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Reducing soil CO_2 emission and improving upland rice yield with no-tillage, straw mulch and nitrogen fertilization in northern Benin

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ABSTRACT

To explore effective ways to decrease soil CO_2 emission and increase grain yield, field experiments were conducted on two upland rice soils (Lixisols and Gleyic Luvisols) in northern Benin in West Africa. The treatments were two tillage systems (no-tillage, and manual tillage), two rice straw managements (no rice straw, and rice straw mulch at 3 Mg ha^{-1}) and three nitrogen fertilizers levels (no nitrogen, recommended level of nitrogen: 60 kg ha^{-1}, and high level of nitrogen: 120 kg ha^{-1}). Potassium and phosphorus fertilizers were applied to be non-limiting at 40 kg K_2O ha^{-1} and 40 kg P_2O_5 ha^{-1}. Four replications of the twelve treatment combinations were arranged in a randomized complete block design. Soil CO_2 emission, soil moisture and soil temperature were measured at 5 cm depth in 6–10 days intervals during the rainy season and every two weeks during the dry season. Soil moisture was the main factor explaining the seasonal variability of soil CO_2 emission. Much larger soil CO_2 emissions were found in rainy than dry season. No-tillage significantly reduced soil CO_2 emissions compared with manual tillage. Higher soil CO_2 emissions were recorded in the mulched treatments. Soil CO_2 emissions were higher in fertilized treatments compared with non-fertilized treatments. Rice biomass and yield were not significantly different as a function of tillage systems. On the contrary, rice biomass and yield significantly increased with application of rice straw mulch and nitrogen fertilizer. The highest response of rice yield to nitrogen fertilizer addition was obtained for 60 kg N ha^{-1} in combination with 3 Mg ha^{-1} of rice straw for the two tillage systems. Soil CO_2 emission per unit grain yield was lower under no-tillage, rice straw mulch and nitrogen fertilizer treatments. No-tillage combined with rice straw mulch and 60 kg N ha^{-1} could be used by smallholder farmers to achieve higher grain yield and lower soil CO_2 emission in upland rice fields in northern Benin.

1. Introduction

Climate change, caused mainly by increased concentrations of CO_2 in the atmosphere (IPCC, 2013), and food security problems owing to the fast-growing human population and loss of farmland have become global issues that seriously threaten developing countries (Liu et al., 2014). Agriculture is an important source of CO_2 emissions, and its contribution to climate change is approximately 14% on an annual basis (Vermeulen et al., 2012). Small changes in the magnitude of soil CO_2 emission could have a large effect on the concentration of CO_2 in the atmosphere (Schlesinger and Andrews, 2000). In order to reduce and mitigate the potential negative effects of climate change on ecosystems and human well-being, a series of strategies are needed to reduce CO_2 emissions and atmospheric CO_2 concentration (Vermeulen et al., 2012). In this respect, enhancement of soil carbon sequestration in agricultural systems is one of the strategies to both offset atmospheric CO_2 increases and achieve food security through improvements in soil quality (Lal, 2004).

Soil CO_2 emission is complex and variable, and is controlled by many abiotic and biotic factors (Liu et al., 2014). Generally, sources of CO_2 from a soil can be attributed to biological and chemical

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activity within the soil. Soil CO_2 emission involves organisms metabolizing substrates producing CO_2 within the soil matrix (Al-Kaisi et al., 2008). Microbial decomposition of organic matter (heterotrophic respiration) and root respiration (autotrophic respiration) also contribute to soil CO_2 emission (Raich and Mora, 2005). The mechanism of soil CO_2 emission to the atmosphere, however, involves the movement of CO_2 through soil pores, and release from the soil system can be measured at the soil surface (Al-Kaisi et al., 2008).

Rice has become the most rapidly growing food source in West Africa as a consequence of population growth, rising income and a shift in consumer preferences in favor of rice, especially in urban areas (Balasubramanian et al., 2007). There are two main ecosystems of rice known as upland and lowland rice. Upland rice, also known as aerobic rice, is generally grown in non-flooded, well drained soils on level to steeply sloping fields. Lowland rice, also known as paddy rice, is generally grown on soils that are flooded or irrigated (Andriesse and Fresco, 1991). The carbon dynamics in upland rice fields significantly differs from that in lowland rice fields. In upland rice fields, the carbon accumulated in the soil is constantly released to the atmosphere due to aerobic decomposition (Nakadai et al., 1996). In lowland rice fields, during the submerged period of rice cultivation, CO_2 emission from the soil is limited mainly due to a decrease in the heterotrophic respiration in the soil deoxidized under the flooding water and due to carbon fixation by algal photosynthesis. During the submerged period in lowland fields, on the contrary, methane emission from the soil increases (Epule et al., 2011). In a comparative analysis of the soil carbon budgets of upland and paddy rice fields, Nishimura et al. (2008) found a carbon accumulation in the soil of the paddy rice plots (from +79 to +137 g C m^{-2} y^{-1}), and a significant carbon loss in the upland rice plots (from −343 to −275 g C m^{-2} y^{-1}).

In Benin, rainfed upland rice ecosystems account for about 27% of the total rice area (Diagne et al., 2013). Rice is typically grown under intensive tillage in slash-and-burn systems (Saito et al., 2010). Such practices have been reported to be major contributors to soil CO_2 emission (Baker et al., 2007).

Application of plant residues as mulch, instead of burning, has beneficial effects for replenishing soil organic carbon (Al-Kaisi and Yin, 2005), and the return to the soil of 1 Mg ha^{-1} of straw (rice, wheat or maize) each year can sequester about 130 kg C ha^{-1} a year (Lu et al., 2009). However, the effects of straw mulching on soil CO_2 emission and crop yield have not been conclusively agreed upon among reported studies. Decomposition of straw added to soil and subsequent release of CO_2 and nutrients are governed by many factors such as soil moisture, soil temperature and soil nitrogen content (Abro et al., 2011). Soil CO_2 emission was reported to be higher in straw-mulched than in non-mulched rice fields (Bhattacharyya et al., 2012). In contrast, cumulative soil CO_2 emission was 24% lower for no-tillage systems with residue amendment than without in corn-soybean fields (Al-Kaisi and Yin, 2005). In the north China Plain, soil CO_2 emissions in a maize field were 35.4% and 19.9% lower in mulching treatments than in non-mulching treatments in 2012 and 2013, respectively (Liu et al., 2014). Straw mulch with optimum N fertilizer in zero tillage reduced soil CO_2 emissions and gave better yields (Tanveer et al., 2013). However, the reports on the effect of straw mulching on soil CO_2 emission and crop yield are not consistent; therefore, further study is required to assess the effect of mulching on soil carbon emission and utilization in cropland.

Tillage is an integral part of rice cultivation in Benin. This technique, however, is considered as one of the most important sources of CO_2 emissions to the atmosphere. Studies have shown that 30–50% of soil carbon has been lost through intensive tillage practices (Baker et al., 2007), and major carbon losses from soils in

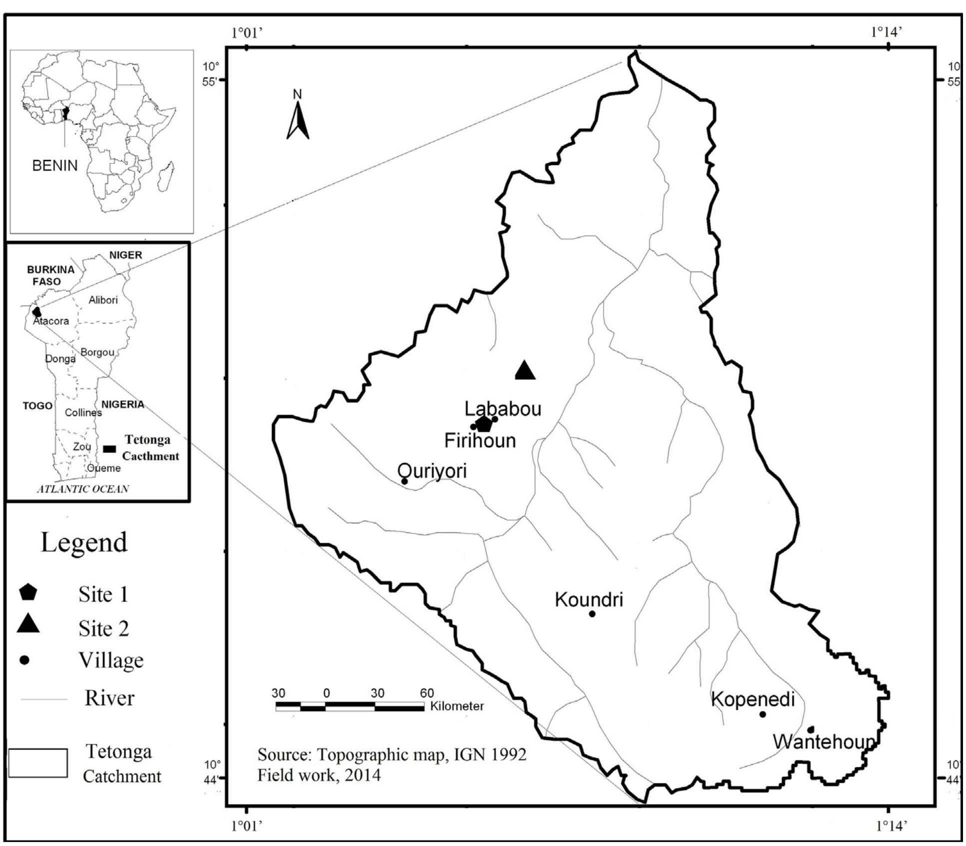

Fig. 1. Location of the experimental sites.

the form of CO_2 occur immediately after tillage (Al-Kaisi and Yin, 2005; La Scala et al., 2006). While it has been well documented that no-tillage, compared with intensive tillage, reduced soil CO_2 emission, its effect on crop yields has not been conclusively agreed upon among reported studies. Tsuji et al. (2000) reported that upland rice yield was higher in no-tillage management than in conventional tillage management in two out of three years in Japan. However, Saito et al. (2010) found that conversion to zero tillage may decrease upland rice yield in southern Benin. The reasons for such contrasting results are not clear; but they might be due to differences in agro-ecosystems and fertilization practices.

Soil nitrogen availability is a major constraint to upland rice productivity in Benin (Saito et al., 2010). Several studies reported the use of low amounts of nitrogen fertilizers by rice farmers which resulted in lower yields (Fageria et al., 2010). However, there is considerable discussion about the response of soil CO_2 emission to nitrogen fertilization, with some studies showing a suppressive effect (Al-Kaisi et al., 2008) and other a positive stimulatory effect (Mulvaney et al., 2009). Also here further research is needed to examine the effects of nitrogen fertilization on soil CO_2 emission.

It is necessary to evaluate the effects of management practices on soil CO_2 emission and upland rice yield in Benin in order to suggest alternative farming strategies to the upland rice farmers. The objectives of this study, therefore, were to (1) identify the effects of tillage systems, rice straw management and nitrogen application on soil carbon emission and upland rice yield, (2) determine the optimum level of nitrogen fertilizers to increase rice yield under various tillage systems and rice straw management, and (3) suggest an optimum combination of factors for efficient management practices to reduce soil carbon emission and increase upland rice yield.

2. Material and methods

2.1. Experimental sites

The study was conducted from June 2014 to February 2015 on two upland rice soils in the Tetonga catchment in northern Benin. The catchment is located between 1°01′ E and 1°14′ E and 10°42′ N and 10°57′ N and belongs to the Sudanian Savannah agro-ecological zone in West Africa. In this area, the climate is semi-arid with one dry season (November–April) and one rainy season (May–October). The mean annual air temperature, precipitation and potential evapotranspiration are 27 °C, 1177 and 1484 mm, respectively (data from 1985 to 2014). The two experimental fields were within 2 km of each other in a gently sloping area with relative difference in elevation between the two fields of about 3 m. Site 1 was located at the upper part, and Site 2 was at the lower part of the toposequence (Fig. 1). According to FAO soil taxonomy, the soil at the upper slope was a Lixisol and at the lower slope a Gleyic Luvisol (Youssouf and Lawani, 2000). Soil samples (0–20 cm soil layer) were collected in each site before the onset of the experiment for sand and clay contents, pH, content of soil organic carbon, total nitrogen, extractable phosphorus and potassium. The sand and clay contents were determined based on the hydrometer method (Bouyoucos, 1951). The soil pH was determined using a soil-water ratio of 1–2.5. The content of soil organic carbon was determined by chromic acid digestion and the total nitrogen by Kjeldahl digestion. The available phosphorus content of the soil was determined using the Bray-1 method (0.5 M HCl + 1 M NH_4F). The soil potassium was extracted with 1 M NH4-acetate and the content was determined by flame emission spectrophotometry. The scheme used in this study for the interpretation of soil chemical characteristics is presented in Table 1.

Soil of Site 1 was loamy, slightly acidic (pH 6.1–6.5) with low organic carbon content (<0.5%), while soil of Site 2 was a clay loam, neutral (pH 6.6–7.3) with medium organic carbon content (1.2%). Both sites had low nitrogen (<0.03%), medium phosphorus (10–20 ppm) and medium potassium (0.8–1.6%) content. The two experimental sites were previously in continuous rice cultivation under manual tillage, rice straw removal and no fertilizer application.

Table 1
Interpretation scheme of soil chemical properties.

Soil chemical characteristics	Interpretation scheme			
	Very low	Low	Medium	High
pH water	<6.1	6.1–6.5	6.6–7.3	>7.3
Organic carbon (%)	<0.58	0.58–0.80	0.80–1.50	>1.50
Total nitrogen (%)	<0.03	0.03–0.045	0.045–0.08	>0.08
Available phosphorus (ppm)	<5	5–10	10–20	>20
Potassium (%)	<0.4	0.4–0.8	0.8–1.6	>1.6

Source: Sys et al. (1993).

2.2. Experimental design and treatments

The experiment consisted of twelve treatment combinations, i.e., two levels of tillage, two levels of crop residue, and three levels of nitrogen (N) application. The two levels of tillage were no-tillage (T_0) and manual tillage (T_1). The two levels of crop residue were no-rice straw mulch (M_0) and rice straw mulch at 3 Mg ha^{-1} of dry rice straw (carbon content: 53.36%, nitrogen content: 0.65%, C:N ratio 82:1) (M_1). The three levels of nitrogen application were N_0: no nitrogen application, N_1: recommended level of nitrogen (60 kg N ha^{-1}) by extension services in north Benin and N_2: high level of nitrogen (120 kg N ha^{-1}). Potassium and phosphorus fertilizers were applied in all the experimental plots to be non-limiting at 40 kg K_2O ha^{-1} and 40 kg P_2O_5 ha^{-1}. Nitrogen, potassium and phosphorus were applied in the form of urea, triple superphosphate and muriate of potash, respectively. The full rate of P and K with 50% of the N was applied as basal fertilizer the day of sowing. 25% of the N was applied in the beginning of the tillering stage (about two weeks after germination) by top dressing. The last 25% of the N was applied at panicle initiation stage by top dressing. With a net plot size of 6 m × 5 m, four replications of the twelve treatment combinations were arranged in a randomized complete block design.

The no-tilled plots were treated with glyphosate to kill the fallow vegetation whereas the tilled plots were ploughed with hand hoes to the depth of 15–20 cm from the soil surface to loosen the soil and to remove the fallow vegetation as commonly practiced in the study area. The desired rates of rice straw were applied on the plots. NERICA14 (WAB 880-1-32-1-2-P1-HB; *O. sativa x O. glaberrima* interspecific progeny) rice variety was sown on 19 July 2014. Rice seeds were directly sown by hand using a dibbling stick at a row and plant-to-plant distance of 20 cm with four seeds per hill. Pre-emergence herbicide (CONDAX©, 30% bensulfuron-methyl-W.P) was applied 24 h after rice sowing. Two weeks after sowing (corresponding to approximately one week after germination of rice seeds), the rice plants were thinned to two plants per hill. Thereafter, weeds were hand-picked when it was necessary so as to keep the plots weed-free. At maturity, two replicates of 1 m^2 were harvested in the center of each plot by cutting the stalk directly on the soil surface. The samples were threshed to determine grain and straw yields. The dry weight of straw biomass was obtained after 72 h in the drying oven at 70 °C. Grain yields were reported at 14% moisture content.

2.3. Carbon dioxide emission, soil temperature and soil moisture measurements

The soil CO_2 emission was measured using a portable infrared CO_2 sensor (Vaisala CARBOCAP Carbon Dioxide Transmitter Series

GMD20, VaisalyOy, Helsinki, Finland) with closed soil respiration chambers. Soil respiration chambers were custom-made of PVC (20 cm diameter and 18 cm height) by the workshop of the Forschungszentrum Jülich, Germany. Chambers contained a vent tube made with plastic material (length: 50 cm, inner diameter: 0.5 cm) for preventing pressure fluctuations in the chamber headspace.

The soil surface CO_2 measurements were conducted by placing soil respiration chambers gas-tight on PVC collars (20 cm diameter) that were inserted into the ground at least one day prior to the first measurement and remained at their position for the entire measurement period. Collars were custom-made by the workshop of the Forschungszentrum Jülich, Germany. Collars were inserted at 5 cm soil depth, leaving approximately 2 cm above the soil surface to prepare a solid foundation for the chamber and to prevent gas from escaping the chamber headspace horizontally through the soil matrix. In addition to avoiding soil disturbance, the collars had also the advantage of allowing repeated measurements in time at the same position, thereby facilitating the characterization of temporal variation of soil CO_2 fluxes (Rochette et al., 1997). Two collars were placed in the center of each plot.

During the growing season (June–November 2014), soil CO_2 emission was measured in 6–10 days intervals. During the non-growing season (December 2014–February 2015), measurements were made every two weeks due to low variability in soil moisture during the dry season and the fact that soil CO_2 emission is expected to depend on soil moisture rather than temperature in Benin (Ago et al., 2014; Lamade et al., 1996; Mulindabigwi, 2005). Measurements were taken between 08:00 and 11:00 h and between 15:00 and 18:00 h to take into account diurnal changes in temperature. The measurement was done at closing time and every five minutes up to thirty minutes. Air temperature inside the chamber was measured with a combined temperature and humidity transmitter (HMD 53, Vaisala Intercap® Sensor, VaisalyOy, Helsinki, Finland) connected to the soil respiration chamber. The slope of changes in CO_2 concentration with time and the air temperature inside the chamber were used to calculate the soil surface CO_2 flux according to Eq. (1). Two soil respiration chambers were placed on the two collars installed in the center of each plot. The mean of the soil CO_2 emission from the two chambers was considered to be the soil surface CO_2 emission for the entire plot.

$$F = \frac{dC}{dt} \times \frac{273.15}{273.15 + T} \times \frac{V}{A} \times \frac{1}{V_m} \times Mc \times 60 \times 1000 \qquad (1)$$

where F is the soil CO_2 flux (mg CO_2-C m^{-2} h^{-1}); $\frac{dC}{dt}$ is the change of CO_2-concentration in time (10^{-6} min^{-1}), T is the temperature inside the soil respiration chamber (°C), V is the chamber volume (m^3), A is the chamber base area (m^2), V_m is the molar volume of air at 0 °C (0.0224 m^3 mol^{-1}), Mc is the molar mass of carbon (12 g mol^{-1}), 60 is the conversion factor from minute to hour and 1000 is the conversion factor from gram to milligram.

Soil temperature and soil moisture were measured in the first 5 cm of soil at the same time when soil CO_2 emission was measured. Soil temperature was measured with a hand-held soil thermometer (Omegaette HH303Type K J, OMEGAEngineering, Inc., Stamford, CT, USA). Soil moisture was measured with a portable TDR probe (ML2x-KIT, Delta-T Devices Ltd., Cambrigde, UK). Soil temperature and soil moisture were measured at four points close to each soil respiration chamber. The means of the soil temperature and soil moisture from the eight points (4 points close to each chamber and 2 chambers per plot) were used as central values of the plot.

During the study period, cumulative soil surface CO_2 emissions were calculated according to Eq. (2) (Grote and Al-kaisi, 2007):

$$M = \sum_{i=1}^{n} \frac{F_{i+1} + F_i}{2} \times (t_{i+1} - t_i) \qquad (2)$$

where M is the cumulative emission of CO_2–C (mg CO_2-C m^{-2}), F_i is the first CO_2 emission value (mg CO_2–C m^{-2} h^{-1}) at time t_i (h), and F_{i+1} is the following value at time t_{i+1} (h); n is the total number of CO_2 emission values.

Soil surface CO_2 emissions continued to vary after harvest between treatments till February when emissions were near zero and no differences were found between treatments. Therefore, the period June 2014–February 2015 was considered appropriate for the calculation of cumulative CO_2 emissions as affected by the different treatments.

The amount of soil CO_2 emission per unit grain yield was calculated according to Eq. (3) (IPCC, 2007) in order to identify treatment combinations which can induce lower soil CO_2 emission

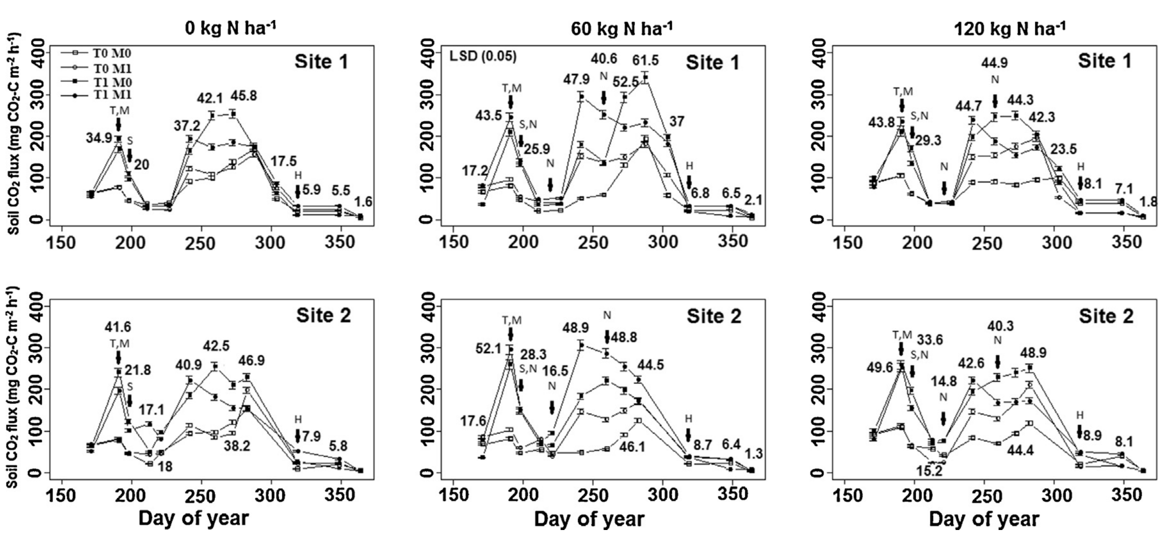

Fig. 2. Tillage and rice straw management effects on daily soil CO_2 emissions at different nitrogen fertilization levels during the growing season at the experimental sites 1 and 2. T: tillage, M: Application of rice straw mulch, S: direct sowing, N: nitrogen fertilizer application, H: harvest, T_0M_0: No-tillage, no straw mulch, T_0M_1: No-tillage, straw mulch, T_1M_0: manual tillage, no straw mulch, T_1M_1: manual tillage, straw mulch. LSD values for daily soil CO_2 emissions at a specific sampling date indicate significant differences at $p \leq 0.05$ between combination of tillage and rice straw management; if no value is shown then the difference is not significant. The error bars represent the standard error.

per unit grain yield.

$$R = \frac{M}{Y} \tag{3}$$

where M is the cumulative emission of CO_2–C (Mg ha^{-1}), and Y is the grain yield (Mg ha^{-1}).

The agronomic efficiency of nitrogen (AEN) was defined as the economic production obtained per unit of nitrogen applied (Fageria et al., 2010). It was used to evaluate optimal response of rice yield to nitrogen application under the various tillage systems and rice straw management. It was calculated according to Eq. (4).

$$\mathrm{AEN} = \frac{(G_f - G_u)}{N_a} \tag{4}$$

AEN is the agronomic efficiency of nitrogen (kg kg^{-1}), G_f is the grain yield of the fertilized plot (kg ha^{-1}), G_u is the grain yield of the unfertilized plot (kg ha^{-1}), and N_a is the quantity of nitrogen applied (kg ha^{-1}).

2.4. Statistical analysis

The statistical tests, models and figures were made with the R statistical software. An analysis of variance was performed on the treatments. Mean values were tested for significant differences by using a least significance difference (LSD). The probability level $\leq$0.05 was designated as significant.

3. Results

3.1. Soil CO_2 emission

Fig. 2 presents the daily evolution of soil CO_2 emission during the growing season for the two sites (Site 1 and Site 2). It was observed that soil CO_2 flux significantly increased soon after tillage from an average of 80 mg CO_2–C m^{-2} h^{-1} to 250 mg CO_2–C m^{-2} h^{-1} and decreased with time after tillage. Two weeks after tillage, no significant variation was found between tilled and no-tilled treatments. With frequent rainfall events followed by crop development, soil CO_2 flux significantly increased in all treatments and reached the maximum at the rice panicle initiation stage (end of September, day of year (doy) 273). The CO_2 flux in the different treatments varied during the growing season between 10 and 350 mg CO_2–C m^{-2} h^{-1} (Fig. 2). Averaged across sites, rice straw management and N fertilization rates, soil CO_2 flux was higher under manual tillage (136 mg CO_2–C m^{-2} h^{-1}) compared with no tillage (82 mg CO_2–C m^{-2} h^{-1}) during the study period. There were no significant differences between soil CO_2 fluxes of the different rice straw mulch treatments early in the growing season. However, starting in early August (doy 220), higher soil CO_2 emissions were recorded in treatments with rice straw addition. In addition, peaks of soil CO_2 emission were generally higher in fertilized treatments compared with non-fertilized treatments. Similar soil CO_2 trends were observed at the two sites.

3.2. Cumulative soil CO_2 emission

Cumulative soil CO_2 emission of the study period was significantly higher under manual tillage (6.37 Mg CO_2–C ha^{-1}) than no-tillage (3.83 Mg CO_2–C ha^{-1}) (Table 2). At the lower site (Site 2), this difference was more pronounced than at the upper site (Site 1). Application of rice straw mulch at 3 Mg ha^{-1} significantly increased cumulative soil CO_2 emission by 0.58 Mg ha^{-1} compared with no straw mulch. Across nitrogen fertilizer levels, lower cumulative soil CO_2 emission was recorded under no-tilled + no straw treatments (on average 3.38 Mg CO_2–C ha^{-1}) and higher under tilled + rice straw treatments (6.51 Mg CO_2–C ha^{-1}) (Fig. 3). Application of nitrogen fertilizer at 60 kg N ha^{-1} increased cumulative soil CO_2 emissions compared with no nitrogen application. However, no significant variation in cumulative soil CO_2 emissions was found between the 60 kg and 120 kg N ha^{-1} treatment (Table 2).

3.3. Soil moisture and soil temperature

Soil moisture fluctuated at both sites with rainfall events. Soil moisture was approximately twice as high in no-till treatments compared with till treatments from the day of tillage to the day of sowing (Fig. 4). After sowing and before rice panicle initiation at the end of September 2014, a tillage and rice straw mulch interaction effect was observed for soil moisture. Soil moisture was lower in till and no straw treatments and higher in no till plus straw treatments. There were no significant differences between N fertilization levels on soil moisture. From mid-October on, a steady decrease in soil moisture was recorded in all treatments due to the end of the rainy season (Fig. 4). On both sites, average soil moisture during the growing season was in the order of no till + straw > no till, no straw > till + straw > till, no straw. No-till treatments had on

Table 2
Cumulative soil CO_2 emission (Mg CO_2–C ha^{-1}) from June 2014 to February 2015, average soil moisture (m^3 m^{-3}) and soil temperature (°C) at 0–5 cm depth of the growing season (June–November 2014), rice biomass (Mg ha^{-1}) and grain yield (Mg ha^{-1}) of the growing season and cumulative soil CO_2 emission per unit grain yield from June 2014 to February 2015 of the different treatments (tillage systems, rice straw application and nitrogen levels) evaluated at two experimental sites.

Treatment	Soil CO_2	Soil moisture	Soil temperature	Biomass	Grain yield	Soil CO_2 per yield
Site 1	4.97 a	0.132 a	28.7 a	6.22 a	2.66 a	2.25 a
Site 2	5.23 a	0.144 b	28.5 a	7.62 b	3.24 b	1.90 a
LSD (main site effect)	ns	0.005	ns	1.16	0.42	ns
Tillage systems (T)						
No-tillage (T0)	3.83 a	0.148 a	28.7 a	7.21 a	2.99 a	1.69 a
Manual tillage (T1)	6.37 b	0.128 b	28.9 a	6.64 a	2.91 a	2.46 b
LSD (main T effect)	0.25	0.004	ns	ns	ns	0.48
Rice straw management (M)						
No straw	4.81 a	0.133 a	30.0 a	6.50 a	2.59 a	2.16 a
3 Mg ha^{-1} of rice straw	5.39 b	0.143 b	27.6 b	7.34 b	3.32 b	1.99 a
LSD (main M effect)	0.52	0.005	0.95	1.1	0.62	ns
Nitrogen levels (N)						
0 kg N ha^{-1}	4.66 a	0.138 a	29.5 a	3.58 a	1.26 a	3.53 a
60 kg N ha^{-1}	5.39 b	0.139 a	28.7 a	7.88 b	3.49 b	1.47 b
120 kg N ha^{-1}	5.24 b	0.137 a	28.2 a	9.31 c	4.11 c	1.23 b
LSD (main N effect)	0.54	ns	ns	0.80	0.48	0.34

Numbers followed by different letters in a column within a set are significantly different at $p \leq 0.05$ by the least significant difference test.
ns: not significant.

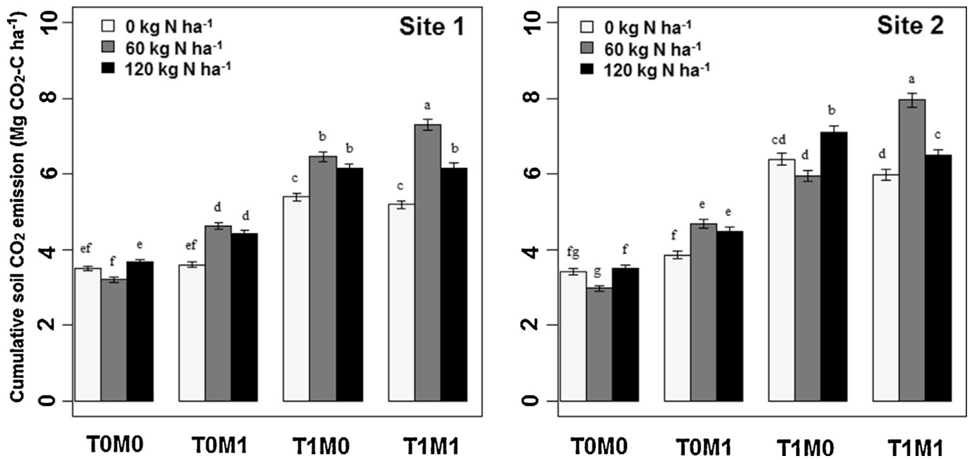

Fig. 3. Tillage and rice straw management effects on cumulative soil CO_2 emissions by nitrogen fertilization level at the experimental sites 1 and 2 from June 2014 to February 2015, T_0M_0: No-tillage, no straw mulch, T_0M_1: No-tillage, straw mulch, T_1M_0: manual tillage, no straw mulch, T_1M_1: manual tillage, straw mulch. Means with the same lower-case letter across treatments within each figure are not significantly different at $p \leq 0.05$. The error bars represent the standard error.

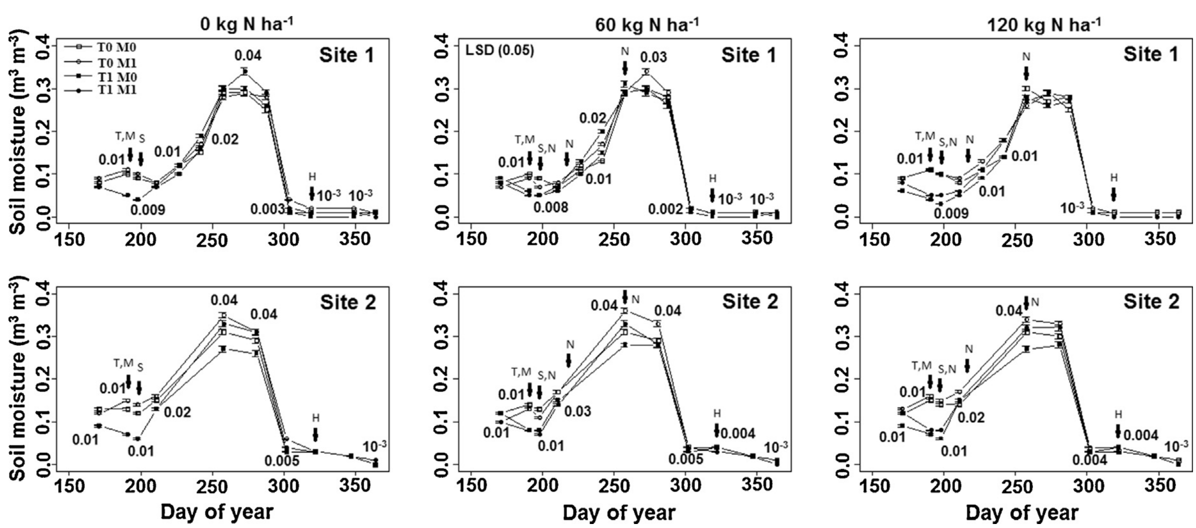

Fig. 4. Tillage and rice straw management effects on daily soil moisture at time of soil CO_2 flux measurement at different nitrogen fertilization levels during the growing season at the experimental sites 1 and 2. T: tillage, M: Application of rice straw mulch, S: direct sowing, N: nitrogen fertilizer application, H: harvest, T_0M_0: No-tillage, no straw mulch, T_0M_1: No-tillage, straw mulch, T_1M_0: manual tillage, no straw mulch, T_1M_1: manual tillage, straw mulch. LSD values for daily soil moisture at a specific sampling date indicate significant differences at $p \leq 0.05$ between combination of tillage and rice straw management; if no value is shown then the difference is not significant. The error bars represent the standard error.

average 0.02 $m^3\,m^{-3}$ higher soil moisture than till treatments. Mulching treatments had on average 0.01 $m^3\,m^{-3}$ higher soil moisture than non-mulching treatments. The lower site (Site 2) had on average 0.012 $m^3\,m^{-3}$ higher soil moisture than the upper site (Site 1) (Table 2).

Soil temperature slightly varied during the rainy season (Fig. 5). A seasonal mean amplitude of 11 °C was found. The lowest soil temperature (24 °C) was recorded at maximum rice tillering stage and panicle initiation. The highest was observed at the beginning and at the end of the rainy season (35 °C). After rice harvest, soil temperature steadily increased. During the growing season, there was a significant interaction effect of tillage and rice straw mulch on soil temperature (Table 3). Soil temperature was lower under no-tillage + rice straw mulch and higher under no-tillage and no rice straw mulch.

At a daily scale, during the growing and the dry season, no clear relationship was observed between soil CO_2 emission and soil temperature (Fig. 6), but a highly significant correlation was found with soil moisture during the growing season ($R^2 = 0.835$, $p < 0.0001$) (Fig. 7). This suggests that soil moisture was the main factor explaining the seasonal variability of soil CO_2 emission at the two sites.

3.4. Dry rice biomass and grain yield

Mean rice biomass and yield were 6.22 and 2.66 Mg ha^{-1} in the upper site (Site 1), respectively and 7.62 and 3.24 Mg ha^{-1} in the lower site (Site 2), respectively. The main effect of rice straw management on rice biomass and yield was significant (Table 2). Application of rice straw mulch at 3 Mg ha^{-1} increased rice biomass and yield by 0.84 Mg ha^{-1} and 0.73 Mg ha^{-1}, respectively. This rice straw effect was observed in the first year when rice straw was applied as mulch in the field after a preceding soil management phase where all the straw had been removed from the field and no N had been fertilized. In addition, rice biomass and yield significantly increased with increase in nitrogen levels. Increases in biomass and yield were 3.3 Mg ha^{-1} and 2.2 Mg ha^{-1}, respectively, when 60 kg N ha^{-1} and when no nitrogen was applied.

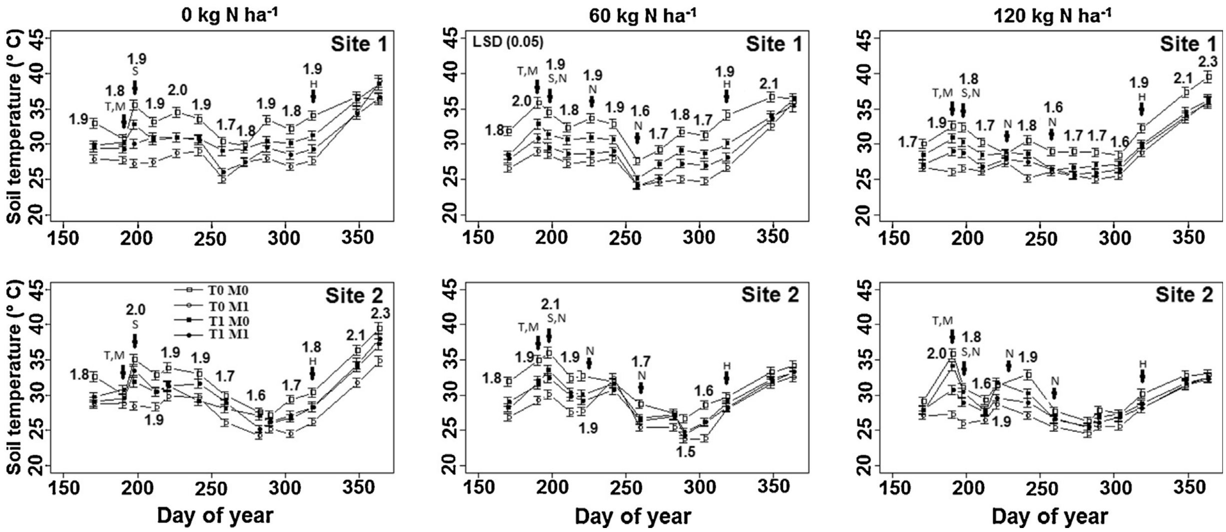

Fig. 5. Tillage and rice straw management effects on daily soil temperature at time of soil CO_2 flux measurement at different nitrogen fertilization levels during the growing season at the experimental sites 1 and 2. T: tillage, M: Application of rice straw mulch, S: direct sowing, N: nitrogen fertilizer application, H: harvest, T_0M_0: No-tillage, no straw mulch, T_0M_1: No-tillage, straw mulch, T_1M_0: manual tillage, no straw mulch, T_1M_1: manual tillage, straw mulch. LSD values for daily soil temperature at a specific sampling date indicate significant differences at $p \leq 0.05$ between combination of tillage and rice straw management; if no value is shown then the difference is not significant. The error bars represent the standard error.

Increase in nitrogen level from 60 kg N ha^{-1} to 120 kg N ha^{-1} enhanced rice biomass and yield by 1.4 Mg ha^{-1} and 0.6 Mg ha^{-1}, respectively (Table 2). There was a significant straw and nitrogen interaction effect on rice biomass and yield. This interaction was not dependent on site location. At both sites, the positive effect of nitrogen application on rice biomass and yield was enhanced when rice straw was applied as mulch (Table 3). The combined effect of tillage, straw management and nitrogen application appeared to be site-specific. At the upper site (Site 1), the highest rice biomass and yield were obtained under manual tillage, rice straw mulch and 120 kg N ha^{-1} while at the lower site (Site 2), the highest biomass and yield were obtained under no-tillage, rice straw mulch and 120 kg N ha^{-1} (Fig. 8).

3.5. Agronomic efficiency of nitrogen and amount of soil CO_2 emission per unit grain yield

The combination of rice straw mulch and nitrogen fertilizer at 60 kg N ha^{-1} achieved significantly higher agronomic efficiency of nitrogen at the two sites (Fig. 9). Results showed that combination of rice straw mulch and 60 kg N ha^{-1} can give rice yield equivalent to that of no straw and 120 kg N ha^{-1} across tillage systems.

There was a significant tillage and nitrogen interaction effect on soil CO_2 emission per unit grain yield (Table 3). Higher amount of soil CO_2 emission per unit grain yield (3.79–4.94) was obtained under manual tillage, and no nitrogen application. On the contrary, lower soil CO_2 emission per grain yield (0.82–1.5) was obtained at the two sites by combining no tillage and 60 or 120 kg N ha^{-1} (Fig. 10). No significant effect of rice straw mulch on soil CO_2 emission per grain yield was found (Table 2).

These results indicate that the current management practices in upland rice fields (manual tillage, with no residue and no nitrogen fertilization) lead to higher amount of soil CO_2 emission per unit grain yield. On the contrary, no-tillage and rice straw mulch and 60 kg N ha^{-1} reduced the amount of soil CO_2 emission per unit grain and increased rice yield response to nitrogen fertilization.

Table 3
p-value from the analysis of variance for cumulative soil CO_2 emission (Mg CO_2–C ha^{-1}) from June 2014 to February 2015, average soil moisture ($m^3\ m^{-3}$) and soil temperature (°C) at 0–5 cm depth of the growing season (June–November 2014), rice biomass (Mg ha^{-1}) and grain yield (Mg ha^{-1}) of the growing season and cumulative soil CO_2 emission per unit grain yield from June 2014 to February 2015 of the different treatments (tillage systems, rice straw management and nitrogen levels) evaluated at two experimental sites.

Source of variation	Soil CO_2	Soil moisture	Soil temperature	Biomass	Grain yield	Soil CO_2 per yield
Site (S)	0.06	<0.001	0.81	0.02	0.04	0.15
Tillage (T)	<0.001	<0.001	0.70	0.33	0.79	<0.001
Rice straw (M)	0.04	<0.001	<0.001	0.04	0.02	0.51
Nitrogen (N)	0.03	0.87	0.32	<0.001	<0.001	<0.001
S × T	0.04	<0.001	0.80	0.23	0.04	0.06
S × M	0.74	0.46	0.18	0.80	0.28	0.91
T × M	0.02	0.04	<0.001	0.51	0.73	0.72
S × N	0.78	0.21	0.87	0.40	0.21	0.06
T × N	0.02	0.24	0.98	0.78	0.51	0.02
M × N	0.04	0.52	0.68	0.02	0.004	0.85
S × T × M	0.72	0.19	0.49	0.52	0.66	0.21
T × M × N	0.02	0.60	0.44	0.95	0.94	0.70
S × M × N	0.80	0.69	0.92	0.69	0.33	0.70
S × T × M × N	<0.001	0.002	0.44	0.08	0.04	<0.001

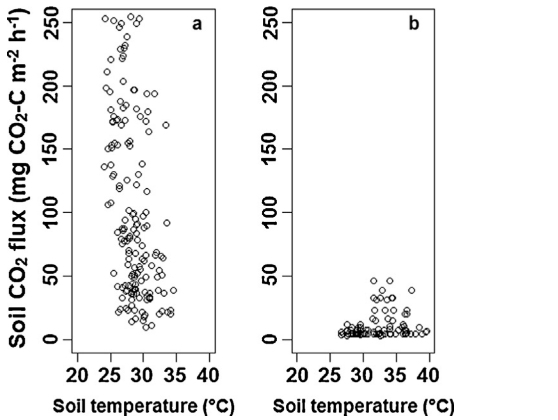

Fig. 6. Relationship between daily soil CO_2 emission and soil temperature across sites, tillage systems, rice straw management and nitrogen levels during (a) the growing season (June 2014–November 2014) and (b) the dry season (December 2014–February 2015).

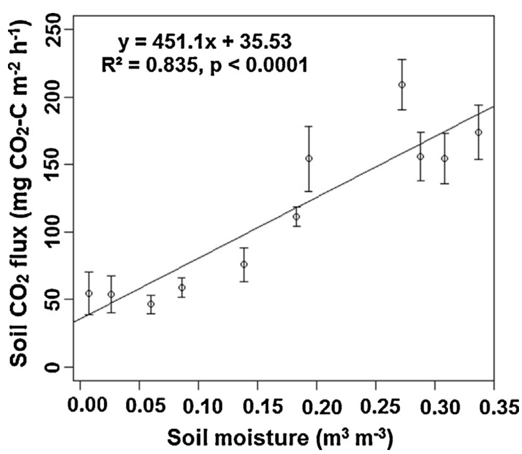

Fig. 7. Relationship between daily soil CO_2 emission and soil moisture across sites, tillage systems, rice straw management and nitrogen levels during the growing season (June 2014–November 2014). Each point of the graph is a mean of 16 data points expect for the last point which corresponds to the mean of eight data points. The error bars represent the standard error.

4. Discussion

Across tillage systems, rice straw management and nitrogen levels, average rate of soil CO_2 emission at the upper site was 91.95 mg CO_2–C h^{-1} m^{-2}. At the lower site, average rate of soil CO_2 emission was 95.73 mg CO_2–C h^{-1} m^{-2}. Mean rates of soil CO_2 emission observed in this study were within the range (54.54–242.72 mg CO_2–C h^{-1} m^{-2}) of a previous study in agricultural ecosystems in northern Benin (Mulindabigwi, 2005). Greater cumulative soil CO_2 emissions were observed in manual tillage than no-tillage (6.37 vs. 3.83 Mg CO_2–C ha^{-1}). This could be attributed to mineralization of soil organic matter due to increase in soil aeration and root-derived CO_2 respiration (Al-Kaisi and Yin, 2005).

The CO_2 flux of as much as 250 mg CO_2–C h^{-1} m^{-2} following tillage operation observed in this study is close to 214 mg CO_2–C h^{-1} m^{-2} found within the first 2 h after tillage on fine loamy soil in Ames by Al-Kaisi and Yin (2005). Tillage can result in an immediate short-term outburst of CO_2 due to decrease in partial pressure of CO_2 in soil air, followed by disturbance of soil aggregates and pores, and sudden release of CO_2 from the soil solution (Rochette and Angers, 1999). Soil CO_2 emissions were low two weeks after tillage regardless of management practices (Fig. 2), suggesting that the effect of tillage on CO_2 flux was short-lived, as found by Sainju et al. (2006) in western North Dakota on a Lihen sandy loam soil. Fluxes were stimulated in tillage treatments when rainfall events were frequent; which increased microbial activity, thereby increasing carbon mineralization and CO_2 flux (Lamade et al., 1996; Mulindabigwi, 2005; Sainju et al., 2006).

Soil carbon emission data showed that the application of rice straw mulch caused an overall increase in soil CO_2 emissions compared with the non-mulched treatments (Table 2). Cumulative soil CO_2 emissions were 0.58 Mg CO_2–C ha^{-1} higher in mulched treatments compared with non-mulched treatments (4.81 in no mulch vs. 5.39 Mg CO_2–C ha^{-1} in mulch). Higher soil carbon emissions in mulched treatments compared with non-mulched treatments were also found by others (Bhattacharyya et al., 2012; Heller et al., 2007). This might be due to higher microbial activity in mulched treatments and the conversion of rice straw carbon to soil organic carbon (Khalil et al., 2005).

Very few studies regarding the effects of management practices on soil CO_2 emissions have previously been reported in West Africa (Lamade et al., 1996; Mulindabigwi, 2005). It is expected that the application of inorganic N fertilizers along with organic materials will affect the mineralization of soil organic matter and crop

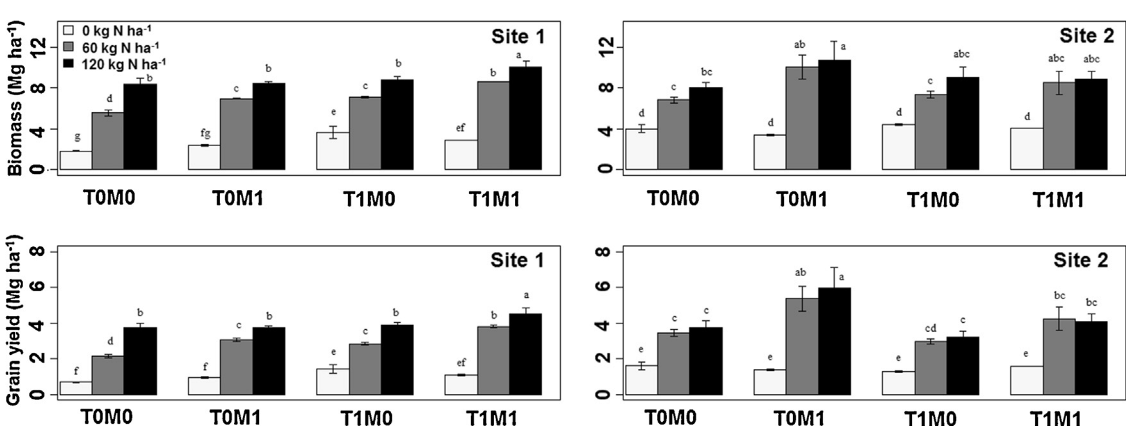

Fig. 8. Tillage and rice straw management effects on rice biomass and grain yield at different nitrogen fertilization levels at the experimental sites 1 and 2; T_0M_0: no-tillage, no straw mulch, T_0M_1: no-tillage, straw mulch, T_1M_0: manual tillage, no straw mulch, T_1M_1: manual tillage, straw mulch. Means with the same lower-case letter across treatments within each figure are not significantly different at $p \leq 0.05$ by the least significant difference test. The error bars represent the standard error.

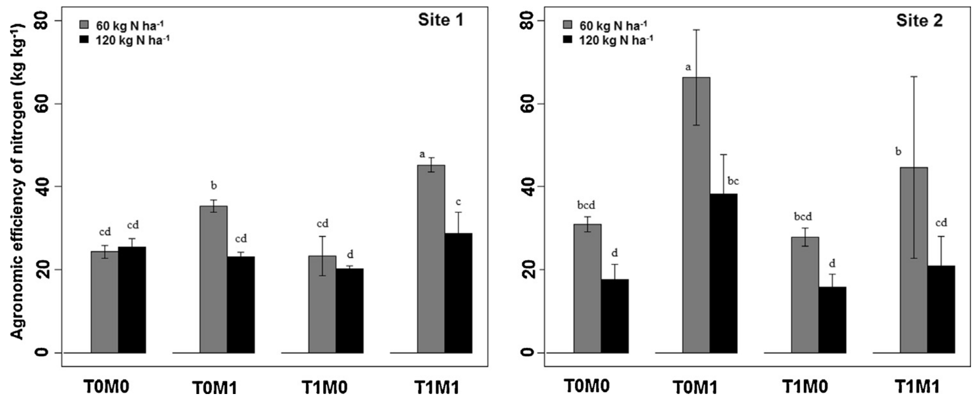

Fig. 9. Agronomic efficiency of two levels of nitrogen under different tillage systems and rice straw management at the experimental sites 1 and 2; T_0M_0: no-tillage, no straw mulch, T_0M_1: no-tillage, straw mulch, T_1M_0: manual tillage, no straw mulch, T_1M_1: manual tillage, straw mulch. Means with the same lower-case letter across treatments within each figure are not significantly different at $p \leq 0.05$ by the least significant difference test. The error bars represent the standard error.

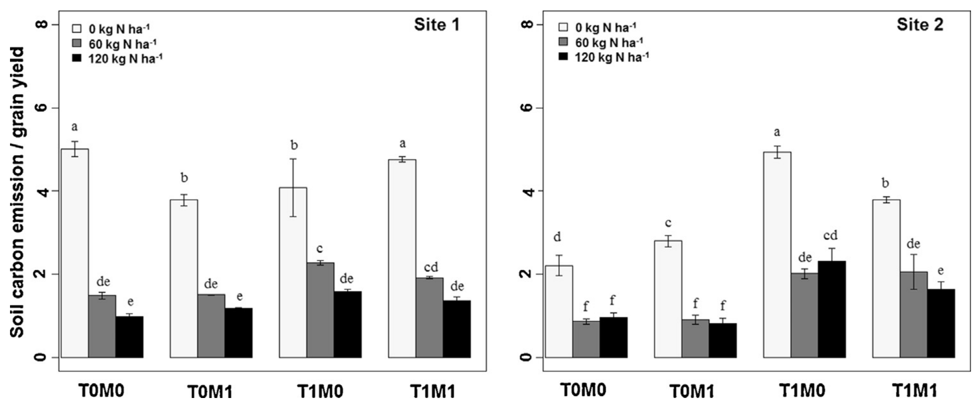

Fig. 10. Tillage and rice straw management effects on the amount of soil CO_2 emission per unit grain yield at different nitrogen fertilizer levels at the experimental sites 1 and 2 from June 2014 to February 2015; T_0M_0: no-tillage, no straw mulch, T_0M_1: no-tillage, straw mulch, T_1M_0: manual tillage, no straw mulch, T_1M_1: manual tillage, straw mulch. Means with the same lower-case letter across treatments within each figure are not significantly different at $p \leq 0.05$ by the least significant difference test. The error bars represent the standard error.

productions, which will ultimately affect soil CO_2 emissions (Lamade et al., 1996). However, reported variations in soil CO_2 emissions following fertilizer applications have not been consistent so far. Several scientists as Al-Kaisi et al. (2008) have reported that fertilizer application suppresses CO_2 emissions, while others as Mulvaney et al. (2009) have reported that it enhances CO_2 emissions. Moreover, some other scientists as Lee et al. (2007) have reported that fertilizer application has no effect on soil CO_2 emissions. Our study showed that the use of 60 kg N ha^{-1} enhanced CO_2 emissions compared with the zero-N fertilizer treatment, but that further increases in N did not increase soil CO_2 emissions (Table 2). Moreover, the use of different levels of N fertilizer relative to the non-fertilized level significantly increased rice biomass and yield (Fig. 8). This result suggests that the higher soil CO_2 emission fluxes associated with nitrogen fertilization use might be due to greater availability of the carbon substrates resulting in higher microbial activity as reported by Fisk and Fahey (2001) or increased root growth and greater root respiration as reported by Lamade et al. (1996).

Soil carbon emission which is mainly dependent on autotrophic (root) and heterotrophic (microbial) activities is mainly controlled by soil moisture at our studied sites as reported by other authors for similar ecosystems in Benin (Ago et al., 2014; Lamade et al., 1996; Mulindabigwi, 2005). Contrary to the results of Brümmer et al. (2008), our studies revealed no relationship between soil CO_2 flux and soil temperature. This could be attributed to the fact that the temperature variability at our investigated sites is relatively low. Mulindabigwi (2005) also reported no significant effect of soil temperature on soil CO_2 flux in northern Benin due to only slight variation of soil temperature and concluded that soil CO_2 flux was mainly dependent on soil moisture.

Though changes in management practices affect soil carbon emission and soil carbon sequestration, the main objective of smallholder rice farmers in West Africa is the immediate increase in yield by using alternative farming management practices (Erenstein, 2002). This study clearly showed that combination of rice straw mulch and nitrogen fertilizer had achieved an overall greater rice biomass and grain yield (Fig. 8 and Table 3). This resulted in higher response of the rice plants to nitrogen fertilizer application, when rice straw was applied as mulch. Similar results were also found by Rahman et al. (2005).

Nitrogen application at 60 kg N ha^{-1} combined with rice straw mulch achieved the maximum rice yield response to nitrogen fertilization. Use of 120 kg N ha^{-1} combined with rice straw mulch resulted in lower agronomic N use efficiency compared with 60 kg N ha^{-1} and rice straw mulch. This may be due to higher loss of nitrogen through nitrification and/or denitrification. Increases in N fertilization in most cases result in greater loss of N through N_2O emissions and nitrate leaching (Pelster et al., 2011).

The no-tillage and nitrogen fertilizer treatments exhibited significantly lower soil CO_2 emission per unit grain yield when compared with manual tillage and zero N fertilizer, but showed no significant difference in response to rice straw management. Thus, even though mulching treatments increased CO_2 emission to the atmosphere due to surface rice straw decomposition, the rice yield was higher due to ample supply of water and better nitrogen use resulting in low amount of soil CO_2 emission per unit rice grain like previously reported by Liu et al. (2014).

5. Conclusions

Continuous rice cultivation under manual tillage and removal/burning of crop residues is detrimental to the soil and also negative for the environment and the quality of the crop yield. Adoption of appropriate tillage methods, crop residue application and proper fertilization are beneficial for the soil, the environment and the quality of the crop yield. These practices are also beneficial for resource-poor farmers by reducing the amount of inorganic fertilizer per unit of harvested product. The findings from our study indicate that application of rice straw mulch at 3 Mg ha^{-1} and nitrogen fertilizer at 60 kg N ha^{-1} significantly increased the response of rice plants to nitrogen fertilization for the two tillage systems. No-tillage combined with nitrogen fertilization resulted in lower soil carbon emission per unit grain yield. No-tillage combined with rice straw mulch and 60 kg N ha^{-1} could be used by smallholder farmers to achieve higher grain yield and lower soil carbon emission in upland rice fields in northern Benin. Long-term studies could be helpful with confirming the effects of these management practices on crop quality, their interactions with varieties, the relevance of interactions between nitrogen fertilization and site, soil and tillage practices as found in this study.

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