Combining no-tillage, rice straw mulch and nitrogen fertilizer application to increase the soil carbon balance of upland rice field in northern Benin

Article *in* Soil and Tillage Research · November 2016

DOI: 10.1016/j.still.2016.05.019

7 authors, including:

Elliott Ronald Dossou-Yovo
Africa Rice Center (Africarice)
40 PUBLICATIONS **251** CITATIONS

SEE PROFILE

Nicolas Brüggemann
Forschungszentrum Jülich
246 PUBLICATIONS **9,372** CITATIONS

SEE PROFILE

Edward Ampofo
University of Cape Coast
11 PUBLICATIONS **71** CITATIONS

SEE PROFILE

Attanda Mouinou Igué
National Institute of Agricultural Research of Benin
33 PUBLICATIONS **306** CITATIONS

SEE PROFILE

Soil & Tillage Research 163 (2016) 152–159

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Combining no-tillage, rice straw mulch and nitrogen fertilizer application to increase the soil carbon balance of upland rice field in northern Benin

Elliott Ronald Dossou-Yovo[a,b,*], Nicolas Brüggemann[c], Edward Ampofo[a], Attanda Mouinou Igue[d], Naab Jesse[e], Joël Huat[f], Euloge Kossi Agbossou[b]

[a] *School of Agriculture, University of Cape Coast, Cape Coast, Ghana*
[b] *Laboratoire d'Hydraulique et de Maîtrise de l'Eau, Institut National de l'Eau, Université d'Abomey-Calavi, BP 2819 Cotonou, Benin*
[c] *Forschungszentrum Jülich GmbH, IBG-3, 52425 Jülich, Germany*
[d] *Laboratoire des Sciences du Sol, Eaux et Environnement, Institut National de Recherche Agronomique du Benin, Benin*
[e] *WASCAL (West African Science Service Center on Climate Change and Adapted Land Use) Competence Center, Ouagadougou, Burkina Faso*
[f] *CIRAD, UR Hortsys, F-34398 Montpellier Cedex 05, France*

ARTICLE INFO

Article history:
Received 30 April 2016
Accepted 22 May 2016
Available online xxx

Keywords:
Heterotrophic respiration
Management practices
Root respiration
Soil carbon storage

ABSTRACT

Agricultural management practices are frequently non conservative and can lead to substantial loss of soil organic carbon and soil fertility, but for many regions in Africa the knowledge is very limited. To study the effect of local agricultural practices on soil organic carbon content and to explore effective ways to increase soil carbon storage, field experiments were conducted on an upland rice soil (Lixisol) in northern Benin in West Africa. The treatments comprised 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 fertilizer levels (no nitrogen, 60 kg ha^{-1}, 120 kg ha^{-1}). Phosphorus and potassium fertilizers were applied to be non-limiting at 40 kg P_2O_5 ha^{-1} and 40 kg K_2O ha^{-1} per cropping season. Heterotrophic respiration was higher in manual tillage than no-tillage, and higher in mulched than in non-mulched treatments. Under the current management practices (manual tillage, with no residue and no nitrogen fertilization) in upland rice fields in northern Benin, the carbon added as aboveground biomass and root biomass was not enough to compensate for the loss of carbon from organic matter decomposition, rendering the upland rice fields as net sources of atmospheric CO_2. With no-tillage, 3 Mg ha^{-1} of rice straw mulch and 60 kg N ha^{-1}, the soil carbon balance was approximately zero. With no other changes in management practices, an increase in nitrogen level from 60 kg N ha^{-1} to 120 kg N ha^{-1} resulted in a positive soil carbon balance. Considering the high cost of inorganic nitrogen fertilizer and the potential risk of soil and air pollution often associated with intensive fertilizer use, implementation of no-tillage combined with application of 3 Mg ha^{-1} of rice straw mulch and 60 kg N ha^{-1} could be recommended to the smallholder farmers to compensate for the loss of carbon from organic matter decomposition in upland rice fields in northern Benin.

1. Introduction

Concerns about rising atmospheric CO_2 levels have prompted considerable interest in recent years regarding the potential of soil organic carbon (SOC) as sink for atmospheric CO_2 (Baker et al., 2007). Soil organic carbon is the largest terrestrial carbon pool, containing approximately twice as much carbon as the atmospheric CO_2 pool (Paustian et al., 1997). Because of the important role of SOC in terrestrial ecosystems and its large stock, minor changes in SOC as a result of perturbations, such as changes in land use or climate (Houghton et al., 1999), may influence both

---

[*] Corresponding author at: School of Agriculture, University of Cape Coast, Cape Coast, Ghana.

E-mail addresses: dossouyovoelliott@gmail.com, dossouyovoelliott@yahoo.fr (E.R. Dossou-Yovo), n.brueggemann@fz-juelich.de (N. Brüggemann), edwardakwasi@yahoo.com (E. Ampofo), igue_attanda@yahoo.fr (A.M. Igue), jessenaab@gmail.com (N. Jesse), joel.huat@cirad.fr (J. Huat), agbossou.euloge@yahoo.fr (E.K. Agbossou).

http://dx.doi.org/10.1016/j.still.2016.05.019

long-term ecosystem functions and the global atmospheric carbon budget (Mu et al., 2008).

Cropland soils contain approximately 170 Pg C, slightly more than 10% the total SOC pool (Paustian et al., 1997). Decomposition of SOC in cultivated soils has contributed to the emission of approximately 50 Pg C to the atmosphere (Paustian et al., 2000). SOC also helps maintaining soil fertility for sustainable crop production (Nishimura et al., 2008). Some activities, including agricultural practices, are proposed by the Kyoto Protocol, an international agreement for reducing CO_2 emission by 5.2% compared to the 1990 emission level, for slowing down the rise of atmospheric carbon dioxide (Lu et al., 2009). The French Government has proposed to the Conference of Parties (COP)21 of the United Nations Framework Convention on Climate Change (UNFCCC) in December 2015 that SOC concentration be increased globally at 0.4% per year to offset atmospheric CO_2 increases and advance food security (Lal et al., 2015). Therefore, an increasing attention is paid to carbon sequestration in agricultural soils.

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, and farmers have relied on extended fallow periods to restore soil fertility. However, rapid population growth and increased demand for land have led to shortened fallow periods, which in turn have resulted in declining soil organic carbon and rice yield (Saito et al., 2010).

A previous study has suggested that introducing no-tillage management may reduce the emission of CO_2 from upland rice soils in Benin (Dossou-Yovo et al., 2016). This was attributed to a reduction of tillage effects that generally increase soil carbon losses by increasing the availability and oxidation of SOC shortly after tillage (Al-Kaisi and Yin, 2005), and destruction of aggregates that physically protect SOC from microbial activities (Six et al., 2000). It has also been suggested that increases in nitrogen fertilization levels may promote soil carbon sequestration due to increases in aboveground biomass and especially root biomass, which can contribute to more stable SOC than aboveground residues (Rasse et al., 2005). However, potential increases in carbon input from increases in nitrogen fertilization level could be counter balanced by increases in carbon mineralization and CO_2 emissions (Zhou et al., 2014). 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} yr^{-1} (Lu et al., 2009). Although it is clear that management practices can significantly affect soil carbon storage through carbon inputs and losses, the detection of SOC changes is often difficult due to the small magnitude of changes relative to the total stock, except in long-term studies (Conen et al., 2003). The calculation of the soil carbon balance from carbon inputs (aboveground residues, root biomass, management-related input of carbon) minus carbon outputs (carbon loss via heterotrophic respiration (R_h)) provides valuable insights into the processes contributing to changes in SOC on a finer temporal scale (Duiker and Lal, 2000).

The primary way of quantifying carbon loss from soils is by measuring soil CO_2 emission (Mu et al., 2008). Most of the soil CO_2 emission is a product of decomposition of plant litter and soil organic matter via heterotrophic respiration (R_h) and from root respiration (R_r) (Raich and Mora, 2005; Rochette et al., 1999). These two components can have different responses to soil moisture and temperature which can stimulate or reduce R_h and R_r and also slow down oxygen diffusion and the release of CO_2 (Guzman and Al-Kaisi, 2014). Thus, the contributions of these components need to be understood in order to quantify carbon losses from soil.

Information on potential changes in soil organic carbon due to management practices is vital for Benin in order to suggest sustainable farming strategies (i.e. associated with no net loss or even an increase of soil carbon) to the upland rice farmers. The objectives of this study were to (1) assess the effects of tillage systems, rice straw mulching and nitrogen application on soil moisture and soil temperature, (2) evaluate the effects of these farming management practices on soil CO_2 fluxes, R_h and R_r, and (3) calculate the soil carbon balance to suggest combination of factors to reduce net loss of carbon.

2. Material and methods

2.1. Experimental site

The study was conducted from June 2014 to May 2015 on an upland rice soil 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. The climate is semi-arid with one rainy season (May-October) and one dry season (November–April) (Fig. 1).The mean annual air temperature, rainfall and potential evapotranspiration are 27 °C, 1177 mm and 1484 mm, respectively (data from 1985 to 2014). According to FAO soil taxonomy, the soil of the experimental site was a Lixisol (Youssouf and Lawani, 2000). Soil samples (0–20 cm soil layer) were collected before the onset of the experiment for particle size distribution, pH, SOC content, total nitrogen, extractable phosphorus and extractable potassium. The particle size distribution was determined based on the hydrometer method (Bouyoucos, 1951). The soil pH was determined using a soil-to-water ratio of 1–2.5. The soil organic carbon content was determined by chromic acid digestion, and the total nitrogen by

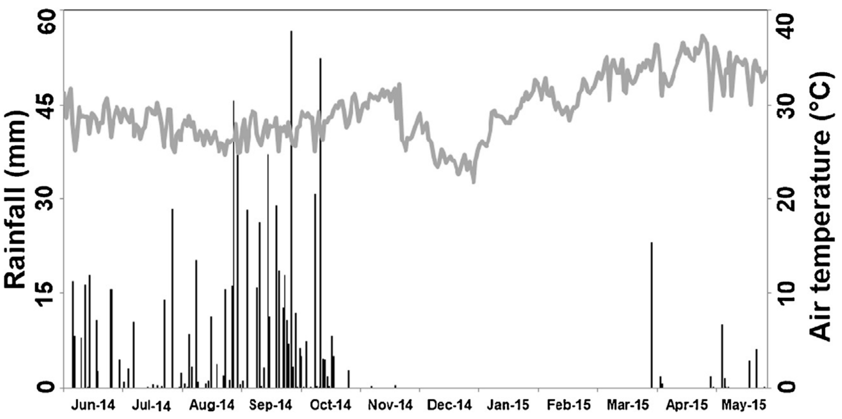

Fig. 1. Seasonal evolution of daily rainfall (dark vertical bars) and daily average air temperature (grey continuous line) from 01 June 2014*31 May 2015.

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 NH_4-acetate and the content was determined by flame emission spectrophotometry.

The soil of the experimental site was loamy, slightly acidic (pH 6.1-6.5) with low organic carbon content (<0.5%), low nitrogen (<0.03%), medium phosphorus (10–20 ppm) and medium potassium (0.8–1.6%) content. The experimental site was previously under continuous rice cultivation with manual tillage and without rice straw and fertilizer application.

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 application (M_0) and rice straw mulch application 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 no nitrogen application (N_0); moderate level of nitrogen (60 kg N ha^{-1}) recommended by the extension services in north Benin (N_1); and high level of nitrogen (120 kg N ha^{-1}) (N_2). Phosphorus (P) and potassium (K) fertilizers were applied in all the experimental plots to be non-limiting at 40 kg P_2O_5 ha^{-1} and 40 kg K_2O ha^{-1}. Nitrogen, P and K 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 on the day of sowing. 25% of the N was applied at 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, also 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 as commonly practiced in the study area. The desired rates of rice straw were applied on the plots. The rice variety NERICA14 (WAB 880-1-32-1-2-P1-HB; *O. sativa x O. glaberrima* interspecific progeny) 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. One week after germination, 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.

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, VaisalaOy, 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 of plastic material (length: 50 cm, inner diameter: 0.5 cm) to allow for pressure equilibration between the chamber headspace and the ambient atmosphere.

The soil 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 at a distance of 2 m from each other.

During the growing season (June 2014-November 2014), soil CO_2 emission was measured in 6- to 10-day intervals. During the non-growing season (December 2014-May 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; Dossou-Yovo et al., 2016; Lamade et al., 1996; Mulindabigwi, 2005). The 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 just after closing the chamber and every five minutes up to 30 min. Air temperature inside the chamber was measured with a combined temperature and humidity transmitter (HMD 53, Vaisala Intercap® Sensor, VaisalaOy, 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.

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

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 with 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., Cambridge, 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 mean values for 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.

2.4. Separation of heterotrophic respiration and root respiration

To quantify percentage of R_h to total soil CO_2 emission (F), a root exclusion experiment was conducted (Hanson et al., 2000). In each treatment plot, soil CO_2 emission was measured between rice plants with no roots (R_h) using a stainless steel base frame (20 cm length × 20 cm width × 20 cm height) as a physical barrier, and with roots present (F) to estimate contribution of R_h to total soil CO_2 emission according to Eq. (3).

$$R_h(\%) = \frac{R_h}{F} \times 100 \quad (3)$$

At the end of the study, root biomass samples were collected in the root exclusion treatments to confirm that there were no roots present. Accordingly, by subtracting R_h contribution (%) from 100%, contribution of R_r to F was estimated.

2.5. Potential carbon input from aboveground and belowground plant biomass

Aboveground and belowground biomass was measured to quantify potential carbon inputs from plant biomass. Rice residues were collected after grain harvest within two replicate frames of 1 m^2 each that were placed close to the center of each plot. Aboveground plant biomass was dried at 70 °C for 72 h, and weighed to determine dry matter weight ($Mg\,ha^{-1}$). Carbon content of aboveground biomass was determined by dry combustion, and the content was multiplied by the aboveground dry matter weight to determine potential carbon input from aboveground biomass in $Mg\,ha^{-1}$.

Belowground plant biomass was collected at rice harvest using a monolith sampling procedure (Henry et al., 2012). Two monolith samplers (20 cm × 20 cm, 20 cm depth) were pounded into the soil in the harvested area of each plot with a sledgehammer until the top of the sampler was levelled with the soil. The soil was stored in labeled plastic bags. Roots were separated from the soil by flotation. The soil sample was transferred into a plastic container and mixed with more water. After mixing, the soil/water/root mixture began to separate: soil settled at the bottom, large roots floated at the water surface and some roots, although not visible, floated below the water surface. Large, visible pieces of roots were picked out with forceps and transferred to a small container of clean water. To collect the small roots floating below the water surface, the liquid portion was poured onto a 1.0 mm sieve. These roots were transferred to the small container of clean water with roots. Water was again added to the soil in the plastic container, and the liquid portion was poured onto the sieve to isolate the roots. This procedure was repeated until no more roots were collected on the sieve. After mixing the soil with water and capturing the roots on the sieve, the soil was visually examined for any remaining roots. All roots from the container were then poured onto the sieve and transferred to a small labeled plastic bag. Root samples were dried in an oven at 70 °C for 72 h. A high-precision balance (milligram) was used to determine the dry weight of the roots. Root samples were analyzed by dry combustion for carbon content, and the content value was multiplied by root biomass to evaluate potential carbon input from root biomass in the top 20 cm soil depth in $Mg\,ha^{-1}$.

2.6. Estimation of soil carbon balance

The soil carbon balance was calculated as the difference between carbon input due to rice straw mulch, above-and belowground biomass carbon, and carbon loss through organic matter decomposition (heterotrophic respiration) for the entire year according to Eq. (4).

$$SCB(MgCha^{-1}yr^{-1}) = C_{straw} + PAC + PBC - CR_h \quad (4)$$

where SCB is soil carbon balance, C_{straw} is carbon input due to rice straw mulching (C_{straw} = 1.6 $Mg\,C\,ha^{-1}$ for rice straw mulch treatments and C_{straw} = 0 for non mulch treatments), PAC is potential carbon input from aboveground plant biomass, PBC is potential carbon input from root biomass, and CR_h is cumulative carbon loss via heterotrophic respiration.

2.7. Statistical analysis

All the statistical tests, models and figures were made with the R statistical software (R Development Core Team, 2011). An analysis of variance was performed on the treatments. Mean values were tested for significant differences by using a least significance difference (LSD) test. The probability level ≤ 0.05 was designated as significant. Stepwise regression analysis was conducted to test the effects of soil moisture, soil temperature, days after sowing (DAS) and soil CO_2 emission on the contribution of R_h to total soil CO_2 emission.

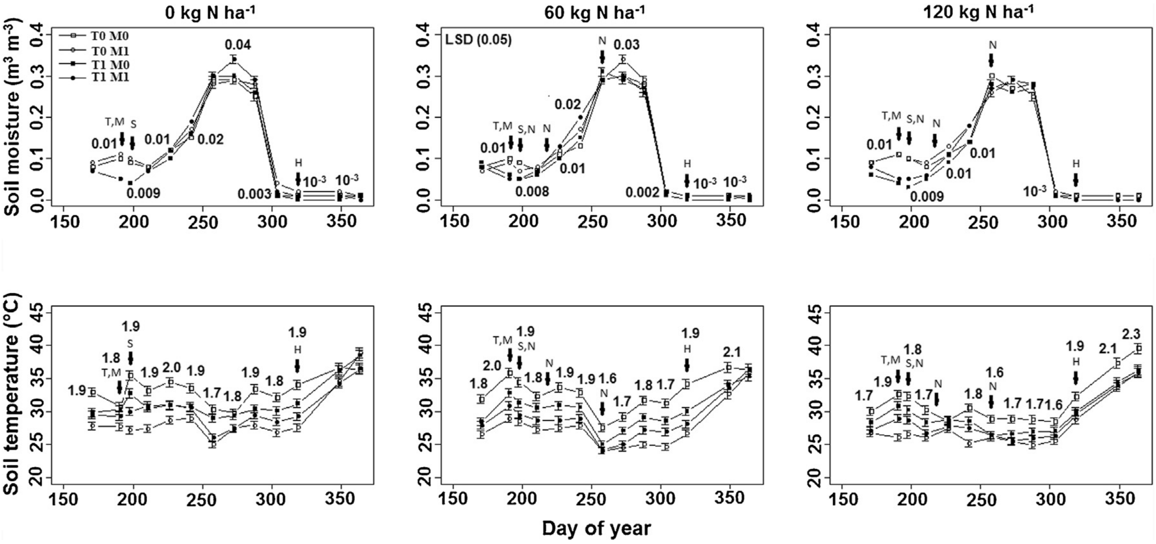

Fig. 2. Tillage and rice straw management effects on daily mean soil moisture and soil temperature at different nitrogen fertilization levels during the growing season. T: tillage, M: application of rice straw mulch, S: direct sowing, N: nitrogen fertilizer application, H: harvest, T_0M_0: No-tillage, 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 at a specific sampling date indicate significant differences at p ü 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.

3. Results and discussion

3.1. Soil moisture and soil temperature

Soil moisture fluctuated with rainfall events. Soil moisture followed a parabolic trend during the growing season, peaking in August and September (day of year (doy) 258–288) (Fig. 2). Soil moisture was approximately twice as high in no-till treatments compared with tilled treatments from the day of tillage to the day of sowing. After sowing and before rice harvest, 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. From mid-October, a steady decrease in soil moisture was recorded in all treatments due to the end of the rainy season (Fig. 2). Average soil moisture during the growing season was in the order of no till + straw > no till, no straw > till + straw > till, no straw.

Soil temperature slightly varied during the growing season (Fig. 2). A seasonal mean amplitude of 5.5 °C was found. The lowest soil temperature (24 °C) was recorded at maximum rice tillering stage and panicle initiation. The highest soil temperature 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. Soil temperature was lower under no-tillage + rice straw mulch (26–27 °C) and higher under no-tillage and no rice straw mulch (30–32 °C).

The lower soil temperature and the higher soil moisture found in no-till + straw treatments could be attributed to the increased amount of rice residues on the soil surface, which would reduce evaporation during the growing season, thus conserving more water in the soil and reducing soil temperature. Our results agree with the findings of Rahman et al. (2005) who described higher soil moisture under no-tillage + rice straw mulch in an Alluvial soil in Bangladesh and with the results of De Vleeschauwer et al. (1980) who found lower soil temperature under no-tillage + rice straw mulch in an Alfisol in Nigeria.

3.2. Soil CO_2 emission

Fig. 3 presents the daily evolution of soil CO_2 emission during the growing season. 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 difference 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 rice panicle initiation stage (end of September, 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. 3). Averaged across rice straw management and N fertilization levels, 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 growing season. 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.

Across tillage systems, rice straw management and nitrogen levels, the average soil CO_2 emission rate was 91.9 mg CO_2—C h^{-1} m^{-2} and was within the range (54.5–242.7 mg CO_2—C h^{-1} m^{-2}) of a previous study in agricultural ecosystems in northern Benin (Mulindabigwi, 2005).

3.3. Heterotrophic respiration and root respiration

During the growing season, R_h varied with tillage system, straw management and nitrogen fertilizer level (Fig. 3). R_h was higher in manual tillage than no-tillage, with the largest difference observed during the day of tillage operation. R_h in rice straw mulch treatments was 8–47% higher than R_h in no-mulch treatments. R_h was also higher in nitrogen fertilizer treatments compared with zero-nitrogen treatments.

Root respiration increased from zero, 14 days after sowing (doy 212), to a peak value of 185 mg CO_2—C m^{-2} h^{-1} in September (doy

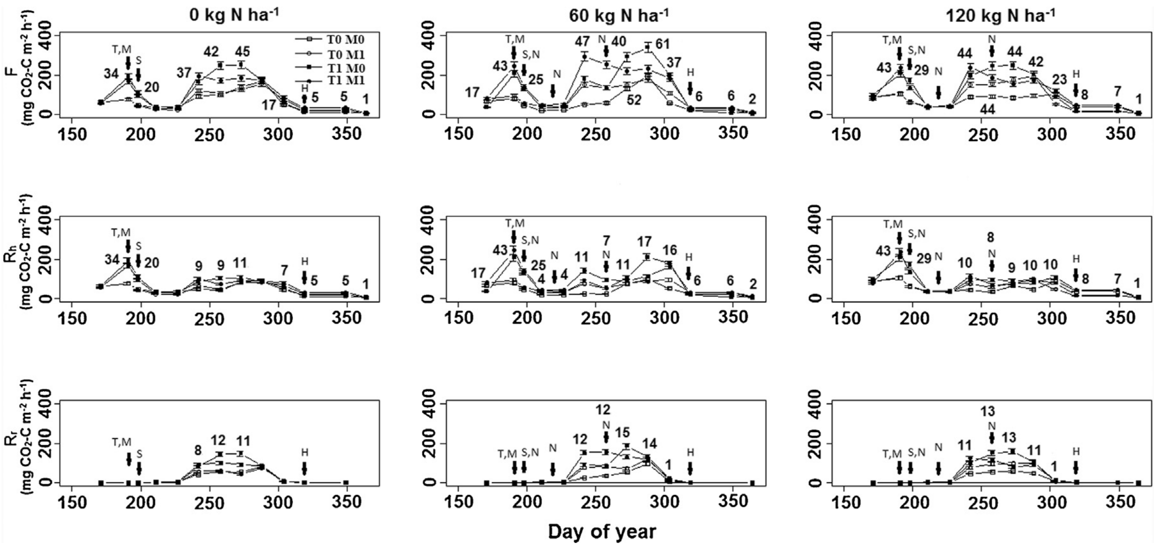

Fig. 3. Tillage and rice straw management effects on daily mean soil CO_2 emission (F), heterotrophic respiration (R_h) and root respiration (R_r) at different nitrogen fertilization levels during the growing season. T: tillage, M: application of rice straw mulch, S: direct sowing, N: nitrogen fertilizer 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 at a specific sampling date indicate significant differences at p ü 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.

273–288) at maximum rice tillering stage, and decreased thereafter until rice harvest (Fig. 3). Contribution of R_r to F ranged from 0 to 63% and varied with tillage system, straw management and nitrogen fertilizer levels. In general, R_r was much greater in manual tillage compared with no-tillage from doy 227 (tillering stage) to doy 288 (flowering stage). There was a slight difference in R_r of manual tillage and no-tillage from flowering stage to harvest. After harvest, R_r ceased. In addition, R_r increased with nitrogen fertilizer addition (Fig. 3).

Using stepwise regression analysis, day after sowing (DAS), soil CO_2 emission (F), and soil moisture (θv) were in general negative drivers of the contribution of R_h contribution to F (Table 1). This indicates that the contribution of R_h relative to R_r, to F was negatively affected by increasing root growth with increasing time after sowing, and that high total soil CO_2 emission values were due to greater contribution from R_r, especially on wet days.

Across tillage systems, rice straw management and nitrogen levels, average contribution of R_r to F during the growing season was 25% (Fig. 3). This value falls within the range of 10–45% reported for annual croplands (Raich and Mora, 2005; Rochette et al., 1999). The peaks of R_r and R_h coincided with some exceptions. This could be attributed to the fact that root respiration is coupled with photosynthesis rates, which are influenced by environmental conditions such as soil moisture, and management practices similar to heterotrophic respiration in Benin (Ago et al., 2015, 2014; Lamade et al., 1996; Mulindabigwi, 2005).

3.4. Cumulative carbon loss via heterotrophic respiration

Cumulative carbon loss via R_h was significantly affected by tillage systems, rice straw management and nitrogen levels (Table 2). On average, manual tillage had 40% greater cumulative carbon loss via R_h than no-tillage. Disturbance of soil aggregates and pores, and sudden release of CO_2 from the soil solution due to tillage operation may be a major reason for having greater cumulative carbon loss via R_h under manual tillage compared with no-tillage (Rochette and Angers, 1999). On average, tillage operation increased R_h by 119 mg CO_2—C m^{-2} h^{-1} on the day of tillage. Similar results were reported by Al-Kaisi and Yin (2005) on fine loamy soil in Ames.

Cumulative carbon loss via R_h was 7% greater with rice straw mulch compared with non-straw mulch (Table 2). This may be attributed to higher availability of carbon substrates for mineralization by rice straw mulch application, which may increase soil microbial activity (Fisk and Fahey, 2001).

Cumulative carbon losses via R_h were 13–16% higher when nitrogen fertilizer was applied as compared to the treatment without nitrogen fertilization (Table 2). The use of nitrogen fertilizer would lead to a decrease in C:N ratio of the carbon substrates, therefore allowing microbes to faster decompose soil organic matter and to produce more CO_2 (Lu et al., 2011), or would increase the soil microbial biomass, thereby increasing the total microbial activity and CO_2 production (Li et al., 2014).

3.5. Aboveground and belowground carbon

Potential carbon input from aboveground biomass varied with tillage systems, straw management and nitrogen levels (Table 2). The lowest potential carbon input from aboveground biomass (0.4 Mg C ha^{-1}) was observed for no-tillage, no straw and no nitrogen application, whereas the highest input (2.3 Mg C ha^{-1}) occurred with manual tillage, straw mulch and 120 kg N ha^{-1}. The average potential aboveground carbon input across tillage systems and straw management was 0.7 Mg C ha^{-1} when no nitrogen was applied, and increased by 1.0 and 1.4 Mg C ha^{-1} with 60 and 120 kg N ha^{-1}, respectively (Table 2). Averaged across tillage systems and nitrogen levels, potential carbon input from aboveground biomass was 0.1 Mg C ha^{-1} higher in straw mulch than in non-mulch treatments (Table 2).

Potential carbon input from root biomass in the top 20 cm soil depth varied with tillage systems, straw management and nitrogen levels (Table 2). The lowest potential carbon input from root biomass (0.1 Mg C ha^{-1}) was observed for no-tillage and no nitrogen application, whereas the highest input (0.4 Mg C ha^{-1}) occurred with rice straw mulch and 120 kg N ha^{-1}. Potential carbon input from root biomass increased by 0.1 and 0.2 Mg C ha^{-1} when 60 and 120 kg N ha^{-1} were applied, respectively, compared with the potential carbon input from root biomass in zero-nitrogen treatments.

Across tillage systems, straw management and nitrogen levels, average potential carbon inputs from aboveground and root biomass were 1.5 Mg C ha^{-1} and 0.3 Mg C ha^{-1}, respectively. These values fall within the range of 1.2–3.0 Mg C ha^{-1} and 0.3–0.7 Mg C ha^{-1} reported by Mulindabigwi (2005), respectively, for aboveground carbon and root biomass carbon in rice fields in northern Benin. Guzman and Al-Kaisi (2014) also reported an increase in potential carbon input from aboveground biomass and root biomass with nitrogen fertilizer addition on loamy clay and silty/loamy clay soils in Iowa. This increase in carbon input from plant biomass with nitrogen fertilizer addition can be attributed to increases in aboveground and root biomass.

3.6. Soil carbon balance

Calculations of the soil carbon balance from estimates of potential carbon inputs from aboveground biomass, root biomass,

Table 1

Regression models of the contribution of heterotrophic respiration (R_h) to soil CO_2 emission (F) during the growing season as affected by days after sowing (DAS), soil CO_2 emission (mg CO_2—C m^{ë2} h^{ë1}), and soil moisture ('v) (m^3 m^{ë3}) under different tillage systems, rice straw management and nitrogen levels.

Tillage[a]	Straw mulch (Mg ha^{ë1})	N fertilization (kg N ha^{ë1})	Regression model	p	R^2
T_0	0	0	113-0.11DAS-189'v-0.09F	0.012	0.73
T_0	0	60	112-0.15DAS-261'v + 0.08F	0.017	0.69
T_0	0	120	119-0.12DAS-213'v-0.15F	0.007	0.78
T_0	3	0	113-0.07DAS-156'v-0.15F	0.007	0.78
T_0	3	60	113-0.06DAS-137'v-0.18F	0.001	0.88
T_0	3	120	120-0.15DAS-168'v-0.17F	î0.001	0.91
T_1	0	0	110-0.10DAS-169'v-0.08F	î0.001	0.93
T_1	0	60	110-0.09DAS-230'v-0.02F	0.002	0.85
T_1	0	120	112-0.11DAS-203'v-0.08F	î0.001	0.91
T_1	3	0	111-0.06DAS-133'v-0.13F	î0.001	0.93
T_1	3	60	117-0.11DAS-208'v-0.07F	î0.001	0.97
T_1	3	120	117-0.11DAS-190'v-0.11F	î0.001	0.93

[a] Tillage systems are no-tillage (T_0) and manual tillage (T_1).

Table 2

Effects of tillage systems, rice straw management and nitrogen fertilizer levels on cumulative carbon loss via heterotrophic respiration (CR_h), potential aboveground carbon (PAC) input, potential belowground carbon (PBC) input and soil carbon balance (SCB).

Tillage[1]	Straw (Mg ha$^{\text{ë}1}$)	N levels (kg N ha$^{\text{ë}1}$)	CR_h (Mg C ha$^{\text{ë}1}$)	PAC (Mg C ha$^{\text{ë}1}$)	PBC (Mg C ha$^{\text{ë}1}$)	C_{straw}[2]	SCB (Mg C ha$^{\text{ë}1}$)
T_0	0	0	3.0 é 0.06 f[3]	0.4 é 0.01 h	0.1 é 0.001 d	0	ë2.5 é 0.05 g
T_0	0	60	2.8 é 0.05 f	1.4 é 0.07 e	0.2 é 0.01 c	0	ë1.2 é 0.05 de
T_0	0	120	3.2 é 0.06 e	1.9 é 0.13 bc	0.3 é 0.01 b	0	ë1.0 é 0.10 d
T_0	3	0	2.9 é 0.06 f	0.6 é 0.02 gh	0.1 é 0.04 d	1.6	ë0.6 é 0.04 c
T_0	3	60	3.5 é 0.07 d	1.6 é 0.03 de	0.3 é 0.01 b	1.6	+0 é 0.06 b
T_0	3	120	3.3 é 0.13 e	1.9 é 0.08 bc	0.4 é 0.02 a	1.6	+0.6 é 0.15 a
T_1	0	0	4.0 é 0.08 c	0.9 é 0.14 f	0.2 é 0.01 c	0	ë2.9 é 0.20 h
T_1	0	60	4.5 é 0.09 b	1.7 é 0.04 cd	0.3 é 0.01 b	0	ë2.5 é 0.05 g
T_1	0	120	4.4 é 0.09 b	2.0 é 0.07 b	0.4 é 0.02 a	0	ë2.0 é 0.12 f
T_1	3	0	3.8 é 0.08 c	0.7 é 0.01 fg	0.2 é 0.006 c	1.6	ë1.3 é 0.06 e
T_1	3	60	5.1 é 0.10 a	2.0 é 0.03 b	0.3 é 0.01 b	1.6	ë1.2 é 0.07 de
T_1	3	120	4.6 é 0.09 b	2.3 é 0.13 a	0.4 é 0.02 a	1.6	ë0.3 é 0.20 b
LSD (treatments combination effects)			0.22	0.23	0.03	*	0.30

[1] Tillage systems are no-tillage (T_0) and manual tillage (T_1).

[2] C_{straw} is carbon input due to rice straw mulching (C_{straw} = 1.6 Mg C ha$^{\text{ë}1}$ for rice straw mulch treatments and C_{straw} = 0 for non-mulch treatments).

[3] Mean values é standard errors followed by different letters in a column within a set are significantly different at p ü 0.05 by the least significant difference test.

and rice straw mulch minus cumulative carbon loss via heterotrophic respiration resulted in differences between tillage systems, rice straw management and nitrogen levels (Table 2). The lowest soil carbon balance was found under the current management practices (manual tillage, no straw and no nitrogen fertilizer) in upland rice fields in northern Benin at −2.9 Mg C ha^{-1}, whereas the highest soil carbon balance was found under no-tillage, rice straw mulch and 120 kg N ha^{-1} at +0.6 Mg C ha^{-1}. Mulching of rice straw was the largest determining factor in net soil carbon changes. With 3 Mg ha^{-1} of rice straw mulch, greater changes in soil carbon were anticipated (−2.0 in no mulch vs. −0.5 Mg C ha^{-1} in rice straw mulch treatments). On average, no-tillage treatments had a 0.9 Mg C ha^{-1} higher soil carbon change value compared with manual tillage. This may be due to the lower carbon loss via heterotrophic respiration found under no-tillage treatments. When no nitrogen was applied, net carbon losses were independent of tillage systems and rice straw management. The soil carbon balance was not significantly different from zero under no-tillage, straw mulch and 60 kg N ha^{-1}. With no other changes in management practices, an increase in nitrogen level from 60 kg N ha^{-1} to 120 kg N ha^{-1} resulted in a positive soil carbon balance. These results point out the importance of using rice straw mulch and nitrogen fertilizer in a no-tillage system for reducing carbon loss via heterotrophic respiration and increasing carbon input in upland rice fields in northern Benin.

4. Conclusion

Under the current management practices (manual tillage, with no residue and no nitrogen fertilization) in upland rice fields in northern Benin, the carbon added as aboveground biomass and root biomass was not enough to compensate for the loss of carbon from organic matter decomposition, rendering the upland rice fields as a net source of atmospheric CO_2. With changes in management practices under no-tillage, 3 Mg ha^{-1} of rice straw mulch and the use of a level of nitrogen (60 kg N ha^{-1}) recommended by the extension services in northern Benin, the soil carbon balance was approximately zero. With no other changes in management practices, an increase in nitrogen level from 60 kg N ha^{-1} to 120 kg N ha^{-1} resulted in a positive soil carbon balance. However, in view of the high cost of inorganic nitrogen fertilizer and the potential risk of soil and air pollution often associated with intensive fertilizer use, no-tillage, combined with the application of 3 Mg ha^{-1} of rice straw mulch and 60 kg N ha^{-1}could be recommended to the smallholder farmers to compensate for the loss of carbon from organic matter decomposition in upland rice fields in northern Benin. Further soil carbon balance studies need to be conducted with different types of soil, at different climatic conditions and in systems which include other crops as well as manure application to develop a general recommendation scheme for a sustainable use of savanna soils in West Africa without further soil carbon losses.

Acknowledgments

This work was supported by the West Africa Science Service Center on Climate Change and Adapted Land Use (WASCAL) programme. The authors thank Expedit Ago and Robert Zougmore for their helpful comments on the manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.still.2016.05.019.

References

Ago, E.E., Agbossou, E.K., Galle, S., Cohard, J.-M., Heinesch, B., Aubinet, M., 2014. Long term observations of carbon dioxide exchange over cultivated savanna under a Sudanian climate in Benin (West Africa). Agric. For. Meteorol. 197, 13–25. doi:http://dx.doi.org/10.1016/j.agrformet.2014.06.005.

Ago, E.E., Serça, D., Agbossou, E.K., Galle, S., Aubinet, M., 2015. Carbon dioxide fluxes from a degraded woodland in West Africa and their responses to main environmental factors. Carbon Balance Manage. 22, 1–16. doi:http://dx.doi.org/10.1186/s13021-015-0033-6.

Al-Kaisi, M., Yin, X., 2005. Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn–soybean rotations. J. Environ. Qual. 34, 437–445. doi:http://dx.doi.org/10.2134/jeq2005.0437.

Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J., 2007. Tillage and soil carbon sequestration—What do we really know? Agric. Ecosyst. Environ. 118, 1–5. doi:http://dx.doi.org/10.1016/j.agee.2006.05.014.

Bouyoucos, G., 1951. A recalibration of the hydrometer for making mechanical analysis of soils. Agro. J. 43, 434–438. doi:http://dx.doi.org/10.2134/agronj1951.00021962004300090005x.

Conen, F., Yakutin, M., Sambuu, A., 2003. Potential for detecting changes in soil organic carbon concentrations resulting from climate change. Glob. Chang Biol. 9, 1515–1520. doi:http://dx.doi.org/10.1046/j.1365-2486.2003.00689.x.

De Vleeschauwer, D., Lal, R., Malafa, R., 1980. Effects of amounts of surface mulch on physical and chemical properties of an alfisol from Nigeria. J. Sci. Food Agric. 31, 730–738. doi:http://dx.doi.org/10.1002/jsfa.2740310718.

Diagne, A., Amovin-Assagba, E., Futakuchi, K., Wopereis, M.C.S., 2013. Estimation of cultivated area, number of farming households and yield for major rice-growing environments in Africa. In: Wopereis, M.C.S., Jonhson, D.E., Ahmadi, N., Tollens, E., Jalloh, A. (Eds.), Realizing Africa's Rice Promise. CAB International, Wallingford, pp. 35–45.

Dossou-Yovo, E.R., Brüggemann, N., Jesse, N., Huat, J., Ago, E.E., Agbossou, K.E., 2016. Reducing soil CO_2 emission and improving upland rice yield with no-tillage, straw mulch and nitrogen fertilization in northern Benin. Soil Tillage Res. 156, 44–53. doi:http://dx.doi.org/10.1016/j.still.2015.10.001.

Duiker, S.W., Lal, R., 2000. Carbon budget study using CO_2 flux measurements from a no till system in central Ohio. Soil Tillage Res. 54, 21–30. doi:http://dx.doi.org/10.1016/S0167-1987(99)00101-4.

Fisk, M., Fahey, T., 2001. Microbial biomass and nitrogen cycling responses to fertilization and litter removal in young northern har. Biogeochemistry 53, 201–223. doi:http://dx.doi.org/10.1023/A:1010693614196.

Grote, J.B., Al-kaisi, M.M., 2007. Topsoil placement effect on soil carbon stock improvement of exposed subsoil in Iowa. J. Soil Water Conserv. 62, 86–93.

Guzman, J., Al-Kaisi, M., 2014. Residue removal and management practices effects on soil environment and carbon budget.Soil Sci. Soc. Am. J. 78, 609–623. doi:http://dx.doi.org/10.2136/sssaj2013.10.0426.

Hanson, P., Edwards, N., Garten, C., Andrews, J., 2000. Separating root and soil microbial contributions to soil respiration: a review of methods and observations. Biogeochemistry 48, 115–146. doi:http://dx.doi.org/10.1023/A:1006244819642.

Henry, A., Torres, R., Holongbayan, L., 2012. Root sampling in the field with soil cores and monoliths. In: Shashidhar, H., Henry, A., Hardy, B. (Eds.), Methodologies for Root Drought Studies in Rice. International Rice Research Institute, pp. 52–61.

Houghton, R.A., Hackler, J.L., Lawrence, K.T., 1999. The U.S. carbon budget: contributions from land-use change. Science 285, 574–579. doi:http://dx.doi.org/10.1126/science.285.5427.574.

Lal, R., Negassa, W., Lorenz, K., 2015. Carbon sequestration in soil. Curr. Opin. Environ. Sustain. 15, 79–86. doi:http://dx.doi.org/10.1016/j.cosust.2015.09.002.

Lamade, E., Djegui, N., Leterme, E., 1996. Estimation of carbon allocation to the roots from soil respiration measurements of oil palm. Plant Soil 181, 329–339. doi:http://dx.doi.org/10.1007/BF00012067.

Li, J.H., Yang, Y.J., Li, B.W., Li, W.J., Wang, G., Knops, J.M.H., 2014. Effects of nitrogen and phosphorus fertilization on soil carbon fractions in alpine meadows on the Qinghai-Tibetan plateau. PLoS One 9 (7), e103266. doi:http://dx.doi.org/10.1371/journal.pone.0103266.

Lu, F., Wang, X., Han, B., Ouyang, Z., Duan, X., Zheng, H., Miao, H., 2009. Soil carbon sequestrations by nitrogen fertilizer application, straw return and no-tillage in China's cropland. Glob. Chang Biol. 15, 281–305. doi:http://dx.doi.org/10.1111/j.1365-2486.2008.01743.x.

Lu, M., Zhou, X., Luo, Y., Yang, Y., Fang, C., Chen, J., Li, B., 2011. Minor stimulation of soil carbon storage by nitrogen addition: a meta-analysis. Agric. Ecosyst. Environ. 140, 234–244. doi:http://dx.doi.org/10.1016/j.agee.2010.12.010.

Mu, Z., Kimura, S.D., Toma, Y., Hatano, R., 2008. Evaluation of the soil carbon budget under different upland cropping systems in central Hokkaido. Japan. Soil Sci. Plant Nutr. 54, 650–661. doi:http://dx.doi.org/10.1111/j.1747-0765.2008.00279.x.

Mulindabigwi, V., 2005. Influence des systèmes agraires sur l'utilisation des terroirs, la séquestration du carbone et la sécurité alimentaire dans le bassin versant de l'Ouémé supérieur au Bénin. PhD Thesis. University of Bonn, Germany, pp. 253.

Nishimura, S., Yonemura, S., Sawamoto, T., Shirato, Y., Akiyama, H., Sudo, S., Yagi, K., 2008. Effect of land use change from paddy rice cultivation to upland crop cultivation on soil carbon budget of a cropland in Japan. Agric. Ecosyst. Environ. 125, 9–20. doi:http://dx.doi.org/10.1016/j.agee.2007.11.003.

Paustian, K., Andren, O., Janzen, H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwijk, M., Woomer, P., 1997. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use Manage. 13, 230–244. doi:http://dx.doi.org/10.1111/j.1475-2743.1997.tb00594.x.

Paustian, K., Six, J., Elliott, E.T., Hunt, H.W., 2000. Management options for reducing CO_2 emissions from agricultural soils. Biogeochemistry 48, 147–163. doi:http://dx.doi.org/10.1023/A:1006271331703.

RDevelopmentCoreTeam, 2011. R: A Language and Environment for Statistical ComputingR Foundation for Statistical Computing, Vienna, Austria. . (ISBN 3-900051-07-0) http://www.R-project.org/.

Rahman, M.A., Chikushi, J., Saifizzaman, M., Lauren, J.G., 2005. Rice straw mulching and nitrogen response of no-till wheat following rice in Bangladesh. Field Crops Res. 91, 71–81. doi:http://dx.doi.org/10.1016/j.fcr.2004.06.010.

Raich, J.W., Mora, G., 2005. Estimating root plus rhizosphere contributions to soil respiration in annual croplands. Soil Sci. Soc. Am. J. 69, 634–639. doi:http://dx.doi.org/10.2136/sssaj2004.0257.

Rasse, D., Rumpel, C., Dignac, M., 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant Soil 269, 341–356. doi:http://dx.doi.org/10.1007/s11104-004-0907-y.

Rochette, P., Angers, D.A., 1999. Soil surface carbon dioxide fluxes induced by spring summer, and fall moldboard plowing in a Sandy loam. Soil Sci. Soc. Am. J. 63, 621–628. doi:http://dx.doi.org/10.2136/sssaj1999.03615995006300030027x.

Rochette, P., Ellert, B., Gregorich, E.G., Desjardins, R.L., Pattey, E., Lessard, R., Johnson, B.G., 1997. Description of a dynamic closed chamber for measuring soil respiration and its comparison with other techniques. Can. J. Soil Sci. 77, 195–203. doi:http://dx.doi.org/10.4141/S96-110.

Rochette, P., Flanagan, L., Gregorich, E., 1999. Separating soil respiration into plant and soil components using analysis of natural abundance of carbon-13. Soil Sci. Soc. Am. J. 63, 1207–1213. doi:http://dx.doi.org/10.2136/sssaj1999.6351207x.

Saito, K., Azoma, K., Oikeh, S.O., 2010. Combined effects of Stylosanthes guianensis fallow and tillage management on upland rice yield, weeds and soils in southern Benin. Soil Tillage Res. 107, 57–63. doi:http://dx.doi.org/10.1016/j.still.2010.03.001.

Six, J., Elliott, E.T., Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32, 2099–2103. doi:http://dx.doi.org/10.1016/S0038-0717(00)00179-6.

Youssouf, I., Lawani, M., 2000. Les sols béninois: classification dans la base de référence mondiale. In: Youssouf, I., Lawani, M. (Eds.), Rapport De La Quatorzième Réunion Du Sous-comité Ouest Et Centre Africain De Corrélation Des Sols. Food and Agriculture Organisation, pp. 29–50.

Zhou, L., Zhou, X., Zhang, B., Lu, M., Luo, Y., Liu, L., Li, B., 2014. Different responses of soil respiration and its components to nitrogen addition among biomes: a meta-analysis. Glob. Chang Biol. 20, 2332–2343. doi:http://dx.doi.org/10.1111/gcb.12490.