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Cover crop rotations in no-till system: short-term CO_2 emissions and soybean yield

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ABSTRACT: In addition to improving sustainability in cropping systems, the use of a spring and winter crop rotation system may be a viable option for mitigating soil CO_2 emissions (ECO_2). This study aimed to determine short-term ECO_2 as affected by crop rotations and soil management over one soybean cycle in two no-till experiments, and to assess the soybean yields with the lowest ECO_2. Two experiments were carried out in fall-winter as follows: i) triticale and sunflower were grown in Typic Rhodudalf (TR), and ii) ruzigrass, grain sorghum, and ruzigrass + grain sorghum were grown in Rhodic Hapludox (RH). In the spring, pearl millet, sunn hemp, and forage sorghum were grown in both experiments. In addition, in TR a fallow treatment was also applied in the spring. Soybean was grown every year in the summer, and ECO_2 were recorded during the growing period. The average ECO_2 was 0.58 and 0.84 g m^2 h^{-1} with accumulated ECO_2 of 5,268 and 7,813 kg ha^{-1} C-CO_2 in TR and RH, respectively. Sunn hemp, when compared to pearl millet, resulted in lower ECO_2 by up to 12 % and an increase in soybean yield of 9% in TR. In RH, under the winter crop Ruzigrazz+Sorghum, ECO_2 were lower by 17%, although with the same soybean yield. Soil moisture and N content of crop residues are the main drivers of ECO_2 and soil clay content seems to play an important role in ECO_2 that is worthy of further studies. In conclusion, sunn hemp in crop rotation may be utilized to mitigate ECO_2 and improve soybean yield.

Keywords: *Glycine max* (L.) Merrill, carbon equivalent, crop residue, management system

Introduction

Although agriculture is one of the main sectors responsible for the increase in CO_2 concentration in the atmosphere, this effect could be considerably mitigated through the use of proper cover crops and soil management (Delgado et al., 2011). Conservation practices under no-till can help mitigate CO_2 emissions (ECO_2) by increasing the amount of crop residue and slowing the decomposition rate, which favors soil organic matter (SOM) accumulation and increases crop yield (Delgado et al., 2007; Stewart et al., 2009).

Greenhouse gas emissions (GHG) in tropical soils differ from other regions due to the high oxidation rate of SOM as a consequence of high temperatures and moisture, resulting in rapid decomposition of plant residues (Bolliger et al., 2006). Furthermore, irregular rainfall and dry winters hinder the addition of C since the growth of cover crops is impaired and the amount of plant residues produced in the off-season may be reduced (Castro et al., 2015). However, cover crop residues left on the soil surface can decrease the soil temperature, and retain soil moisture and eventually ECO_2 (Brito et al., 2015; Carbone et al., 2011). ECO_2 also depends on the crop rotations used in the agricultural system, which are affected by the quality of crop residue left on the soil and the amount of easily mineralizable C (Kögel-Knabner, 2002). Crop rotations with lower N inputs may favor ECO_2 and decrease C assimilation by soil microbial biomass (Marquez et al., 2000). Conversely, crop residues with high N content and low C/N are more readily decomposed by microorganisms due to the lower straw recalcitrance, resulting in a fast loss of CO_2 to the atmosphere (Zhou et al., 2016). Depending on the crop grown before soybean, the supply of biologic nitrogen fixation may not be enough to produce high yields (Salvagiotti et al., 2008). Thus, there is a mutual need for the effect of crop rotation in the soil GHG emission and grain yields to estimate the yield-scaled emissions. Little is known about the effects of cover crops on ECO_2 in tropical soils with the same crop rotations under the no-till system for at least 10 years. We hypothesized that in tropical and non-N-fertilized soils, crop rotation with legumes could result in higher soybean [*Glycine max* (L.) Merrill] yields, lower C-CO_2 emitted per kilogram of soybean grain produced, and lower yield-scaled ECO_2. Thus, the aim of this study was to determine ECO_2 during the soybean cycle so as to assess the effectiveness of each crop sequence in producing high soybean yield with lower $ECO_{2.}$

Materials and Methods

Study site and climate

Two experiments were conducted in Botucatu, SP, Brazil, (22°49′ S;48°25′ W at an altitude of 780 m), on a Typic Rhodudalf (TR) and a Rhodic Hapludox (RH) (Soil Survey Staff, 2010). In the 0 to 0.10 m depth the clay contents are 655 and 405 g kg^{-1} in TR and RH, respectively. The climate is mesothermal with a dry austral winter and a well-defined dry season from May to Sept, with mean annual rainfall of 1,450 mm. The daily minimum and maximum air temperatures and rainfall from Apr 2011 to Apr 2012 are shown in Figure 1.

Description of the field experiments

Both experiments were conducted in a completely randomized block design, split plot arrangement with four replications. The main plots consisted of crops grown in the fall-winter and the subplots of spring crops, grown before sowing soybean (*Glycine max* (L.) Merril) in the entire area. The crop rotations were repeated annually since 2003 and 2006 for TR and RH, respectively.

The experiment in TR began in 2003 with triticale (*X Triticosecale* Wittmack) or sunflower (*Helianthus annuus* L.) cropped in the fall-winter period (in 32 m × 5 m plots), followed by pearl millet (*Penninsetum glaucum* L.), sunn hemp (*Crotalaria juncea* L.), forage sorghum (*Sorghum bicolor* L.) or fallow during the spring (in 8 m × 5 m subplots). The fallow sub-plots were chisel plowed in 2003, 2007 and 2009, just before soybean planting due to the high soil penetration resistance measured (Calonego and Rosolem, 2010) and at the same time represented minimum tillage. The designated plots were chiseled using a chisel plow with seven shanks mounted on two parallel bars on a square tool carrier. The shanks, inclined 25° forward, were set 0.60 m apart resulting in an effective between-shank spacing of 0.30 m, with a maximum operating depth of 0.30 m. Triticale and sunflower were planted, respectively, at row spacings of 0.17 and 0.51 m, and seed density of 165 and 22 kg ha^{-1} . Fall-winter crops were harvested every year since 2003 from the second half of Aug to the first half of Sept using a plot harvester.

Crop rotations began in 2006 for the RH experiment when grain sorghum (*Sorghum vulgare* L.*)*, ruzigrass (*Urochloa ruziziensis* R. Germ & Evrard) or both (intercropped) were cropped in the fall-winter in 30 m × 5 m plots. In the spring, pearl millet, sunn hemp, or forage sorghum were grown in 10 m × 5 m sub-plots. Ruzigrass was planted at a row spacing of 0.17 m at a seed rate of 22 kg ha^{-1} and forage sorghum at 0.34 m spacing and 11 kg ha^{-1} of seeds. For intercropping, the same spacing and seed rates were used. Ruzigrass seeds were placed in the fertilizer box of the planter and distributed in the same row as grain sorghum. In both experiments, the spring crops were planted in the first half of Oct at a spacing of 0.17 m between rows. Pearl millet, sunn hemp, and forage sorghum seeds were planted at rates of 25, 30, and 15 kg ha^{-1}, respectively. In the first half of Dec, approximately 60 days after planting, each year the spring crops were chemically desiccated with glyphosate and then soybean was planted. Soybean was grown every year in the summer since the beginning of the experiments. In the 2011/2012 crop season the cultivar Dow Agrosciences 5D688 RR was planted in both experiments on 13 Dec 2011 at a between-row spacing of 0.45 m with a population of 355 thousand seeds ha^{-1}, and fertilized with 50 kg ha^{-1} of K_2O and 50 kg ha^{-1} of P_2O_5, as potassium chloride and triple superphosphate, respectively.

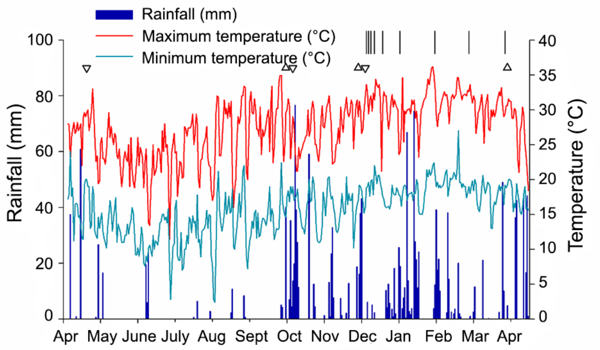

Figure 1 – Rainfall (mm) and main daily temperature in the experimental areas from Apr 2011 to Apr 2012. Sowing (▼) and harvest (▲) of the sequences of fall-winter and spring crops and soybean in the summer. (I) Evaluation of CO$_2$ emission.

Crop residues and soybean yield

After desiccation of the spring crops, at the soybean flowering (R2 stage) and after harvest, two samples of the plant residues were taken randomly from each subplot using a 0.5 m × 0.5 m wooden frame. The samples were dried to constant weight in an air-forced oven at 60 °C and were ground and a subsample was used to determine the C and N concentrations in an elemental analyzer following the procedure recommended by the manufacture (LECO-TruSpec® CHNS). Samples from each crop plant were mixed and homogenized. Two subsamples were taken and analyzed for cellulose, hemicellulose, and lignin (Silva and Queiroz, 2002). These analyses were not performed for the mixture of ruzigrass + grain sorghum (Table 1). The amount exceeding the subsample was returned to its original place in the field. Soybean was planted on 13 Dec 2011 and harvested on 14 Apr 2012. The grain yield was adjusted to 13 % moisture.

Soil CO$_2$ flux, temperature and moisture

Soil ECO$_2$, soil temperature and soil moisture were measured during the soybean growing season. Readings were taken from 8h00 to 10h00 a.m. in TR and from 10h00 to 12h00 p.m. in RH plots. Right after soybean planting, 12 cm high and 20 cm wide PVC collars were installed in the plant rows with the lower edge buried at 5 cm in the soil. CO$_2$ emissions were identified using a portable infrared gas analyzer (IRGA, LI-8100A; Li-Cor, 2007). Once the chamber had been placed on the PVC collars, CO$_2$ mea-

Table 1 – Selected chemical characteristics of the crops in the crop rotation systems.

Crop	C/N	Lignin/N	N	C	Hemicellulose	Cellulose	Lignin
			%				
Triticale	96	37	0.47	45.1	20.0	49.2	17.3
Sunflower	66	32	0.67	44.2	9.9	48.0	21.1
Grain sorghum	61	10	0.74	45.4	35.9	34.7	7.1
Soybean straw	61	41	0.75	45.3	12.0	44.6	30.4
Forage sorghum	53	6	0.87	46.3	34.7	35.4	5.4
Pearl millet	34	4	1.30	43.8	32.5	28.4	4.7
Ruzigrass	18	4	2.44	44.5	27.5	24.0	10.1
Sunn hemp	16	5	2.86	44.7	11.9	33.8	14.9

surements were performed in a 120 s run, with 15 s to perform a pre-purging, 15 s for a post-purging, and 90 s for the CO_2 readings, at a frequency of one reading per second. At the time of each CO_2 flux measurement, soil temperature and moisture were measured at 5 cm deep in the soil using a 5TM sensor (Decagon Devices).

Data analysis

The accumulated ECO_2 during the study period was determined by integrating the area under the emission versus time curve, using the Origin 7 software program (Originlab, 2011). The results of accumulated emissions were converted into kg ha^{-1} of C-CO_2. Finally, C-CO_2 yield-scaled emission for each treatment was calculated, i.e. the weight of C-CO_2 emitted to produce 1 kg of soybean grain, and the results were expressed in kg kg^{-1}. The results were subjected to ANOVA ($p < 0.05$) and the mean values were compared by Fisher's protected LSD (least significant difference) test ($p < 0.05$). Correlation analysis was undertaken to compare the ECO_2, soil moisture and soil temperature results and the Pearson coefficient was calculated.

Results

ECO_2, soil temperature and soil moisture

On the first day after planting (DAP), mean emissions were close to 0.35 and 0.65 g CO_2 m^{-2} h^{-1} in the TR and RH experiments (Figures 2A and 3A, respectively), but showed no significant differences when crop rotations were compared in each of the experiments. After this, ECO_2 increased in all plots in both TR and RH, with a minimum of two-fold mean increases on the second DAP in both experiments. The majority of significant soil ECO_2 differences between different crop rotation systems were observed in the RH experiment, especially after 2, 3 and 60 DAP. RH at 2 DAP, crop rotation with ruzigrass + grain sorghum/pearl millet and ruzigrass/sunn hemp increased ECO_2, by 1.99 and 1.78 g m^{-2} h^{-1}, respectively, differing from the other crop rotations (Figure 3A). On the next day (15 Dec 2011), again ruzigrass/sunn hemp differed from the other rotations with ECO_2 of 1.24 g m^{-2} h^{-1}.

The fourth evaluation (20 Dec 2011) revealed a slight decrease in ECO_2. Even so, differences were observed in both experiments in crop sequences with pearl millet in the spring. In TR the sunflower/pearl millet (0.41 g m^{-2} h^{-1}) differed from triticale/forage sorghum or fallow. Whereas for RH ruzigrass + grain sorghum/pearl millet (0.79 g m^{-2} h^{-1}) was at least two times higher than other crop rotations.

Lower CO_2 soil emission was observed during the fifth evaluation (27 Dec 2011) with an average around 0.3 g m^{-2} h^{-1} in both experiments. Moreover, the crop rotations in TR resulted in higher ECO_2 with sunflower in winter and sunn hemp and pearl millet in the spring, as well as triticale/fallow. These crop rotations differ from the others with averages around 0.34 g m^{-2} h^{-1}. During this fifth evaluation, for both experiments, soil temperature (Figures 2B and 3B) and moisture averages (Figures 2C and 3C) were higher and lower, respectively, in relation to other evaluation dates. The soil temperature averages were 40 and 44 °C for TR and RH, respectively, and soil moisture averages were 0.125 and 0.06 m^3 m^{-3} for TR and RH, respectively. An important aspect is that the average ECO_2 in RH was 40 % higher than in TR in these first five assessments, with overall means of 0.58 and 0.84 g m^{-2} h^{-1}. Furthermore, the highest soil temperature and the lowest soil moisture were observed in RH and from 20 Dec 2011 all other determinations were significantly affected by the crop rotation system, except for the last one (13 Apr 2012) in TR. By 13 Jan 12, increased emissions had been observed in TR in the rotation of sunflower in winter crop followed by sunn hemp, pearl millet and forage sorghum with ECO_2 of 1.1, 1.08 and 0.95 g m^{-2} h^{-1}, respectively which differed from other crop rotations. From this time on, emissions slightly decreased and to a certain extent stabilized although they were still considered high until the end of the soybean cycle. At that time, as well as on 13 Feb 12, the emissions were lower when triticale was grown in

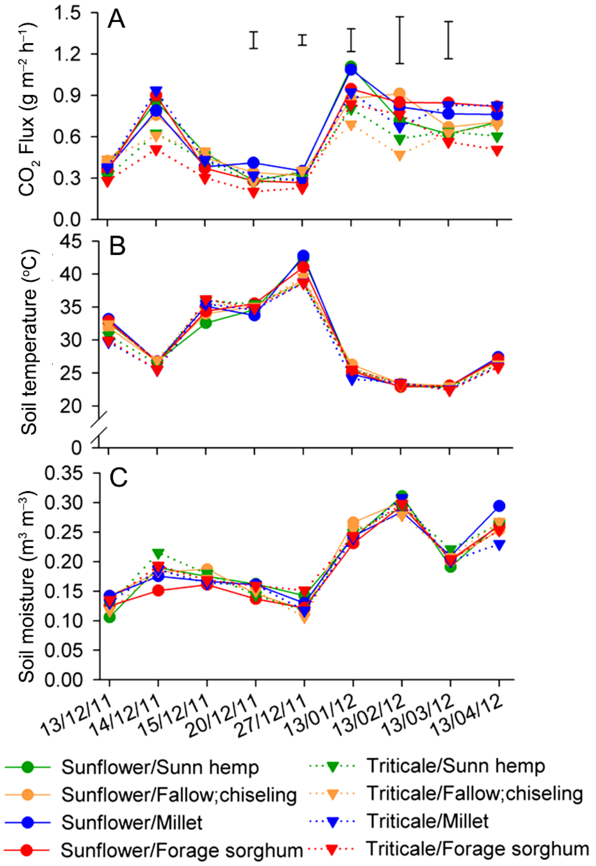

Figure 2 – CO_2 flux in g m^{-2} h^{-1} (A), soil temperature in °C (B), and soil moisture in m^3 m^{-3} (C), at 1, 2, 3, 8, 15, 30, 60, 90 and 120 days after sowing of soybean in accordance with different crop sequences in the Typic Rhodudalf soil. Vertical bars correspond to the LSD (least significant difference) at the 5 % probability level.

autumn-winter, mainly with fallow and sunn hemp in the spring, differing from the other rotations. This crop rotation also resulted in lower soil temperatures. However, in RH sorghum grown in the spring, mainly with grain sorghum in autumn/winter ECO_2 and soil moisture were lower in a number of determinations, suggesting correlation between these variables.

The highest ECO_2 in RH was observed on 13 Feb 12 in plots cropped by ruzigrass in the autumn-winter followed by pearl millet and sunn hemp in spring emitting 2.28 and 2.04 g m^{-2} h^{-1}, respectively, differing from other crop rotations. These treatments also had the highest ECO_2 on 13 Mar 12 and 13 Apr 12, which, although decreasing, differed from the other crop rotations only in the later assessment. Differing from other experiments, the high temperature in RH may have restricted the ECO_2. It was observed that in the highest emission, both crop rotations also had lower soil temperatures on 13 Mar 2012.

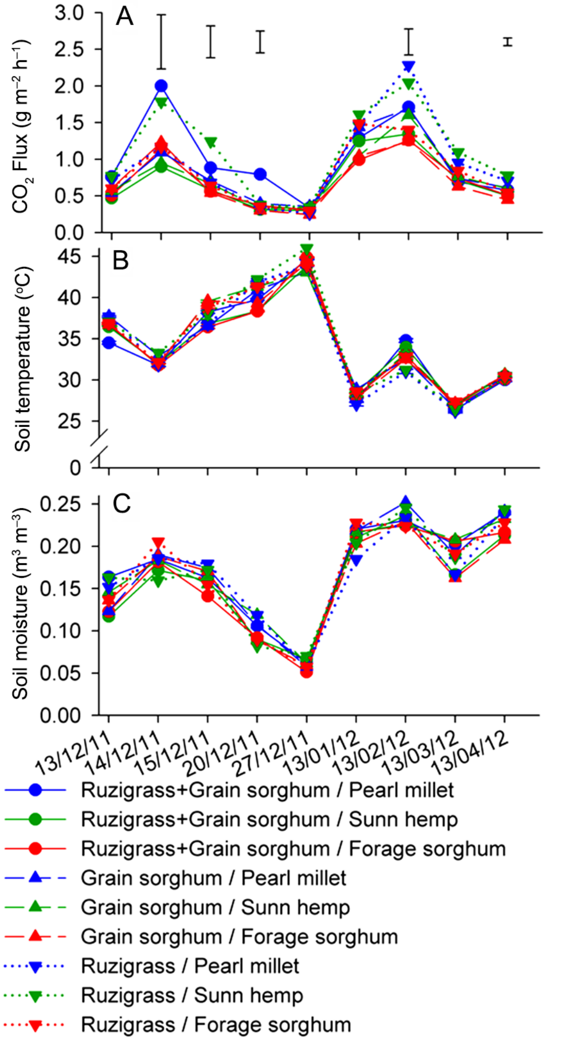

Figure 3 – CO_2 flux in g m^{-2} h^{-1} (A), soil temperature in °C (B), and soil moisture in m^3 m^{-3} (C), at 1, 2, 3, 8, 15, 30, 60, 90 and 120 days after sowing of soybean in accordance with different crop sequences in the Rhodic Hapludox soil. Vertical bars correspond to the LSD (least significant difference) at the 5 % probability level.

The ECO_2 during the soybean cycle correlated positively with soil moisture (Figure 4A) and negatively with soil temperature (Figure 4B) in both experiments. According to the linear regressions, the rate of ECO_2 had a range between 1.58 and 3.24 g CO_2 m^{-2} h^{-1} per m^3 m^{-3} moisture in both TR and RH, respectively. This difference in ECO_2 sensitivity to soil moisture or soil temperature could be related to soil type and properties such as color, texture and bulk density. It should also be noted that the quality of crop residues on each soil affects the shading and partitioning of incident radiation and the amount of energy expended to evaporate water or warm the soil (Sauer and Horton, 2005).

Effects of yield and N content in crop residues on ECO_2

There was also a significant effect on the amount and quality of crop residues on emissions. ECO_2 in TR correlated positively with the N accumulated and dry matter content of spring crops (Figure 5A). In the spring, fallow and forage sorghum residues accumulated lower N contents, irrespective of the autumn-winter crops (about 20 g

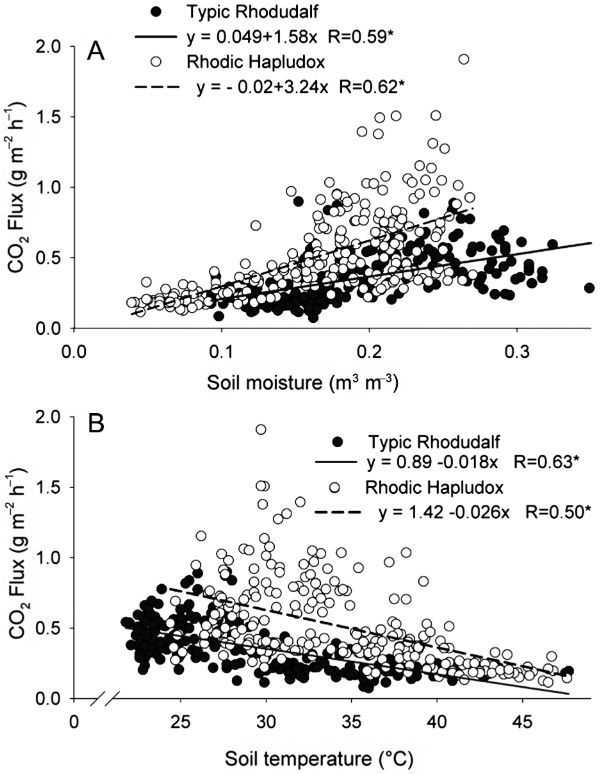

Figure 4 – Pearson correlation (*p < 0.05) between the CO_2 flux (g m^{-2} h^{-1}) and soil moisture (m^3 m^{-3}) (A) and soil temperature (°C) (B) in the Typic Rhodudalf and the Rhodic Hapludox.

kg^{-1}), and also resulted in lower ECO$_2$. Conversely, sunn hemp and pearl millet accumulated more N, from 40 to 60 g kg^{-1}, which resulted in higher ECO$_2$. Similarly, in RH the N content in the spring crop residues correlated positively with ECO$_2$ in 30 and 120 DAP (Figure 6A and C). At 120 DAP the lower N content was observed in the forage sorghum, under 20 g kg^{-1}, as well as a lower ECO$_2$, about 0.5 g m^{-2} h^{-1}, while N contents in sunn hemp and pearl millet residues were over 20 g kg^{-1} and ECO$_2$ up to 1.0 m^2 g^{-1} h^{-1}.

A significant effect was also observed on soybean dry weight at flowering, which greatly increased ECO$_2$ in 30, 90 and 120 DAP (Figure 6A, B and C) with linear correlation ($p < 0.05$, R = 0.55; 0.34 and 0.33, respectively). As a consequence, higher soybean yields resulted in higher accumulated ECO$_2$ ($p < 0.05$, R = 0.37 and 0.36) in TR and RH, respectively (Figures 5B and 6D).

In TR, crop rotations had no effect on accumulated C-CO$_2$ emission, but they did have an impact on soybean yield, resulting in different yield-scaled ECO$_2$, i.e., the C-CO$_2$ emitted in the production of 1 kg of soybean grain (Table 2). Sunflower showed a higher C-CO$_2$ loss than triticale in the autumn-winter and resulted in similar soybean grain yields. For the spring crops, lower emissions were observed with sunn hemp and fallow/chisel by 1.67 and 1.60 kg^{-1} C-CO$_2$ kg^{-1} respectively, differing from forage sorghum and pearl millet (2.02 and 2.07 kg^{-1} C-CO$_2$ kg^{-1} respectively).

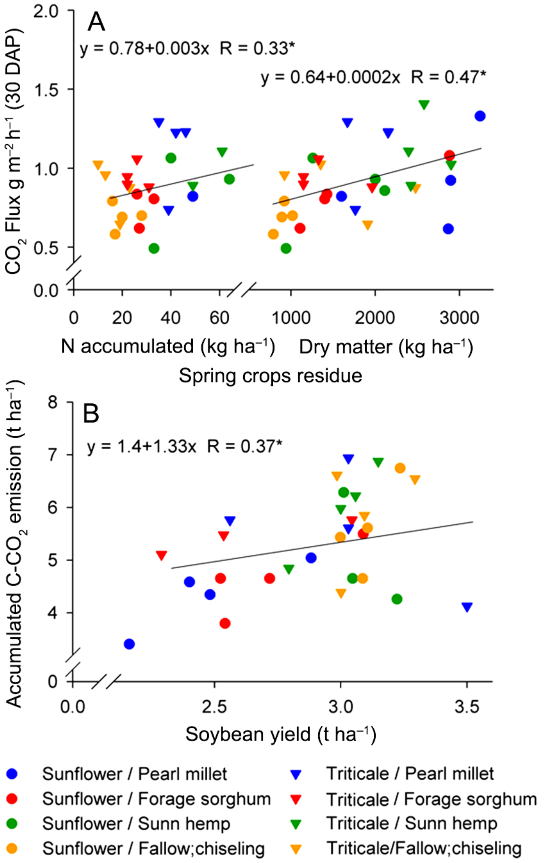

Figure 5 – Pearson correlation (*$p < 0.05$) between CO$_2$ flux (g m^2 h^{-1}) at 30 DAP and N accumulated and dry matter on the spring crops (A); accumulated emission and soybean yield (B) in the Typic Rhodudalf soil.

In RH, there was interaction between the autumn-winter and spring crops on accumulated C-CO$_2$ emission. Ruzigrass was cropped in the autumn winter and produced the highest accumulated C-CO$_2$ emission when followed by sunn hemp in the spring (9840 kg ha^{-1} C-CO$_2$). The result was little different for ruzigrass/pearl millet (9744 kg ha^{-1} C-CO$_2$). The accumulated C-CO$_2$ emission with ruzigrass/sunn hemp was roughly 25 to 30 % higher than for grain sorghum/sunn hemp and ruzigrass + grain sorghum/sunn hemp (Table 3). Soybean grain yield with pearl millet cropped in the spring was higher when ruzigrass was cropped singly in the autumn winter (3517 kg ha^{-1}), but it was around 10 % lower than when grain sorghum/pearl millet were grown (3183 kg ha^{-1}). Although crop rotations affected accumulated C-CO$_2$ emissions and soybean grain yields, there was no difference in the yield-scaled ECO$_2$ (Table 3) and the overall mean was 2.54 kg C-CO$_2$ kg^{-1} of grain.

Discussion

ECO$_2$, soil temperature and soil moisture

The high amount of fresh C ready for mineralization on the soil surface in rotations including cover crops under no-till, added to the disturbance in rows at planting might contribute to ECO$_2$, and as such, higher CO$_2$ emissions were expected soon after soybean planting. However, this was not, in fact, observed. The lower ECO$_2$ on the first day after planting are explained in part by the low soil moisture, approximately 0.135 m^3 m^{-3} in both experiments. After this, rainfall increased ECO$_2$ with a slight decrease in soil temperature (under 32 °C), suggesting soil moisture was a driving factor of an increase in microbial activity as supported by the finding (Brito et al., 2015). Conversely, when soil moisture is adequate for microbial growth, soil

Table 2 – Accumulated C-CO$_2$ emissions, soybean grain yield, and relative C-CO$_2$ emissions in the Typic Rhodudalf soil.

Crop sequence before soybean	Accumulated emission C-CO$_2$	Soybean yield	Yield-scaled C-CO$_2$
	kg ha^{-1}		
	Fall-Winter crops		
Sunflower	5727 a	2838 a	2.01 a
Triticale	4810 a	2915 a	1.65 b
	Spring crops		
Sunn hemp	5062 a	3023 a	1.67 b
Pearl millet	5728 a	2756 ab	2.07 a
Forage sorghum	5312 a	2627 b	2.02 a
Fallow;chisel	4974 a	3100 a	1.60 b

Mean values followed by different letters in the column differ between themselves by the t test (LSD = least significant difference) at the 5 % probability level.

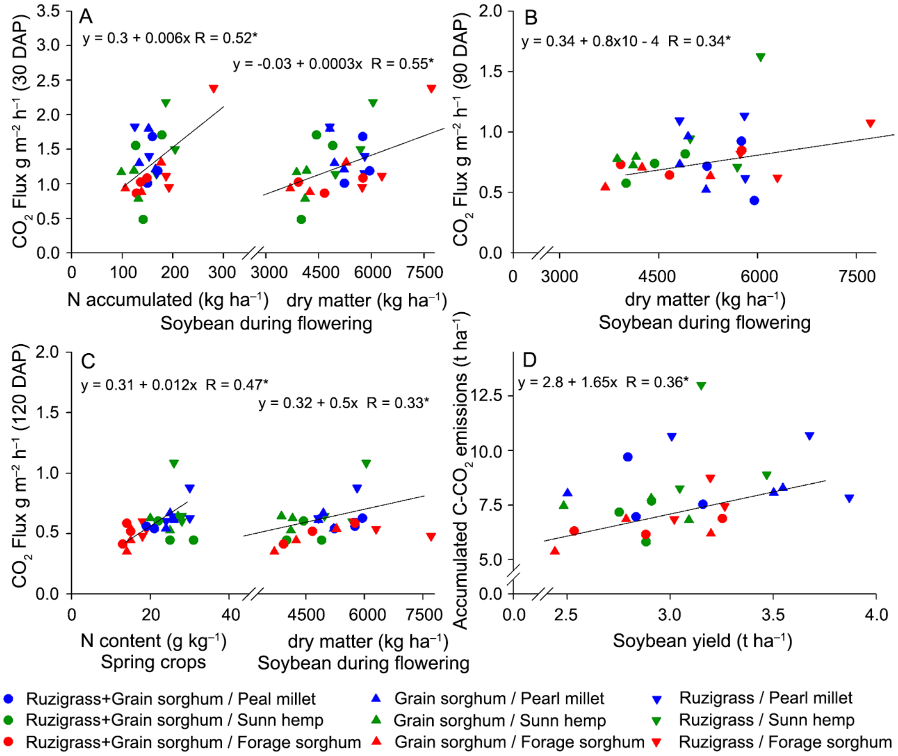

Figure 6 – Pearson correlation (*$p < 0.05$) between CO_2 flux (g m^2 h^{-1}) at 30 DAP and N accumulated and dry matter on soybean during flowering (A); in 90 DAP dry matter on soybean during flowering (B); in 120 DAP and N content on the spring crops and dry matter on soybean during flowering (C); accumulated emission and soybean yield in the Rhodic Hapludox soil.

Table 3 – Accumulated C-CO_2 emissions, soybean grain yields, and yield-scaled C-CO_2 emissions in the Rhodic Hapludox soil.

Crop sequence before Soybean	Sunn hemp	Pearl millet	Forage sorghum
	Accumulated emission of C-CO_2 (kg ha^{-1})		
Ruzigrass + Grain sorghum	6888 bA	8064 aA	6456 aA
Grain sorghum	7368 bA	8136 aA	6144 aA
Ruzigrass	9840 aA	9744 aAB	7680 aB
	Soybean grain yield (kg ha^{-1})		
Ruzigrass + Grain sorghum	2848 aA	2929 bA	2889 aA
Grain sorghum	2827 aA	3183 abA	2808 aA
Ruzigrass	3221 aA	3517 aA	3159 aA
	yield-scaled C-CO_2 (kg kg^{-1})		
Ruzigrass + Grain Sorghum	2.40 aA	2.73 aA	2.23 aA
Grain sorghum	2.61 aA	2.54 aA	2.18 aA
Ruzigrass	3.04 aA	2.76 aA	2.42 aA

Mean values followed by different letters, upper case letters in the row and lower case letters in the column, differ between themselves by the t test (LSD = least significant difference) at the 5 % probability level.

temperature could be an important factor for controlling soil respiration (Carbone et al., 2011). There was also an indirect effect of aboveground biomass and plant residues on soil moisture and temperature, because the crop residues left on the soil surface under no-till attenuate the temperature and moisture loss (Omonode et al., 2007).

Crop root respiration is considered low up to 30 days after sowing (Yang and Cai, 2006; Hatfield and Parkin, 2012), leading to the inference that the low ECO_2 observed during the emergence stage of soybean until then was due to the dry soil (averages 0.12 and 0.15 m^3 m^{-3} in TR and RH, respectively). Thus it is important to mention that soil moisture conditions before rewetting, as well as the length and severity of drought periods, also influence ECO_2 (Harms and Grimm, 2012; Unger et al., 2010). A threshold in soil moisture mainly under mediterranean and temperate zone conditions was identified at 12-20 % gravimetric moisture, below which, after rewetting, a pulse of ECO_2 is observed (Kim et al., 2012).

In our experiments, both a positive effect of soil moisture and a negative effect of temperature on ECO_2 were observed (Figure 4A and B). Soil moisture and temperature are recognized as major factors which control the CO_2 flux in the soil by modifying microorganism activity (Smith et al., 2003; Van Hemelryck et al., 2011). Therefore, the effect of soil temperature may have been influenced indirectly, since soil moisture content has its own effect on soil temperature (Rey et al., 2002). At high soil temperatures, soil moisture becomes a limiting factor for respiration in tropical soils (Mohantya and Panda, 2011). In our experiments soil temperatures ranged from 22 to 47 °C which are typical for tropical regions, while the most favorable temperature considered for microbial activity is around 30 °C (Tavares et al., 2015). It was found that even under ideal temperature conditions for ECO_2 between 30 and 35 °C, as in the first, third and fourth assessments, ECO_2 were low due to low soil moisture on these dates, which hindered microbial activity (Unger et al., 2010). Moreover, corroborating results were reported by Panosso et al. (2009), also under tropical climate conditions.

The ECO_2 peak observed at 30 and 60 DAP (13 Jan 11 and 13 Feb 12), in both experiments, was due to the rainfall in the days preceeding the evaluations (Figure 1) along with high temperatures (about 30 °C) which favor soil microbial activity (Morell et al., 2011), generating a pulse of ECO_2 after rewetting of the soil. The typical values of soil CO_2 emission in this period were similar to those observed by Smith et al. (2014) in soybean in a temperate zone. During these periods (30 and 60 DAP), the maximum soybean canopy covering the bare soils probably contributed to the maintenance of both soil moisture and low soil temperatures. This suggests that the cover and field crops have the potential to improve soil and water conservation and sustainability in rotation systems under no-tillage.

Root respiration is another factor related to ECO_2, as this may represent up to 50 % of total ECO_2 in soils, with higher values during the growing and flowering stages (Hatfield and Parkin, 2012; Morell et al., 2012). Fu et al. (2002) observed that soybean root respiration at different growth stages could increase ECO_2 from the vegetative to the late flowering stage (Figures 2A and 3A). Such an effect was also reported in maize (Omonode et al., 2007), rice (Feng et al., 2013), barley (Sainju and Singh, 2008) and soybean (Wilson and Al-Kaisi, 2008). According to these authors, a peak in ECO_2 might be attributed to an increase in substrate availability due to root exudation. In our experiment, in addition to soybean root respiration, decaying cover crop straw and roots contributed to high levels of ECO_2.

Effect of Crop residues on ECO_2

The quality of crop residues impacted ECO_2 mainly in spring, when the fastest rate of N rich straw decay was observed (Bremer et al., 1991). This is mainly due to residue C and N contents, and the biochemical characteristics related to crop residue decomposition (Trinsoutrot et al., 2000). Despite the absence of N fertilization, the elevated N content of cover crops resulted in a high mineralization rate and consequently a high level of ECO_2, as has been observed in other studies (Jacinthe et al., 2002; Sainju et al., 2012). This was confirmed in rotations with Ruzigrass in fall-winter and sunn hemp or pearl millet in spring in RH, which had the highest CO_2 emission during the soybean cycle. These crops had the highest levels of N and lowest C/N in the shoot (Table 1), facilitating decomposition by microorganisms (Zhou et al., 2016). What is noteworthy is that the lowest N content together with high C/N from forage sorghum in spring independent of the fall-winter crop resulted in lower CO_2 emissions (Figure 6C) and further mineralization.

In TR, sunn hemp and pearl millet residues had the highest N content, which resulted in high ECO_2 at 30 DAP, whereas under fallow, chisel yielded the lowest ECO_2 result (Figure 5A). In general, fallow/chisel resulted in high ECO_2. This increase is related to soil aggregate disruption by tillage; exposing the once protected organic matter to decomposition (La Scala et al., 2008). When fallow is introduced in a rotation, generally a lower level of labile C and lower microbial activity are observed (Bell et al., 2003) which explains the lower ECO_2 from this treatment (fallow/chisel) as was the case at 60 DAP (13 Feb 12), where the fallow/chisel, after triticale in fall-winter, was responsible for the lowest ECO_2. On the other hand, this evaluation revealed that the fallow/chisel under sunflower in fall-winter had the highest ECO_2. The high N content, lower C/N ratio and lignin/N in sunflower residue, when compared to triticale, could result in a lower limitation on decomposers during the early stage of decomposition intensified by rainfall in the day preceding this evaluation as has been described. According to Li et al. (2013), crop residues with a high C/N ratio and, consequently, lower N availability favor soil N immobilization, resulting in lower rates of ECO_2 (Sainju et al., 2012). A higher CO_2 flux was observed in the presence of common vetch residue (C/N = 15.4) compared with black oats (C/N = 36.3) (Costa et al., 2008), and this difference was attributed to the fast decomposition of plant tissue with low C/N ratios, especially under no-till. The period either side of 60 DAP corresponded to the soybean flowering stage and it is probable that the ECO_2 suffered from a higher influence of root respiration rather than crop residues. At this crop stage most ECO_2 are due to root respiration, and we did not observe a strong relationship with crop residues in this period in either experiment which confirms that ECO_2 behavior is attributable to the dynamic system and interactions with environmental conditions.

The GHG intensity indicates the improvement in agronomic management highlighting the need to link agronomic productivity and environmental sustainability to lower GHG emission (Mosier et al., 2006). However, as shown by Plaza-Bonilla et al. (2014) the idea of yield-scaled emissions could also be applied to CO_2 and agricultural management practices. There was no difference in the accumulated C-CO_2 emitted to the atmosphere in TR and it was lower than the 16.8 t ha^{-1} C-CO_2 which had been observed in soybean under a conventional system in a temperate zone (Smith et al., 2014). However, accumulated ECO_2 was similar to other studies which have evaluated soybean in silty clay soils, even according to climate zone (Omonode et al., 2007; Wilson and Al-Kaisi, 2008; Qiao et al., 2014).

The yield-scaled emission of C-CO_2 in TR was on average 25 % lower than that obtained in the RH. Considering that crop yields were similar in the experiments, the different emissions apparently resulted from the quality of crop residues and other factors. The higher CO_2 fluxes in the RH may also be explained by a lower soil clay content which leads to less physical protection of SOM, and favors a higher SOM mineralization rate and higher CO_2

fluxes (Gentile et al., 2010). Feiziene et al. (2011), in an 11 year experiment on different management systems, observed that CO_2 emission rates were 13 % higher in treatments under no-till in sandy soil compared with clay soil. Sugihara et al. (2012) also observed lower efficiency in converting C from plant residues into SOM in a sandy soil compared with a clay soil, which indicates a high probability of loss of C-CO_2 in soils with low clay contents. In addition to the greater capacity to store carbon in the soil, low CO_2 emission in the TR experiment, even with high C/N plant residues, can be due to low macroporosity also (Calonego and Rosolem, 2010), limiting gas exchange and soil respiration. Nevertheless, not all C decomposed from residues is emitted as CO_2, but these results did indicate that crop rotations may be used for carbon emission mitigation and simultaneous improvements in soybean yield.

Conclusion

Emission of CO_2 during the soybean growing season is mainly driven by soil moisture and is not impacted by crop rotations. Accumulated CO_2 emission during the main crop season is higher when followed by cover crops with low C/N residues rich in N. Furthermore, there is no effect on yield scaled emissions; however, this was not seen when soil clay content was very high.

Although it is a challenging task to use cover crop to increase soybean yield, without increase the ECO_2. The cover crop sunn hemp followed by winter crops triticale in TR and Ruzigrazz + Sorghum in RH may be used for ECO_2 mitigation and a simultaneous improvement in soybean yield.

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