for the three sampling occasions (plowing,

Table 1. CO_2-C released (mg C 100 g^{-1} soil) as affected by treatments during incubation.

Parameter	CO_2-C			Min.day	CO_2-C	
	1st day	7th day	14th day	mean	cumul_d7	cumul_d14
Uncultivated	11.77^{b}	2.90^{a}	2.77^{ab}	4.23^{a}	43.13^{a}	59.15^{a}
Control	10.89^{ab}	2.93^{a}	2.64^{ab}	4.26^{a}	43.70^{a}	59.57^{a}
fmv	10.58^{ab}	2.83^{a}	2.18^{ab}	4.26^{a}	42.63^{a}	59.62^{a}
fov	11.76^{b}	3.76^{b}	3.12^{bc}	4.63^{a}	47.20^{a}	64.81^{a}
fmv+fov	9.44^{a}	3.49^{ab}	3.94^{bc}	4.55^{a}	43.58^{a}	63.67^{a}
Uncultivated+OA	10.25^{ab}	3.25^{ab}	3.15^{bc}	4.48^{a}	43.66^{a}	62.70^{a}
OA	10.29^{ab}	2.93^{a}	3.26^{bc}	4.39^{a}	43.53^{a}	61.42^{a}
OA+fmv	11.83^{b}	2.76^{a}	2.82^{ab}	4.55^{a}	46.44^{a}	63.77^{a}
F Fisher	20.03	6.48	50.72	2.68	5.76	2.68
Prob.	<0.0001	<0.002	<0.0001	<0.055	0.385	<0.055

CO_2-C = carbon of carbon dioxide; d7= 7th day; d14 = 14th day; Min. day = daily mineralization; Prob. = probability

Table 2. CO_2-C released (mg C 100 g^{-1} soil) as affected by sampling occasion during incubation

Parameter	CO_2-C			Min.day	CO_2-C	
	1st day	7th day	14th day	mean	cumul_d7	cumul_d14
Plowing	9.62^{a}	3.02^{b}	2.99^{ab}	4.05^{a}	39.76^{a}	56.43^{a}
Tillering	10.88^{b}	2.65^{a}	2.57^{a}	4.12^{a}	42.12^{a}	57.66^{a}
Harvest	12.06^{c}	3.64^{c}	3.38^{c}	5.08^{b}	50.83^{b}	71.11^{b}
F Fisher	74.41	252.25	63.87	840.10	6370.34	453.15
Prob.	<0.001	<0.0001	<0.001	0.0001	<0.0001	<0.0001

CO_2-C = carbon of carbon dioxide. d7 = 7th day; d14 = 14th day; Min.day = daily mineralization; Prob.= probability.

tillering, harvesting). The release of CO_2-C, first decreased abruptly, then gradually and sharply from the second day but with small peaks until day 7 (phase 2). Then, the release of CO_2-C stabilized gradually (phase 3), tended to rise slightly after the 13th day.

The first phase resulted in a peak with importance varying on soil sampling occasion and treatment. Regarding the different treatments (Table 1), analysis of variance showed a significant difference between them ($p < 0.0001$). The highest CO_2-C released were observed with treatments "OA+fmv" (11.83 mg C 100 g^{-1}soil d^{-1}), "fov" (11.76 mg C 100 g^{-1} soil d^{-1}) and "uncultivated" (11.77 mg C 100 g^{-1} soil).

The CO_2-C released during the first two days were significantly higher ($p < 0.0001$) at harvest (12.06 mg C 100 g^{-1} soil), compared to tillering (10.88 100 mg C g $soil^{-1}$ d^{-1}) and plowing (9.62 mg C 100 g^{-1} soil d^{-1}) occasions (Table 1). Respiration was similar to the treatments "OA", "uncultivated+OA", "fmv" and “control”. The lowest respiration was recorded for "fmv+fov" treatment (9.44 mg C 100 g^{-1} soil d^{-1}). The decline in respiration was high (37%) for the vulgarized dose of organo-mineral fertilizer ("fmv+fov"), followed by treatment "fov" and "uncultivated+OA" (32%). The smallest decline (23%) was observed with "OA+fmv" treatment. Treatments "control” and "fmv" showed a decline in CO_2-C released (27%). The decline respiration was more at tillage (31%) than at harvest (30%) or tillering (24%). The 14th day, the CO_2-C released was lower for tillering samples (2.57 mg C 100 g^{-1} soil), compared to plowing (3.0 mg C 100 g^{-1} soil) or harvesting (3.4 mg C 100 g^{-1} soil) (Table 2). The CO_2-C released on the 14th day was lower for the treatment bringing vulgarized mineral fertilizer ("fmv") (Table 1). The highest CO_2-C released was observed on the 14th day in treatments "fmv+fov" (3.94 mg C 100 g^{-1} soil), with respiration the first day (9.44 mg C 100 g^{-1} soil) compared to other treatments.

The results of the cumulative amounts of CO_2-C allowed a better comparison of the different treatments (Figure 2). The cumulative amounts of CO_2-C showed no significant difference between treatments in the 14th day (data not shown). However, the arithmetic mean cumulative amounts of CO_2-C indicate superiority for the treatment with organic fertilizer, especially "fov" (65 and 100 mg C g^{-1} soil), "fmv+fov" and "OA+fmv" (64 and 100 mg C g^{-1} soil). Control treatments ("uncultivated" and "control") had the lowest cumulative quantities (59 mg C 100 g^{-1} soil). Between the 7th and 14th day of incubation, the increased of accumulation of CO_2-C were 46% ("fmv+fov"), 44% ("uncultivated+OA") and 41% ("OA"). The cumulative amounts of CO_2-C (Figure 2) were significantly higher for samples collected at harvest (51 and 71 mg C 100 g^{-1} soil) respectively for 7th and 14th day of incubation) compared with those taken at tillering (42 and 57 mg C 100 g^{-1} soil respectively for the 7th and 14th day), as well as those of plowing (40 and 56 mg C 100 g^{-1}

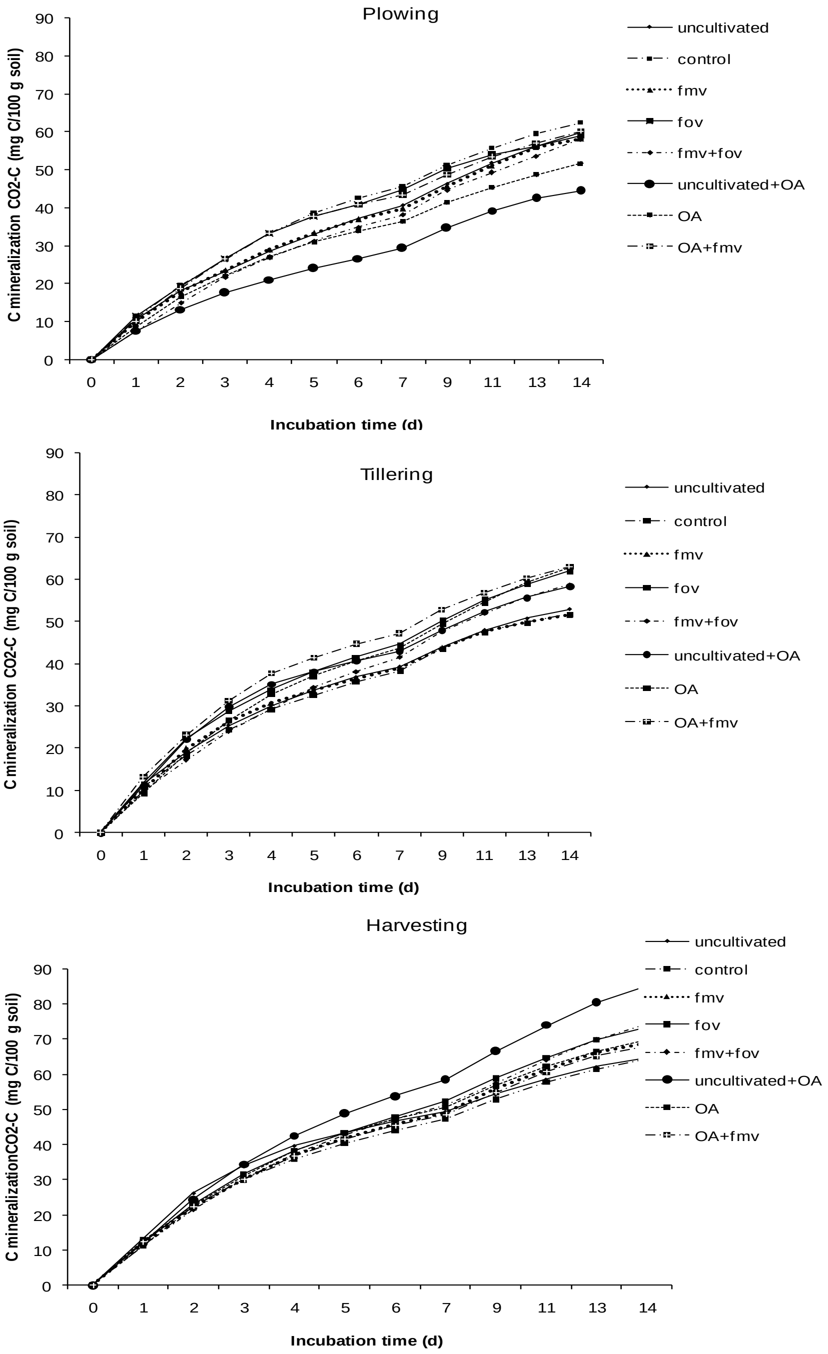

Figure 2. Cumul of CO_2-C released in 14 days of incubation for samples taken at plowing. active tillering and harvesting.

soil) respectively for 7th and 14th day of incubation).

Relations between the fractions content in total carbon and the mineralized soil organic carbon

The values of the C/N ratio of the fractions are shown in Table 3. In the 0 to 0.20 m horizon, organic matter associated with the coarse sand fraction (F > 50 µm) had a C/N ratio lower (3 to 7) than the fine organic matter associated with clay and silt fraction (F < 50 µm) which was characterized by a C/N ratio higher (11 to 18). The same trend was observed in the 0.20 to 0.50 m horizon, organic matter of the fraction F > 50 µm with a C/N ratio of 3 to 4, whereas for the fraction F < 50 µm the C/N ratio was between 8 and 11.

The fractions content in total organic carbon (mg g^{-1} fraction) were collected in Table 4. Generally, the carbon

Table 3. Effect of fertilization on carbon/nitrogen distribution in particle size fractionation (carbon/nitrogen) in the layers 0 to 0.20 m and 0.20 to 0.50 m.

Parameter	Carbone/Azote (C/N) ratio			
	0-0.20 m		0.20-0.50 m	
	F > 50 µm	F < 50 µm	F > 50 µm	F < 50 µm
"fallow"	6.8	12.0	3.8	9.3
"uncultivated"	4.4	18.4	3.4	10.5
"control"	5.3	14.5	3.0	8.8
"fmv"	3.3	11.2	2.7	8.6
"fov"	3.0	17.4	3.4	9.7
"fmv+fov"	3.3	19.4	3.8	8.4
"uncultivated+OA"	6.3	13.1	3.5	8.7
"OA"	4.8	17.7	3.5	8.6
"OA+fmv"	4.9	17.7	3.9	8.0

of different treatments decreased with cultivation compared to "fallow" on the horizon 0-0.20 m, except carbon contents of treatments providing organic fertilizer vulgarized ("fov" 6 t ha^{-1} yr^{-1}) and combining mineral and organic fertilizer ("fmv + fov"). The F> 50 µm fraction represented 7.8% of total fractionated soil organic carbon. In the 0.20 to 0.50 m horizon in contrast, the carbon content of all treatments except the control without irrigated rice ("uncultivated") increased from 0.6 to 8.4% compared to the "fallow".

However, variations in the organic stock registered with manures do not affect the fractions in the same way. The F> 50 µm fraction represented 7.5% of the total soil organic matter fractionated. The F < 50 µm fraction contained more than 92.2% of the total soil organic matter fractionated (Table 4) in the 0 to 0.20 m horizon. Compared with the original stock, its carbon content generally decreased for all treatments except for carbon contents of treatments providing organic fertilizer ("fov" 6 t ha^{-1} yr^{-1}) and the combination of mineral and organic fertilizer ("fmv + fov"). In the "fallow" soil for 0.20 to 0.50 m layer, the F < 50 µm fraction represented 92.5% of the total soil organic matter fractionated. Almost all organic matter was accumulated in the lower horizon (0.20 to 0.50 m) and in the organo-mineral fraction. This result indicates an increase in carbon content in relation to the "fallow" and allows the hypothesis of an accumulation of organic matter after cultivation in irrigated rice conditions.

The correlations between carbon contents (in sand fractions (F > 50 µm), the organo-mineral fraction (F < 50 µm) and total carbon), and the cumulative quantities of CO_2-C released the 7th and 14thday of incubation were assessed. The CO_2-C released after the 7th day of incubation was more correlated with the carbon in the fine fraction (r = 0.205) than the total carbon (r = 0.121) (Table 5 and Figure 3). This was also true for total CO_2-C released after the 14th day with r = 0.748 ($p < 0.033$) for F < 50 µm and r = 0.657 ($p < 0.076$) for total carbon. There were slight correlations (and low negative) between CO_2-C released on the 7th and 14th day of incubation, respectively and the coarse fraction of the carbon on the one hand, and on the other hand the correlation between total carbon and fraction F< 50 µm (r = 0.932, $p < 0.001$) and between the total carbon and the fraction F>50 µm (r = 0.712, $p < 0.048$). The fine fraction therefore was involved significantly in the process of biodegradation and mineralization of soil organic matter.

Evolution of paddy related yield

Figure 4 showed yields for five combined paddy cropping cycles. The difference was significant ($p < 0.0001$) between treatments for the five combined cropping cycles (Figure 4). For the variety FKR 19, paddy yield evolved as "OA+fmv"> "fmv+fov"> "fmv"> "OA"> "fov"> “control”. The ANOVA also showed that the difference was significant ($p < 0.0422$) between paddy yields of varieties x treatment interaction (Figure 4, data not shown). With FKR 14 variety, the difference was significant between the paddy yield treatments "OA+fmv", "fmv+fov" and "fmv". For contrast, the difference was not significant between yields of treatments "fmv+fov" and "OA+ fmv" with variety FKR 19. The paddy yields of these two treatments were significantly superior to paddy yields obtained with the FKR 19 variety for treatment "fmv". The paddy yields of both varieties were significantly higher for treatments "OA" and "fov", but the yields were very low compared to treatment "fmv", "fmv+fov" and "OA+fmv". For the “control” treatment, there was no significant difference between the two varieties. For contrast, the paddy yields of both varieties were significantly lower for “control” compared to other treatments.

DISCUSSION

Carbon mineralization pattern observed with incubations soils allowed better understanding of some mechanisms governing the dynamics of soil organic matter under

Table 4. Effect of fertilization on total soil carbon distribution in particle size fractions.

Parameter	Total C				F > 50 µm			F < 50µm		
	Bulk soil		Fractioned soil							
	mg C/ g sol	%C total	mg C/ g fraction	Indice	mg C/ g fraction	% C total	Indice	mg C/ g fraction	% C total	Indice
0-20 cm										
"fallow"	5.59	100	5.23	100.0	0.41	7.8	100.0	4.82	92.2	100.0
"uncultivated"	6.05	108	5.19	99.3	0.40	7.7	98.2	4.79	91.6	99.4
"control"	6.14	110	5.01	95.8	0.37	7.1	91.3	4.64	88.7	96.2
"fmv"	6.23	111	5.02	95.9	0.30	5.8	74.7	4.71	90.1	97.7
"fov"	6.46	116	5.44	103.9	0.39	7.4	94.8	5.05	96.5	104.7
"fmv+fov"	6.61	118	5.24	100.1	0.39	7.5	96.2	4.84	92.6	100.4
"uncultivated+OA"	6.40	114	4.89	93.5	0.57	10.9	139.4	4.32	82.6	89.6
"OA"	6.15	110	5.15	98.5	0.38	7.3	93.1	4.77	91.3	99.0
"OA+fmv"	6.26	112	5.12	98.0	0.34	6.5	82.9	4.79	91.5	99.3
20-50 cm										
"fallow"	5.56	100	5.04	100.0	0.38	7.5	100.0	4.66	92.5	100.0
"uncultivated"	5.81	104	4.97	98.6	0.37	7.3	97.3	4.60	91.3	98.7
"control"	5.97	107	5.27	104.6	0.33	6.6	88.6	4.94	97.9	105.9
"fmv"	5.93	107	5.19	103.0	0.30	5.9	79.0	4.89	97.0	104.9
"fov"	6.18	111	5.38	106.8	0.34	6.7	89.4	5.05	100.1	108.2
"fmv+fov"	6.32	114	5.07	100.6	0.38	7.6	101.7	4.68	92.9	100.5
"uncultivated+OA"	6.46	116	5.47	108.4	0.42	8.4	112.1	5.04	100.0	108.1
"OA"	6.14	110	5.29	104.9	0.39	7.8	103.6	4.90	97.2	105.1
"OA+fmv"	6.00	108	5.12	101.6	0.39	7.8	103.8	4.73	93.8	101.4

Table 5. Matrice of correlations.

Parameter	F < 50 µm	F > 50 µm	C total
Cumul of CO_2-C released in the 7th day	0.205	- 0.095	0.121
Cumul of CO_2-C released in the 14th day	0.748*	0.206	0.657

*significative (5%); CO_2-C = carbon of carbon dioxide.

irrigated agriculture and the impact of soil fertility management systems. The phase of rapid decline of CO_2-C observed from the second to the 7th day was a reduction in biological activity due to the decrease of easily biodegradable compounds. The small peaks observed during this phase corresponded to a slight increase due to the degradation of newly formed products (Sedogo, 1993; Hadas et al., 2004; Haney et al., 2008). The phase of slow and linear mineralization corresponded to the degradation of more resistant compounds such as lignin (Hofmann et al., 2009;

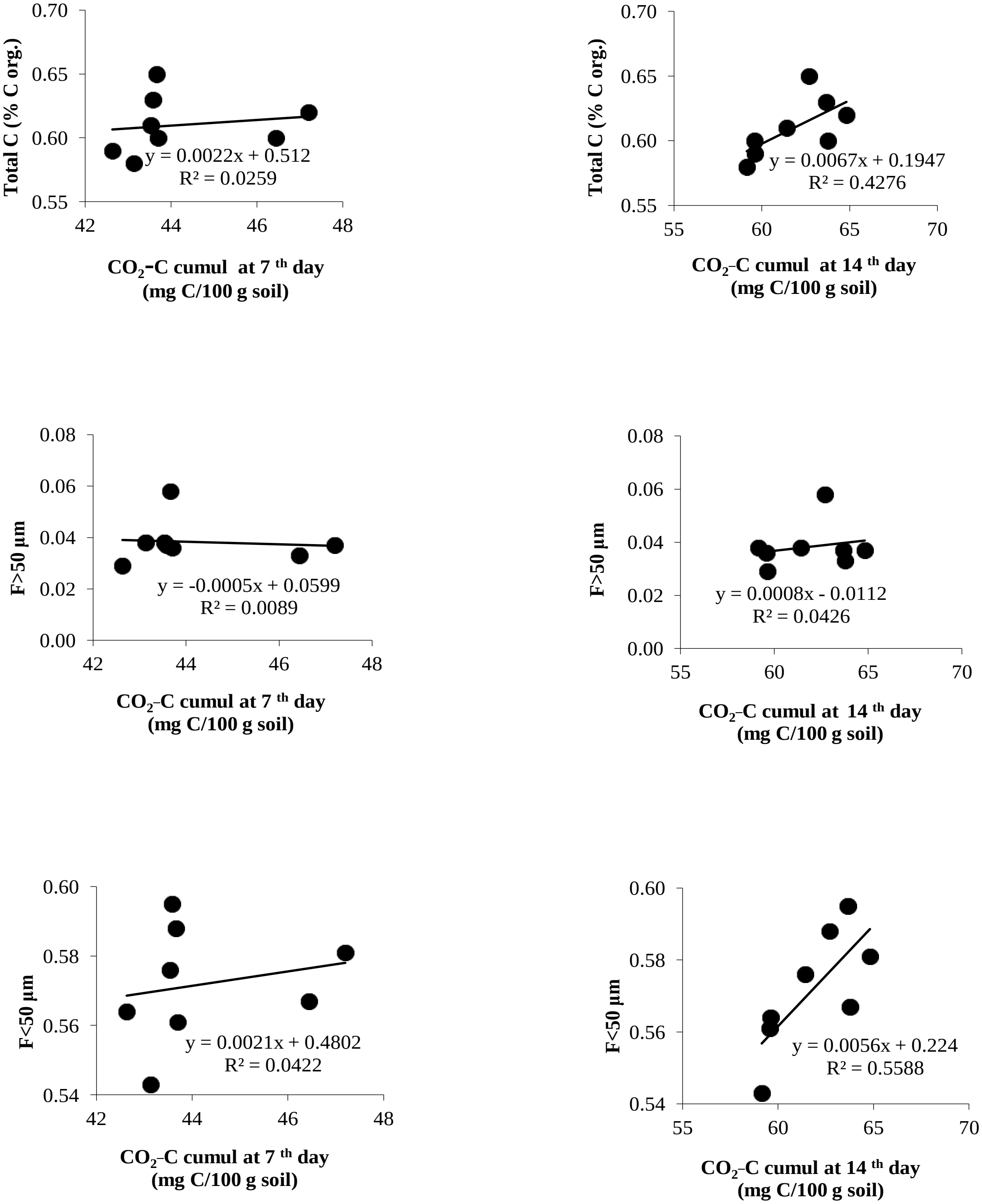

Figure 3. Relations between total carbon (C tot.). coarse fraction (F>50 µm). fine fraction (F < 50 µm) and cumulative CO_2-C released at 7 and 14 days of incubation.

Wisal, 2010). Treatments without organic matter application had lowest cumulative quantities of CO_2-C, compared to treatments providing organic fertilizer, especially "fov", "fmv+fov" and "OA+fmv". Similar results were reported (Sedogo, 1993; Thuriès et al., 2002; Gnankambary et al., 2007; Lompo et al., 2009). The cumulative amounts of CO_2-C were higher at harvest compared to tillering and tillage. These results suggested that during a crop cycle, flooding increased the level of total organic carbon in the soil, confirming the hypothesis of an accumulation of organic matter in irrigated rice with time, supported by previous findings (Kanke, 1988). Being cautious in relation to the size of observations number (eight), the primary conclusion was that in the Bagré

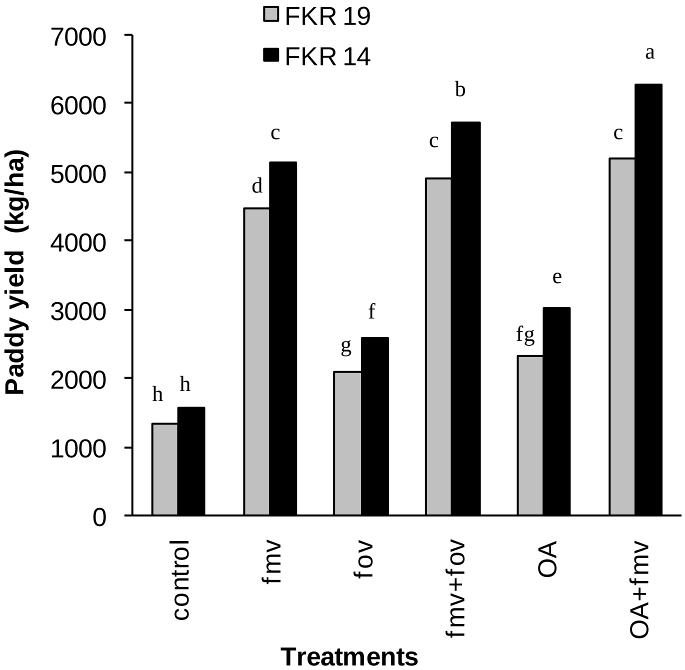

Figure 4. Average paddy yields for varieties FKR 19 (TOX 728-1) and FKR 14 (4418) for five combined cropping seasons in the Bagré plain.

soil under irrigation, the fine fraction was more prone to mineralization processes. The few studies of carbohydrate accumulation reported conflicting comparisons between submerged and aerated soils. Kanke (1988) found a higher accumulation of carbohydrates under submerged conditions, especially for the pentose fraction, whereas Ye and Wen (1992) found no effect of soil submergence on carbohydrate accumulation, although the type of amended plant materials differed between their submerged and upland soils. The carbon storage would occur through mainly by increasing the root biomass and secondly by the percolation of the dissolved organic material with time (between plowing and harvesting). Fine turning experiments would help to better understand the process of carbon sequestration during the paddy irrigated crop cycle.

Cultivation caused faster mineralization of soil organic matter. This mineralization mainly occurred from organic stock of the coarse and fine fractions. The results suggested that organo-mineral fraction concentrated the majority of the total soil carbon. It seems to be the carbon compartment reserves used in the long run, which was consistent with the results from Feller et al. (1991) and Sedogo (1993). In contrast, the higher C/N ratio of the fine fraction than the coarse fraction, contradicted these same authors. This phenomenon can be explained by the breakdown of soil particles with the soil management techniques used in irrigated rice. The mechanisms related to tillage effect on carbon biodegradation rates have been the subject of a review by Balesdent et al. (2000). The main effect seems to be a waiver of the physical protection of organic matter (Oades, 1995). Rotating harrows used in irrigated rice to mix the soil would have a direct effect by breaking aggregates and thus the de-protection of organic matter (Chenu et al., 2000). Induced disintegration of solid particles by tillage (plowing, puddling, harrowing and leveling) in the 0.0 to 0.20 m depth redistributed aggregate size spectrum, including breaking the macro aggregates (size > 250 µm) associated with the coarse fraction whose stability is reduced due to the decrease in biological activity (Cassman et al., 1998; Six et al., 2000). The organic matter of these aggregates was exposed to mineralization, inducing a faster retrieval of carbon. In contrast, micro-aggregates (size < 250 µm) associated with the fine fraction (clay + silt) might resist more to disintegration. Tillage broken soil solid particles, which might induce the decomposition of organic matter by the reduction or loss of physical protection in the soil upper layer "plowed" (0.0 to 0.20 m). Indeed Tisdall and Oades (1982) demonstrated that macro aggregates are easily destroyed by tillage, while micro aggregates are more stable. In dryland soils, Reicosky (1997) reports good correlation between CO_2 loss and tillage intensity, and demonstrates why farming systems that use mould-board ploughing inevitably lose soil C.

In the lower horizons (0.20 to 0.50 m) undisturbed by tillage (data not shown), we can hypothesize more "stabilization" of the fine fraction and reduced microbial activity. Our finding was supported by the results of Six et al. (2004). Our results showed that 92.5% of the total soil organic carbon originated from the 0.20 to 0.50 m horizon. This could be explaining by the fact that the stability of aggregates protected soil particles against microbial attacks, contributing to carbon sequestration in the lower horizons. The term carbon storage will depend on the ability of organic materials to resist to biodegradation by micro-organisms in the soil (Agu et al., 2000).

Recent studies highlighted “the self protection” of organic matter due to soil constituents slowing their mineralization (Chenu et al., 2000; Six et al., 2004). The C pool is generally considered as physically protected in macro-aggregates (Six et al., 2002), and is shown as not readily accessible to microbial mineralization even under warming (Garten et al., 1999). Many studies have demonstrated that the C sequestration in paddy soils was characterized by the increase of SOC in physically protected coarse aggregates in the size of sand particles (Yuan et al., 2004). For Zhang et al. (2007), C mineralization of paddy soils depends not only on the chemical lability of SOC (pool distribution), but also on the microbial metabolic activity and the soil N status. Although labile C may give significant contribution to mineralizable C, accumulation of younger or labile C does not necessarily enhance the C mineralization potential, which could be considered as a result of mutual interaction of C availability, accessibility to the protected labile C pools, and the metabolic activity of microbes affected by soil nutrient and moisture regimes (Zhang et al., 2007). Our results also corroborated previous studies (Kiem et al., 2002; Quenea et al., 2004; John et al., 2005) and Zheng et al. (2007) who showed that SOC associated with fine particle size fractions (PSFs) were basically refractory and slow to turnover. Previous work on humus fractionation in different size fractions also showed increasing humification with the decreasing size of the PSFs (Ding et al., 2006).

The result of the existence of more or less stable aggregates depending on the presence of young organic matter helps to understand that the biodegradation rates will vary depending on the degree of humification of organic matter and association with the mineral phase of the soil (Agu et al., 2000). This could explain the fact that fine fraction associated to micro aggregates seems "labile" in the upper horizon and "stable" in the 0.20 to 0.50 m layer, thus contributing to an improvement in soil fertility in organic conditions for irrigated rice. This study was a contribution for further research into other parameters such as enzymes activity, determination of microbial populations taking part in the processes of catabolism and anabolism of compounds containing carbon and nitrogen in this environment. For example, the extraction of humic substances by fractionation could provide further understanding of the physical protection of organic matter.

Contrary to the results obtained by Flinn and De Datta (1984), Cassman et al. (1996), Yadav et al. (2000), the positive effect of treatments receiving organic and mineral fertilizer on paddy yields was obvious. The significantly higher yields were obtained with treatments providing mineral fertilizer ("fmv") or organo mineral fertilizer ("fmv + fov" and "OA + fmv"). Saleque et al. (2004) obtained similar results to ours. Application of organic manure alone ("fov" or "OA") does not stabilize yields. They are lower than those obtained with mineral fertilizer ("fmv") only. Mineral fertilizer vulgarized ("fmv") allows a very significant increase in paddy yields compared to organic fertilization. In addition, treatments "OA+fmv", "fmv+fov", "OA" have significantly higher yields. The superiority of organo-mineral fertilization on paddy yield was demonstrated. Several authors have observed similar results in both dry crops (Sedogo, 1993; Bonzi, 2002) and in irrigated cropping (Yadav et al., 2000; Yan et al., 2013). At the Office du Niger, cattle manure combined with 50 kg ha^{-1} of nitrogen applied at panicle initiation provides a level comparable to high mineral fertilization with 100 kg N ha^{-1} + 30 kg P_2O_5 ha^{-1} (Narteh and Sahrawat, 2000). Dawe et al. (2000) also reported an increase in paddy yields in several long-term trials in the Philippines. In two long-term fertilization experiments, Yan et al. (2013) showed that chemical and/or organic fertilization not only increased crop yield but also reduced its yearly variation. In the view of agriculture sustainability, the combined chemical and organic fertilization is a promising practice with which to obtain a high and stable crop yield irrespective of climate change. Our results were consistent with many other studies’ findings that application of organic manure increased yield as compared to chemical fertilizer alone (Cai and Qin, 2006; Fan et al., 2008; Bi et al., 2009; Li et al., 2010; Yan and Gong, 2010; Zhang et al., 2012; Yan et al., 2013). The combined chemical and organic fertilization is the most promising practice for crop yield as well as C sequestration (Yan et al., 2013).

CONCLUSION

The distribution of organic matter fractions with different characteristics (C/N) affected the behavior of the soil, in particular, its ability to carbon mineralization. The maximum amounts of carbon released as carbon dioxide occurred on the first day of incubation. They were proportional to the amount of organic carbon available. During a crop cycle, flooding increased the level of total organic carbon in the soil, confirming the hypothesis of an accumulation of organic matter in irrigated rice in the long term.

The C/N ratio of the fine fraction was higher than that of the coarse fraction. Mixing undergone by the soil under intensive irrigated rice cultivation conditions (plowing, puddling, harrowing, leveling) with two growing seasons per year in the surface horizon (0.0 to 0.20 m) contributed to destroy the aggregation particles (especially macro-aggregates), thereby reducing their physical protection by clay: the physico-chemical degradation became faster this time, contributing to the release of nutrients and improved mineral nutrition of plants. In contrast, in the lower horizons (e.g. 0.20 to 0.50 m), where the mixing does not occur (the plow being located up to 0.20 m deep), the mineralization of organic matter would be much slower. The accumulation of organic matter is greater in the lower horizons (0.20 to 0.50 m for example); this could partly explain the sustainability of irrigated rice and relatively small decline in soil fertility in this agricultural system. The labile C played an important role in the mineralization of SOC in paddy soils. Moreover, the data here indicated that there were different subpools of the mineralizable C in the paddy soils that had different accessibility to mineralization and different responses to soil fertility management. The role of C availability and microbial community in the C mineralization of these paddy soils still deserves further study.

ACKNOWLEDGEMENTS

The authors are grateful to the anonymous reviewers for their suggestions in improving both the scientific and linguistic quality of the manuscript.

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