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Soil carbon dioxide flux in a no-tillage winter system

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Soil carbon dioxide flux is a complex process which depends on variations of different factors related to climate and soil. The objective of this study was identifying the abiotic factors that most contributed to this flux during different phonologic stages of the sequence black oat-vetch, cultivated under the no tillage system, in the winter, and find out the most important factors. Soil carbon fluxes were measured every 15 min with a LI-COR "long-term" (stationary) chamber, installed on the no tillage site of the rotation: soybean/black oat/soybean/black oat + vetch/corn/turnip/wheat. The factor that mostly influenced soil carbon fluxes was soil temperature, explaining 57% of the flux variation during the cycles of the crops and 80% from tillering to the begin of the elongation stage of the black oat. The phonologic stages of the black oat in the consortium black oat + vetch that mostly contributed to the carbon soil flux were from the begin of the tillering to the begin of the elongation, and from the elongation to massive grain of the black oat.

Key words: Greenhouse effect, soil temperature, phenologic stages, soil conservations system, *Avena strigosa*, *Vicia sativa*.

INTRODUCTION

Agriculture in the global warming context can be part of the strategy of the greenhouse effect. This fact is associated to the extension of the area managed with no-tillage practices in Brazil and to the flexibility of the adoption of practices that promote carbon (C) influx and the reduction of greenhouse gas emission (GGE) (Amado et al., 2006). The Intergovernmental Panel on Climate Change (2007) highlights the role of agricultural soils having in mind that depending on the management practices that are adopted, the soil can become a GGE absorber, mainly in the case of carbon dioxide (CO_2). The production of CO_2 in the soil is related to biological activity (Lou et al., 2004; Iqbal et al., 2008, 2009; Ussiri and Lal, 2009), including root respiration and soil organic matter (SOM) decomposition. The no-tillage management system (NT) can reduce CO_2 emissions, increasing C stocks (Amado et al., 2006).

The NT system has emerged as an effective technique to act as a biological C drain, this process is however a function of the climate (rainfall and temperature), soil (texture, clay type, mineralogy), cultivation systems (annuals, pastures), agricultural practices (soil preparation, fertilization) and conservation practices (erosion control), being therefore very variable (La Scala et al., 2005, 2006; Pes et al., 2011; Marcelo et al., 2012).

Soil temperature is the variable that best has explained the changes in CO_2 emissions (La Scala et al., 2005; Almaraz et al., 2009; Ussiri and Lal, 2009; Wang et al., 2009). In a similar form, the soil water content also had been reported (Franzluebbers et al., 2002; La Scala et al., 2006; Sotta et al., 2006).

Another aspect that has to be mentioned is that variations in soil CO_2 fluxes depend on the phenologic stage of the crop. Few studies were presented to date, most of them related to forest species (Davidson et al., 2006). Studies carried out with soybean (Verma et al., 2005; Hollinger et al., 2005 and Rodrigues et al., 2013) show that the greatest CO_2 fluxes were observed between the phonological stages V5 and V9, that is, during stages of leaf emission and greatest plant vigor. Lower fluxes were found close to the maturation point. These reports, however, take into account the soil CO_2 flux added to the canopy emission.

The objective of this study was the identification of abiotic factors that contribute more to the soil CO_2 flux in the different phenological stages of the black oat + vetch in the NT cultivation system and consequently define the stages that most contribute to this flux.

MATERIALS AND METHODS

The field experiment was carried out in Cruz Alta, RS, Brazil, (28°36'S, 53°40'W), 409 m absl. The climate of the region is of the type Cfa 2a, tropical humid, according to Köppen´s classification. The average air temperature is 18.7°C, with an average minimum 9.2°C in July and an average maximum 30.8°C in January (Pes et al., 2011). Annual average rainfall is 1,721 mm, uniformly distributed along the year.

Sowing of the oat (*Avena strigosa* Schreb) (75%) + vetch (*Vicia sativa* L.) (25%) crop was made on 13 May, 2010. The crop was desiccated on 16 September, 2010, with Glyphosate [N-(phosphonomethyl)glycine]. During this period rainfall was well distributed, reaching 643 mm, corresponding to 37.4% of the annual average (Figure 1). The black oat + vetch were chosen to conduct this study because it is a typical management of southern Brazil, however no studies on these crops.

The soil is classified as a LATOSSOLO VERMELHO Distrófico típico (EMBRAPA, 2006) or a Typic Hapludox (Soil Survey Staff, 2010), with a predominance of caolinite and iron oxides, with a clay content of 570 g kg^{-1} (Table 1).

The study was performed on an area cultivated by NT for 25 years, using a 40 x 60 m parcel. The area was subjected to crop rotation (summer and winter): black oat/soybean/black oat + common vetch/corn/turnip (*Raphanus sativus* var. *oleiferus*)/wheat/soybean. Seeding was performed directly over the previous crop residuals remaining on soil surface. Soil disturbance was limited to the seeding line using a double disc system to open a narrow furrow for seed deposition.

Measurements of instantaneous CO_2 soil flow were performed at soil surface of the NT plot with a stationary LI-COR "long-term" chamber made by LI-COR (LI-8100, LI-COR, NE, EUA). The chamber monitors changes in CO_2 concentration using an infrared gas analyzer (IRGA) with an internal volume of 991 cm^3, and an exposed area to the soil surface of 71.6 cm^2. The chamber was installed over a PVC ring, previously introduced into the soil. Once closed and ready for measurement, 1.5 min. are necessary for the time interpolation of the CO_2 concentration change in the chamber.

Measurements were performed between 22 May and 16 September, 2010. Due to the lower proportion of vetch in the field and the difficult recognition of its phenologic stages, the study was performed based on the stages of the black oat. Three stages were used: Stage I, seedling emergence to tillering (May 22 to June 29; Stage II, beginning of tillering to beginning of elongation (June 30 to August 13); and Stage III, beginning of elongation to massive grain, when the desiccation of the crop was done (14 August to 16 September). Periodical evaluations of the CO_2 flux were made, with a frequency of 15 min, and CO_2 values were converted into C-CO_2. Soil heat fluxes were also measured in the center of the plot using a Hukseflux sensor, model HFP01SC–L, installed at the depth of 0.02 m; soil temperature with a Campbell Scientific sensor, model TCAV-L, also at 0.02 m depth; and soil water content with a TDR sensor, model CS616-L Campbell Scientific, installed at an angle that allows the measurement of the full 0 to 0.20 m soil layer. All data were stored in a CR 1000 - Campbell Scientific logger.

Air temperature, rainfall and solar radiation data were obtained from an automatic weather station of INMET, located 400 m away from the experimental site. Data were submitted to multiple regression through the "stepwise" method, procedure PROC REG of the program SAS (2009) to verify associations and interdependencies between C-CO_2 emissions and the group of variables related to the environment, as follows: C-CO_2 soil flux = a + b_1Tair + b_2Tsoil + b_3Fg + b_4Usoil + b_5Rg; where a is the intersept; air temperature (Tar); soil temperature (Tsoil); soil heat flux (Fg); soil water content (Usoil); solar radiation (Rg); applied for all three stages separately and also for the whole experimental period. The significance level for the F test was 5% probability for the inclusion of the variables in the model. Regression analysis and the significance level between the C-CO_2 flux and the average daily soil temperature, were also made by the SAS (2009) program.

RESULTS AND DISCUSSION

The average daily C-CO_2 flux observed from 22 May to 16 September was 24.4 kg ha^{-1} d^{-1} (Figure 2), totalizing

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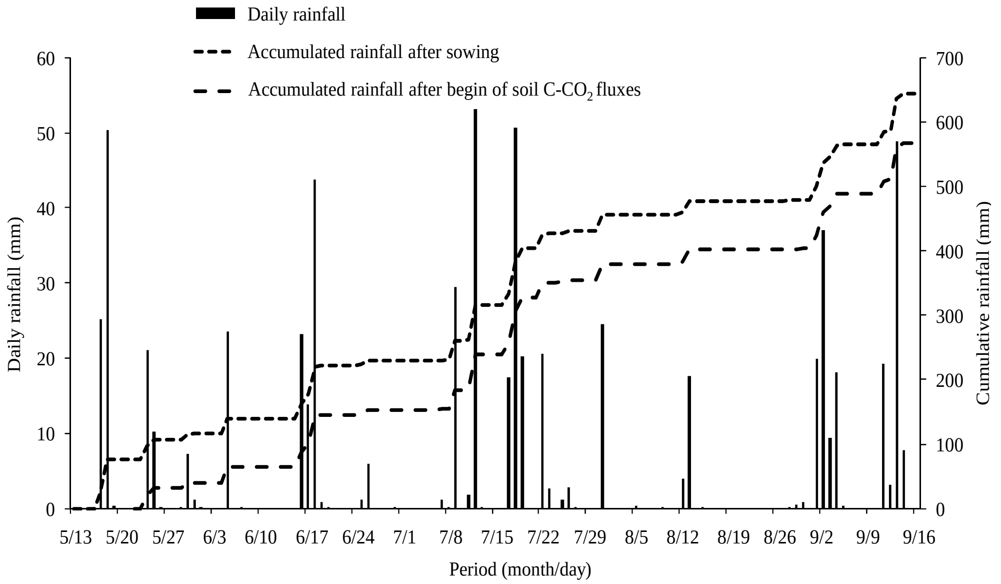

Figure 1. Daily and accumulated rainfall during the experimental period.

2,879.4 kg C-CO_2 per ha, with great variability along the crop cycles.

These changes were similarly the variations in soil and air temperatures (Figure 2a) and of the soil heat flux (Figure 2b). This result corroborates the studies performed by La Scala et al. (2005); Almaraz et al. (2009); Ussiri and Lal (2009) and Wang et al. (2009), who report that soil temperature is highlighted as the isolated variable in best explaining the changes in C-CO_2 emissions.

Soil water content apparently did not influence soil C-CO_2 flux (Figure 2c), probably due to the regular rainfall events of the period under study, however, several studies mention the soil water content as one of the main variables affecting soil gas fluxes (Iqbal et al., 2009; La Scala et al., 2006).

Solar radiation (Figure 2d) apparently did also not influence the C-CO_2 soil flux, although some studies propose solar radiation as the control variable of the soil to atmosphere C-CO_2 flux (Ouyang and Zheng, 2000).

In relation to the phenologic stages, during stage I (Table 2) of the black oat, the C-CO_2 emission presented a positive and significant regression coefficient with soil temperature (Table 2). This variable explained 50% of the variation of the C-CO_2 emissions during the development stage of the crops, that is, from emergency to tillering.

In relation to the development stage II (Table 2), in the same way as for stage I, the emission of C-CO_2 presented a significant positive regression coefficient with soil temperature, however the soil heat flux did also adjust to the model in this development stage. In total, the variables explain 82% of the C-CO_2emissions, 80% being singly attributed to soil temperature. Stage II presented the highlight of being the stage with highest percentage of explanation of the emissions by the variables.

For stage III (Table 2), corresponding to massive grain - elongation the C-CO_2 emissions presented significant positive coefficients of variation with soil temperature (54%) and soil water content (9%), these two variables explaining 63% of the variation of the C-CO_2 emissions.

Analyzing the three development stages during the 118 days of observation The C-CO_2 emissions presented significant positive coefficients of variation with soil temperature and soil water content, and additionally a negative significant coefficient with soil heat flux. This set of variables explains 62% of the variation of the C-CO_2 emissions during this period. Soil temperature was responsible of 57% of the C-CO_2 flux. Soil heat flux and soil water content also influenced the C-CO_2 flux, however in low intensity, reaching 2 and 3%, respectively. Soil water content was affected by the regular rainfall which amounted to 567.4 mm during the observation period, and 643.4 mm during the whole growth cycle of the crops (Figure 1). The obtained results corroborate to the studies of Xu and Qi (2001), Luo and Zhou (2006), Franzluebbers et al. (2002), La Scala et al. (2006) and Sotta et al. (2006) who cite soil water content as one of the factors that determine the C-CO_2 soil flux. A quick raise of the C-CO_2 emission right after a rainfall or irrigation event, with a consequent increase of soil water content has been described in various reports (Beare et al., 2009; Zhang et al., 2011).

According to Ouyang and Zheng (2000), La Scala et al. (2003) and Iqbal et al. (2008) solar radiation is one of the most important factors that determine soil C-CO_2 fluxes, due to its influence on daily variations of soil temperature and water evaporation. However, in a cropped area

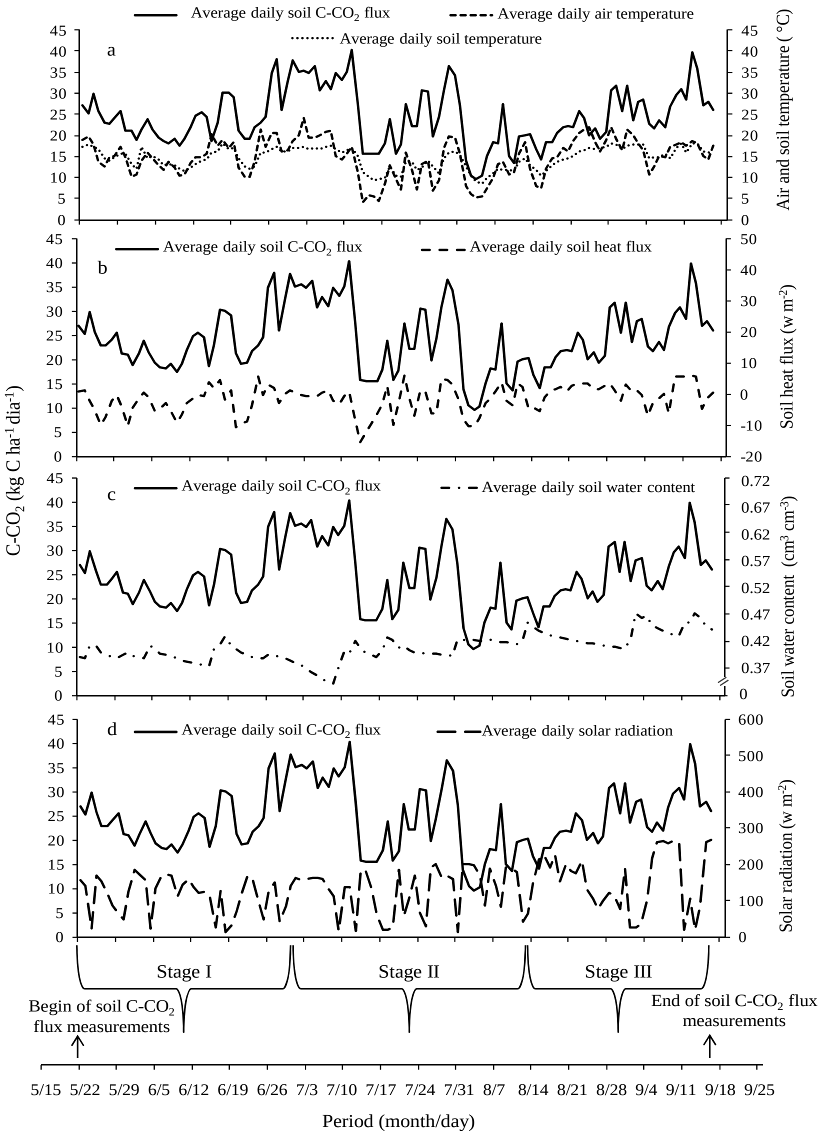

Figure 2. Daily soil carbon dioxide (C-CO$_2$) flux, soil and air temperatures (a), Soil heat flux (b), Soil water content (c) and solar radiation (d) during the experimental period Stage I: emergency to begin of tillering; stage II: begin of tillering to begin of elongation and stage III: begin of elongation to massive grain.

Table 1. Chemical and textural characteristics of the 0-0.20 m soil layer at the beginning of the experiment.

Period	pH H_2O	P[1]	K[2]	Ca[3]+Mg[4]	Al[5]	Sand	Silt	Clay
		- mg kg^{-1} -	------ cmol$_c$ kg^{-1} ------			-------- g kg^{-1} ---------		
1985	4.5	19.0	0.21	4.2	1.2	-	-	-
2010	4.9	9.1	0.18	6.5	1.0	310	120	570

[1] Phosphorus. [2] Potassium. [3] Calcium. [4] Magnesium. Aluminum[5]. All measured according to Tedesco et al. (1995).

leaves difficult the direct incidence of radiation on the soil surface. Therefore, it is expected that in this study solar radiation is of little effect on soil C-CO$_2$ fluxes (Table 2). Soil heat flux is an important component of the energy balance of the Earth-Atmosphere system, representing 5 to 15% of the balance of a cropped area during the day

Table 2. Multiple regression coefficients through the "stepwise" method between the variables and the soil C-CO_2 flux at stages I, II and III of the black oat crop.

State of evaluation of the soil C-CO_2 flux	Intercept (a)	Tair (b1)	Tsoil (b2)	Fg (b3)	Usoil (b4)	Rg (b5)	Test F	R^2 model
Stage I	-2.582	-	1.777	-	-	-	37.4***	0.50
R^2 partial		-	0.50	-	-	-		
Stage II	-8.898	-	2.544	0.300	-	-	97.1***	0.82
R^2 partial		-	0.80	0.02	-	-		
Stage III	-46.553	-	2.113	-	87.661	-	26.1***	0.63
R^2 partial		-	0.54	-	0.09	-		
Whole cycle	18.889	-	1.742	-47.830	0.250	-	61.2***	0.62
R^2 total		-	0.57	0.02	0.03	-		

Tar- ais temperature; Tsoil – soil temperature; Fg- soil heat flux; Usoil- soil water content; Rg – solar radiation; R^2- determination coefficient; ***Significant at 0.5% probability.

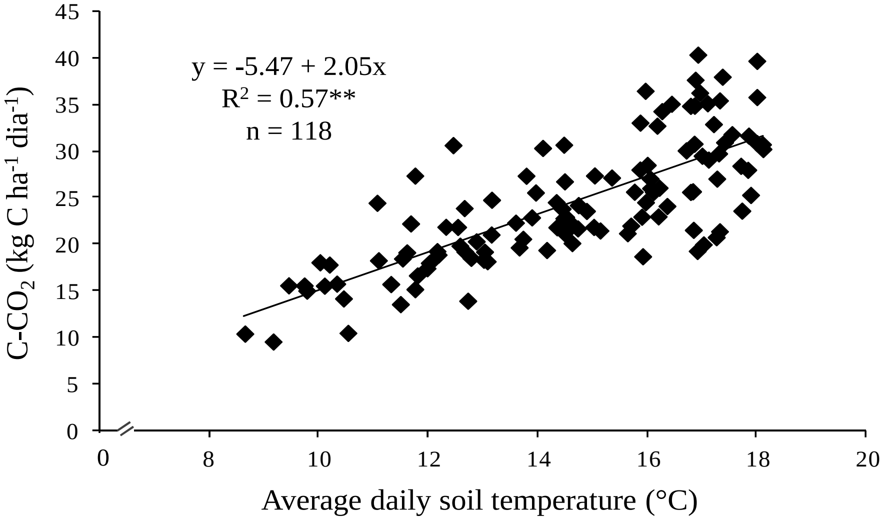

Figure 3. Relation between the average daily soil C-CO_2 flux and the daily average air temperature, during the experimental period.** Significant at $p < 0.01$.

and about 50% during the night, for different crops (Stull, 1988; Heusinkveld et al., 2004). Vertical variations in soil temperature are determined by physical soil properties and by the soil heat flux. In this paper, however, no significant influence was found for the soil heat flux on the soil C-CO_2 flux, in relation to soil temperature. This result might be due to the analyses made using daily means of the variables.

The low air temperatures 14.7°C which occurred during the study period imposed a low soil temperature (14.5°C) limiting the C-CO_2 flux in the soil, as it can be seen in Figure 3. Under conditions of soil temperature below average, a small dispersion of the C-CO_2 flux is observed, related to these soil temperatures. However, the greatest dispersion occurred with temperatures above 15°C, which might be an indicative that above this temperature biological activity is not restricted. Other factors like rainfall events and soil water content might define changes of the soil C-CO_2 flux. From emergence to begin of the tillering in stage I (Figure 4a), due to soil temperatures above 15°C, a greater dispersion of the flux data was observed. Although the soil average temperature had been 14.9°C, the determination coefficient was the lowest ($R^2 = 0.50$; $p<0.0001$), with an average C-CO_2 flux of 23.88 kg C ha^{-1} d^{-1}. From the begin of tillering to the begin of elongation (stage II), the average soil C-CO_2 flux was 24.45 kg C ha^{-1} d^{-1}. During this period a lower average soil temperature (13.4°C) was observed, and consequently a better determination coefficient was obtained with C-CO_2 (R^2=0.80; $p<0.0001$) fluxes (Figure 4b), a result of the lower dispersion of the data. From the begin of elongation to the stage of massive grain (stage III), the highest soil temperature average was observed (15.8°C) with an average C-CO_2

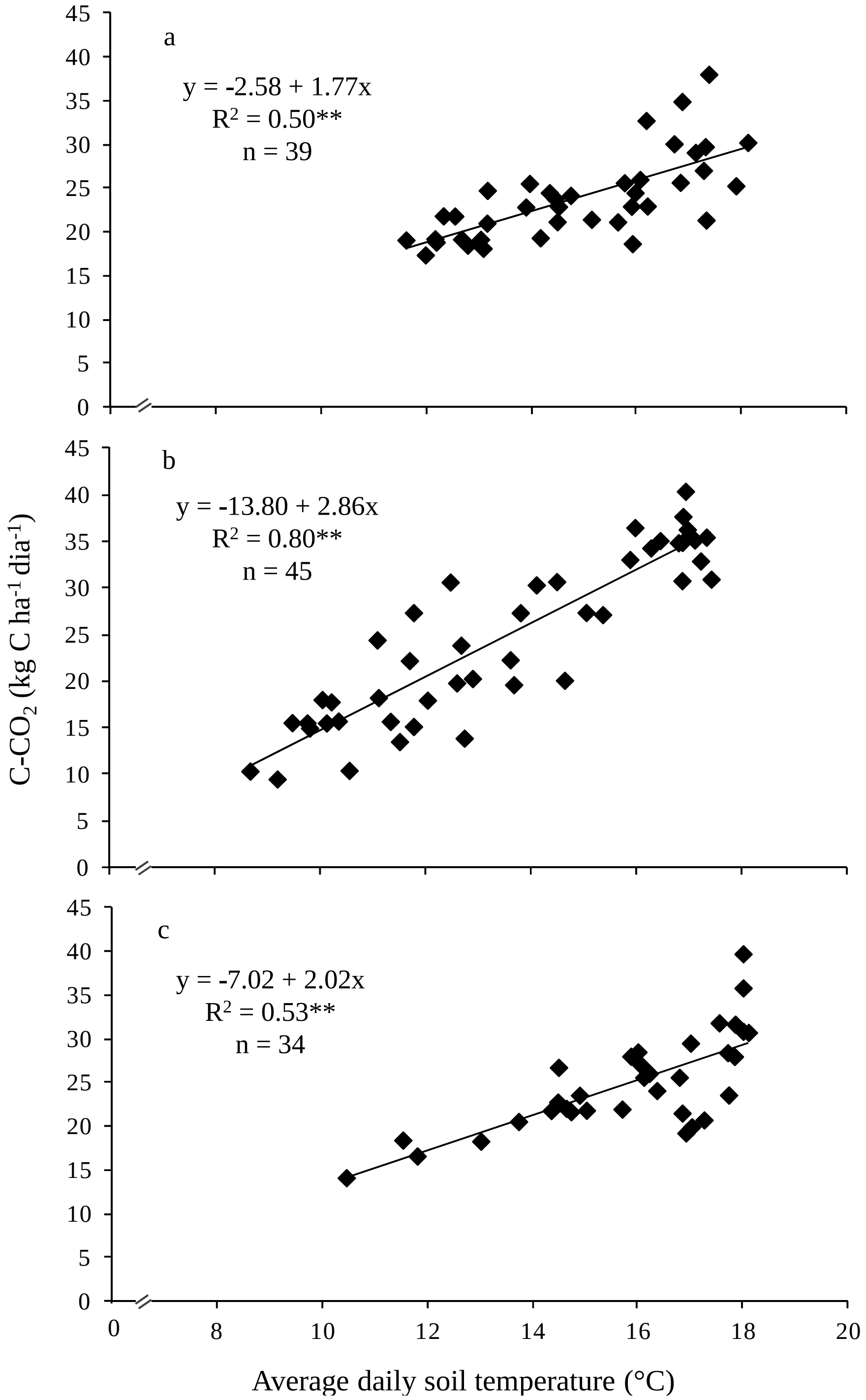

Figure 4. Relation between the daily average soil C-CO_2 flux and average daily air temperature, for stages I (a), 2 (b) and III (c). ** Significant at $p < 0.01$.

flux of 24.92 kg ha^{-1} d^{-1} , therefore presenting a lower adjustment of the data due to the larger dispersion for the C-CO_2 (R^2=0.53; p<0.0001) flux measurements (Figure 4c).

These results corroborate partially with the data of Verma et al. (2005), Hollinger et al. (2005) and Rodrigues et al. (2013) for the soybean crop, who observed that the greater soil C-CO_2 fluxes and the best adjustments were found for the intermediate stages when air and soil temperatures were not too high.

During days of higher temperatures, associated to adequate soil water content conditions, the CO_2 flux may be a result of the increase of biological soil activity (Lou et al., 2004; Iqbal et al., 2008, 2009; Ussiri and Lal, 2009). On the other hand, low fluxes observed on cooler days should be related to a decrease in biological activity in the soil (Lou et al., 2004; Al-Kaisi and Yin, 2005). According to this reasoning, one can say that seasonal changes of the soil CO_2 flux are directly associated to soil temperature and other environmental factors (Lou et al., 2004; Iqbal et al., 2008, 2009).

Conclusions

Soil temperature mostly influenced winter C-CO_2 soil fluxes, contributing with 57% during the whole cycle and 80% from the beginning of tillering to the elongation stage of the black oat. In all stages of the crops was checked linear and significant relationship between the soil temperature and the increase in the CO_2 flux. The greatest dispersion of soil C-CO_2 fluxes occurred when the soil temperature were highest. Soil water content and soil heat flux influenced the C-CO_2 soil fluxes to a lesser intensity. The phenologic stages of the black oat in the consortium black oat-vetch, in which the soil C-CO_2 fluxes were mostly affected by the environmental factors were: beginning of tillering to the beginning of elongation, and elongation to massive grain.

Conflict of Interest

The authors have not declared any conflict of interest.

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