CARBON DIOXIDE EFFLUX IN A RHODIC HAPLUDOX AS AFFECTED BY TILLAGE SYSTEMS IN SOUTHERN BRAZIL[1]

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SUMMARY

Agricultural soils can act as a source or sink of atmospheric C, according to the soil management. This long-term experiment (22 years) was evaluated during 30 days in autumn, to quantify the effect of tillage systems (conventional tillage-CT and no-till-NT) on the soil CO_2-C flux in a Rhodic Hapludox in Rio Grande do Sul State, Southern Brazil. A closed-dynamic system (Flux Chamber 6400-09, Licor) and a static system (alkali absorption) were used to measure soil CO_2-C flux immediately after soybean harvest. Soil temperature and soil moisture were measured simultaneously with CO_2-C flux, by Licor-6400 soil temperature probe and manual TDR, respectively. During the entire month, a CO_2-C emission of less than 30 % of the C input through soybean crop residues was estimated. In the mean of a 30 day period, the CO_2-C flux in NT soil was similar to CT, independent of the chamber type used for measurements. Differences in tillage systems with dynamic chamber were verified only in short term (daily evaluation), where NT had higher CO_2-C flux than CT at the beginning of the evaluation period and lower flux at the end. The dynamic chamber was more efficient than the static chamber in capturing variations in CO_2-C flux as a function of abiotic factors. In this chamber, the soil temperature and the water-filled pore space (WFPS), in the NT soil, explained 83 and 62 % of CO_2-C flux, respectively. The Q_{10} factor, which evaluates

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CO_2-C flux dependence on soil temperature, was estimated as 3.93, suggesting a high sensitivity of the biological activity to changes in soil temperature during fall season. The CO_2-C flux measured in a closed dynamic chamber was correlated with the static alkali adsorption chamber only in the NT system, although the values were underestimated in comparison to the other, particularly in the case of high flux values. At low soil temperature and WFPS conditions, soil tillage caused a limited increase in soil CO_2-C flux.

Index terms: no-till, greenhouse gases, soil temperature, soil moisture.

RESUMO: *EMISSÃO DE DIÓXIDO DE CARBONO EM LATOSSOLO VERMELHO ALTERADA POR SISTEMAS DE PREPARO NO SUL DO BRASIL*

Os solos agrícolas podem atuar como dreno ou fonte de C atmosférico, dependendo do sistema de manejo adotado. Este estudo foi desenvolvido em experimento de longa duração (22 anos), durante o período de 30 dias do outono, com o objetivo de avaliar o impacto de sistemas de preparo de solo (preparo convencional-PC e plantio direto-PD) nas emissões de C-CO_2 de um Latossolo Vermelho distrófico, em Cruz Alta, RS. As emissões de C-CO_2 do solo foram avaliadas com câmaras dinâmica (Flux Chamber 6400-09, Licor) e estática (com captação em solução alcalina), imediatamente após a colheita da soja. A temperatura e a umidade do solo foram registradas, concomitantemente com as emissões de C-CO_2, por meio de sensor de temperatura e TDR manual, respectivamente, integrantes do Licor-6400. Estimou-se que, em 30 dias, uma quantidade equivalente a menos de 30 % do C aportado pelos resíduos de soja foi emitida na forma de C-CO_2. As emissões de C-CO_2 no solo em PD foram similares às emissões do solo em PC, independentemente do tipo de câmara utilizada. Diferenças entre sistemas de preparo quanto à emissão de C-CO_2, avaliadas com a câmara dinâmica, foram verificadas somente a curto prazo (leituras diárias), com o PD apresentando maiores emissões do que o PC no início do período experimental e menores no final. A câmara dinâmica foi mais eficiente do que a estática em captar as alterações das emissões de C-CO_2 em função da variação da temperatura e a porosidade preenchida por água (PPA) no solo em PD, as quais explicaram 83 e 62 % das emissões de C-CO_2, respectivamente. O fator Q_{10}, que avalia a sensibilidade da emissão de C-CO_2 à temperatura do solo, foi estimado em 3,93, indicando alta sensibilidade da atividade microbiana à temperatura do solo durante o outono. As emissões de C-CO_2 registradas no solo em PD com a câmara estática foram correlacionadas às da câmara dinâmica, porém com valores subestimados em relação àquela notadamente nos maiores valores de fluxo. Em condições de baixa temperatura e PPA, o preparo de solo induziu limitado incremento de emissão de C-CO_2.

Termos de indexação: plantio direto, gases de efeito estufa, temperatura do solo, umidade do solo.

INTRODUCTION

Global warming, which is associated to the recent increase of greenhouse gases in the atmosphere, is a result of a series of actions directly related to the productive sector (IPCC, 2007). Carbon dioxide is the main greenhouse gas, being estimated that agriculture sector could contribute up to 75 % of total Brazilian emission (Embrapa, 2006). Soil CO_2-C flux is increased by the land use change and biomass burning, fossil fuel use, consumption of industrialized products that demands high energy to manufacture, and by tillage, that increases the biological activity and soil C oxidation (Reicosky & Lindstrom, 1993).

Soil is an important natural C pool and it is estimated that the amount of C stored in its first meter is 1350 ± 250 Pg (1Pg = 10^9 Mg), therefore more than twice the amount stored in the atmosphere (750 Pg) (Sundquist, 1993). Soil management practices influence soil C flux to atmosphere and can define if the soil will act as a source or a sink of atmospheric C. In the conventional tillage (CT), plowing followed by harrowing, induces aggregate breakdown and increases C turnover as a consequence of the exposure of organic matter to microbes activity and their enzymes (Six et al., 1998, 2006). Soil aggregation has been considered the main mechanism of C protection of a wide range of soil classes (Six et al., 2000; Bayer et al., 2000a; Denef et al., 2004; Dieckow et al., 2005; Fabrizzi et al., 2008). In addition, soil tillage results in a higher contact between soil and residues and increases soil temperature, both processes that favor organic matter decay and increase of soil CO_2-C flux (Reicosky & Lindstrom, 1993; Bayer et al., 2000a; La Scala et al., 2001; Lal, 2003). On the other hand, management systems associated to minimum soil disturbances, such as no-tillage (NT), when combined with high input of crop residues, favors soil C storage (Mielniczuk, 1999; Amado et al., 2001; Bayer et al., 2006).

The effect of tillage systems on soil CO_2-C flux has been intensively investigated, but the results found about its impact are divergent. Usually, short-term CO_2-C flux after tillage is higher in the CT plots (Reicosky & Lindstrom, 1993; La Scala et al., 2006) or in some cases similar (Sanhueza et al., 1994; Fortin et al., 1996; Campos, 2006; Costa et al., 2008) to the ones registered in the NT plots. On the other hand, some researchers found higher emissions in NT than in CT systems (Hendrix et al., 1998; Ball et al., 1999), which indicates that the effect of soil tillage on soil CO_2-C flux could be related to: duration, season, soil moisture and temperature, soil type, the mechanism of soil C stabilization and C stock (Liu et al., 2006).

This study aimed to investigate the effect of tillage systems on soil CO_2-C flux in the fall season, determined by static and dynamic chambers, in a Rhodic Hapludox in Cruz Alta, Rio Grande do Sul State, Southern Brazil.

MATERIALS AND METHODS

Climate, soil and location

The study was carried out in a long term experiment (22 years), in Cruz Alta, Rio Grande do Sul State (Brazil), at FUNDACEP station (28 º 36 ' S; 53 º 40 ' W; 409 m asl). The soil was classified as clay Rhodic Hapludox according to the soil taxonomy (USDA, 1999) and "Latossolo Vermelho distrófico típico" (LVd) by the Brazilian soil classification (Embrapa, 2005), and is cited in this paper as Oxisol. The soil analysis at the beginning of the experiment (0–0.20 m layer) determined contents of: 570 g kg^{-1} clay, 120 g kg^{-1} silt, 310 g kg^{-1} sand, 32 g kg^{-1} soil organic matter, pH (H_2O) = 4.5, P = 19 mg dm^{-3}, K = 0.21 $cmol_c$ dm^{-3}, Al^{3+} = 0.12 $cmol_c$ dm^{-3} and Ca^{2+} + Mg^{2+} = 0.42 $cmol_c$ dm^{-3} (Campos, 2006). The Fe content determined by ditionite-citrate-bicarbonete was 63.5 g kg^{-1}; hematite was predominant over goethite (Inda Jr. et al., 2004).

The climate was classified as humid subtropical, Cfa 2a, according to Köppen (Moreno, 1961). Mean annual precipitation is 1755 mm (from 1974-2006), with uniformly distributed rainfall during the year and mean air temperature of 18.7 °C (from 1998-2006), minimum temperature of 8.6 °C in July and maximum of 30 °C in January, according to data of a meteorological station (FUNDACEP) near the experimental area. The experiment evaluated two tillage systems (CT and NT) in the main plots (40 x 60 m) and three crop rotation systems in split plots (40 x 20 m). Measurements were performed in both tillage systems, but only in the following crop rotation system: black oat (*Avena strigosa* Schreber) /soybean (*Glycine max* (L.) Merr.)/ black oat + common vetch (*Vicia sativa* (L.) Walp.) /maize (*Zea mays* L.)/ radish oil (*Raphanus sativus* L. var. *oleiferus* Metzg.)/ wheat (*Triticum aestivum* L.)/ soybean. The CT treatment consisted of tilling in a plow operation with four disk plow. The CT treatment consisted of soil tilling in a plow operation with four disk plow. The plow tillage was done at a depth of 0.20 m followed by a harrow disk operation with 36 disks at 0.15 m. Soil disturbance in the NT treatment was minimal; the soil was only mobilized along the rows, while the interrow soil surface was maintained under a cover of crop residues. In both tillage systems a planter with double disk system was used (SEMEATO SHM mid land 15/17).

CO_2-C flux measurements

Soil CO_2-C flux was evaluated after soybean harvest by using static and dynamic chambers. Soybean was harvested on April 18, 2007, and soil CO_2 flux measurements started on May 06, 2007 (static chamber) and May 08, 2007 (dynamic chamber) and lasted for 30 days.

In the static chamber a CO_2-capturing method was applied in an alkaline solution for 24 h in a closed chamber (Anderson, 1982), while the method in the dynamic chamber was based on direct measurements of CO_2 concentration changes within a closed chamber by using infrared absorption spectroscopy (Soil CO_2 Flux Chamber 6400-09, Licor, NE, USA), during a few minutes.

The static chamber consisted of a PVC cylinder (diameter 0.3 m, height 0.3 m) that was inserted into the soil to a depth of 0.05 m. The top of the chamber was covered with rubber aiming to seal it completely, and a Zn cover over it fixed with four screws distributed symmetrically on the circumference. On the inside, 0.05 m above the soil, an x-format table was built to support the plastic cup with alkaline 1 mol L^{-1} NaOH solution to capture CO_2-C emitted during the 24 h period (Campos, 2006). Four chambers were installed in the soil three days before tillage, to determine baseline values of emission. In the CT plot, all chambers were removed during soil tillage and replaced immediately after. The soil was tilled with a disk plow on May 09, 2007, with a harrow on May 11, 2007, and winter sowing occurred on May 29, 2007. The CO_2 flux was registered on May 6, 9, 11, 14, 24, 29, and 30, 2007, totalizing 7 days of measurement within 30 days.

The dynamic chamber consisted of a closed system inserted over 0.10 m diameter PVC collars that were displayed in soil at 0.01 m depth two days before the beginning of CO_2-C evaluation (Healy et al., 1996). The chamber had an internal volume of 991 cm^3, with an exposed area to soil of 71.6 cm^2, and was coupled to a portable infrared gas analyzer (IRGA), which determined the changes in CO_2 concentration inside the chamber by means of optical absorption spectroscopy. In this system, air passes continuously from the chamber through the IRGA, and soil CO_2 is inferred based on the gas exchange rate within the chamber (D'Andréa et al., 2006). The exchange rate based on CO_2 concentration within the chamber was calculated every 2.5 s, and the soil CO_2 was computed for approximately 90 s per measurement. Ten PVC collars were installed in each of the CT and NT plots. The CO_2 flux measurements started one day before disk plowing, and were carried out on 15 measurement days (May 8, 9, 10, 11, 12, 14, 15, 17, 18, 21, 24, 28, 29, and 30, and July 6, 2007). On the measurement days, soil CO_2-C flux was determined at 9:00 and 15:00 h, and a daily mean was calculated. During tillage and sowing, measurements were intensified, with 5 daily replications after disk harrowing, 11 after harrowing and 4 after sowing, to calculate the mean daily flux on those days. The soil CO_2 flux results from both chambers were expressed in C equivalent fluxes (CO_2-C).

Soil temperature, soil moisture measurements and meteorological data

Soil temperature and soil moisture were evaluated at 0.10 m depth simultaneously to the CO_2-C flux measurements by a temperature sensor (thermistor) and a TDR (time domain reflectometer) Campbell® systems (Hydrosense TM, Campbell Scientific, Australia), respectively. As soil density was also measured at all points it was possible to calculate the WFPS. Data of air temperature and rainfall during the studied period were obtained from the meteorological station FUNDACEP 50 m away from the study site.

Statistical analysis

The effects of soil management systems on CO_2-C flux were investigated by descriptive data analysis. The soil CO_2-C flux relation with soil temperature and WFPS was analyzed by the correlation coefficients of exponential and linear relationships, respectively. Soil CO_2-C fluxes from static and dynamic chambers were compared by linear regression adjustments and standard mean error was used to compare the data.

RESULTS AND DISCUSSION

Meteorological conditions during the studied period

In terms of meteorological conditions at the study site in May and June 2007, temperatures were colder and rainfall higher than usually registered. A total rainfall of 179 mm was recorded in May (Figure 1a), corresponding to a 24 % higher volume than the mean monthly rainfall (136 mm). Five rainfall events were observed in the 30 day period when soil CO_2-C flux was measured, where 63 % of the total rainfall volume of the period was recorded in only two events. As expected, higher WFPS values were found immediately after the stronger rains (Figure 1a). In general, the values of WFPS in the NT soil were higher than in the CT plot, which is in agreement with results reported by Linn & Doran (1984), with exception of May 28 (Figure 1a). These results confirm the higher capacity of NT system to infiltrate and hold soil moisture in relation to CT. Higher WFPS differences (Figure 1a) between tillage systems occurred just after the disk plow and harrow disk operations on the CT plot. It is noteworthy that around 85 % of the total rainfall volume occurred after soil tillage. Therefore, after soil tillage, smaller WFPS values were found in CT compared to NT. This result is probably associated to the wind effect that dried the bare soil surface of CT.

A mean air temperature of 14 °C was registered during the studied period, which is 13 % below the mean temperature registered for this month (16 °C). Besides, a high thermal amplitude was verified, since the air temperatures ranged from 4 to 22 °C, with a declining trend throughout the experimental period. In May, the soil temperature was similar in the two tillage systems. However, measurements performed in the first week of June, after sowing, indicated a higher soil temperature in the CT than the NT plot (Figure 1b).

Soil CO_2-C flux

Daily soil CO_2-C flux measured with the dynamic chamber in the NT plot ranged from 9 to 25 kg ha^{-1} day^{-1}, while soil flux in the CT ranged from 5 to 20 kg ha^{-1} day^{-1} (Figure 2a). Measurement results of the static chamber indicated lower amplitudes than the dynamic chamber, where results varied from 10 to 22 kg ha^{-1} day^{-1} in NT and from 11 to 18 kg ha^{-1} day^{-1} in CT soil (Figure 2b).

A mean daily CO_2-C flux of 12.7 ± 2.2 kg ha^{-1} day^{-1} was measured with the dynamic chamber under CT and 15.7 ± 2.9 kg ha^{-1} day^{-1} under NT (Figure 2a). A 19 % higher flux was observed in the NT than the CT plot, although this result was not significantly different ($p > 0.05$). A similar trend was registered for the static chamber with a mean flux of 14.2 ± 1.0 kg ha^{-1} day^{-1} in the CT plot, compared to the 13.4 ± 2.1 kg ha^{-1} day^{-1} in NT soil (Figure 2b). With this chamber, the CO_2-C flux in CT soil was 6 % higher than in NT, again without significant difference ($p > 0.05$). The similarity in the mean soil CO_2-C flux registered in tillage systems in a 30 day period agrees with results of a long-term evaluation previously reported by Campos (2006). However, this author found a mean CO_2-C flux of 24.4 kg ha^{-1} day^{-1} in CT and 26.0 kg ha^{-1} day^{-1} in NT soil in a two-year period, which exceeds the results found here by 42 and 48 %, in the CT and

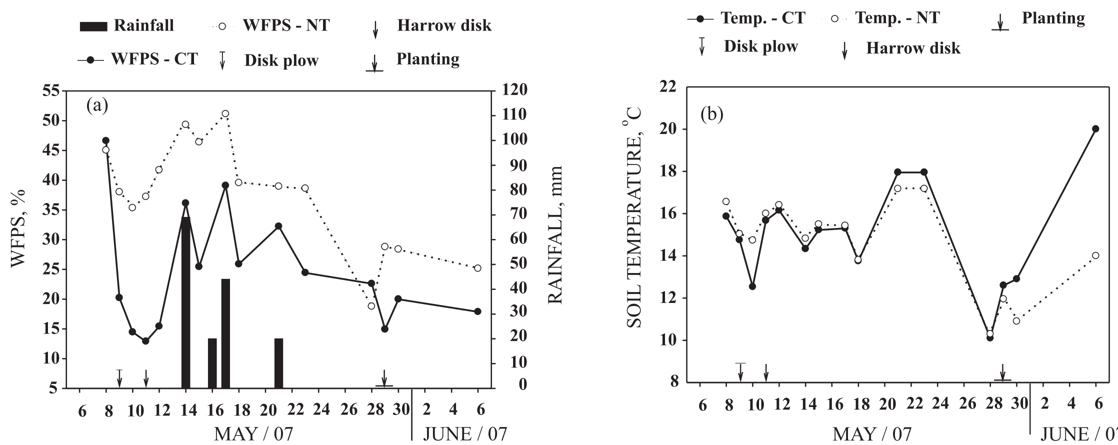

Figure 1. Rainfall and water-filled pore space (WFPS) (a) and soil temperature (Temp) (b) in conventional tillage (CT) and no-tillage (NT) systems, in Cruz Alta (RS), Southern Brazil.

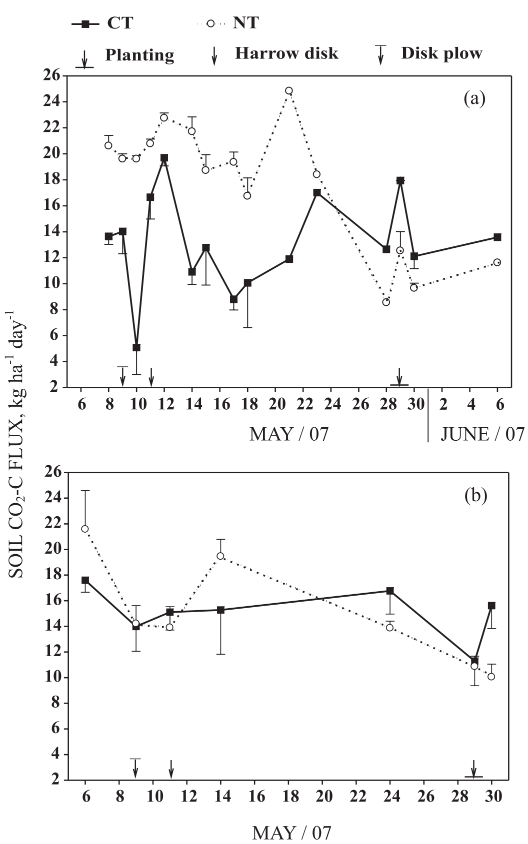

Figure 2. Soil CO_2-C flux in conventional tillage (CT) and no-tillage (NT) systems measured in dynamic chamber (a) and static chamber (b). Vertical bars represent the mean standard error.

NT plots, respectively. The lower soil temperature and absence of plant growth during the study period, compared to the investigation of Campos (2006), could explain the lower soil CO_2-C flux. Paul et al. (1999), using static chambers, found a mean soil CO_2-C flux of 20 kg ha^{-1} day^{-1} during the growth period of alfalfa (*Medicago sativa* L.). This value is closer to the highest CO_2-C flux registered in May, and slightly lower than the biannual flux reported by Campos (2006).

The mean separation procedure of the daily fluxes revealed that differences in emissions induced by soil tillage system have a complex nature, due to the daily flux variability. In the short term (single daily readings), significant differences ($p < 0.05$) between soil tillage systems were verified in the CO_2-C flux, independent of the soil chamber, mainly in the first weeks after tillage. In the first two weeks of this study, NT had a higher soil CO_2-C flux than CT, when evaluated by the dynamic chamber, which was more efficient than the static to capture the temporal flux variability. This result is probably related to several aspects: the presence of easily decomposable soybean residues on the soil surface, higher WFPS values (Figure 1a), higher stocks of labile soil organic carbon (Campos, 2006) and higher microbial biomass in NT compared to CT, as reported previously at the same experimental site (Fabrizzi et al., 2008). The higher soil CO_2 – C flux under NT compared to CT, especially at sites under longstanding no-tillage systems, have been reported elsewhere (Yamulki & Jarvis, 2002; Campos, 2006; Liu et al., 2006; Oorts et al., 2007). This could be related to an improvement in soil quality and biomass input potential in the conservation system, compared to conventional systems (Amado et al., 2007). In a 15-year-experiment, the soil CO_2-C flux in NT growing black oat+common vetch/ maize+cowpea was 64.7 kg ha^{-1} day^{-1}, while in NT with black oat/maize the flux was 51.6 kg ha^{-1} day^{-1} and in CT with black oat/maize 36.6 kg ha^{-1} day^{-1}. The soil CO_2-C flux followed the order of soil quality (Amado et al., 2007). The soil quality kit test guide (USDA, 1998) classifies a soil CO_2-C flux of 35.8 to 71.7 kg ha^{-1} day^{-1} as ideal and a range of 17.9 to 35.8 kg ha^{-1} day^{-1} as medium.

Soil tillage by disk plowing followed by disk harrowing as well as the sowing procedure, both in the CT plot, resulted in changes in soil CO_2-C flux. Fluxes registered by the dynamic chamber in the CT plot had an irregular pattern with an increase of around 40 % after the last tillage operation, compared to the baseline CO_2-C flux. This increase in the flux is at least partially associated to an exposure of occluded particulate organic matter within the aggregates (Six et al., 1998, 2006). However, in our experiment the increase in soil CO_2-C flux induced by tillage was much lower than reported by Reicosky & Lindstrom (1993), in USA, in the first 24 h after tillage. In an Oxisol in Southern Brazil, La Scala et al. (2006) also stated a higher CO_2-C flux after tillage, with CO_2-C, values by up to 143 kg ha^{-1} day^{-1} higher. It should be emphasized that although the soils here and in the study of La Scala et al. (2006) were similar, the soil temperature in the two studies differed markedly, so the lower soil temperature during and after tillage operations in our study could partially explain the lower flux. In the CT soil the CO_2-C flux was lower than under NT, mainly in the rainy period (just after tillage and shortly before sowing). On the other hand, the CO_2-C flux in NT was more stable during the rainy period (Figures 1a and 2a). The sowing procedure induced a significant increment of 44 % soil CO_2-C flux in both tillage systems. This result is associated with the reduced spacing between rows in winter crops (0.175 m), resulting in a considerable soil disturbance.

The dynamic chamber was more efficient than the static to capture short-term soil flux changes, e.g., those associated to the soil disturbances caused by plow and disk operations (Figure 2). In CT soil, one day after plow tillage, the soil CO_2-C flux decreased by more than 40 % (Figure 2a). Therefore, soil C-CO_2 flux decreased from 13.6 to 5.1 kg ha^{-1} day^{-1}, after a soil temperature decline (from 15.9 to 12.5 °C) (Figure 1b) and mainly the WFPS decrease (from 48 to 12 %) (Figure 1a). In spite of an increase after plowing, the soil CO_2-C flux in CT was lower than in NT (Figure 2a). In this short-term study carried out during the fall season the significant declines in soil temperature and WFPS values probably affected the soil biological activity and, consequently, CO_2-C production and diffusive transport to a greater extent than the expected tillage impact on flux.

Fifteen days after the beginning of the experiment, the soil flux in the NT plot dropped to a lower value than measured in the CT plot (Figure 2a). The higher initial CO_2-C flux in NT can be associated to the input of soybean crop residues, 21 days before the experiment began. The higher initial CO_2-C flux in the conservation system could be explained by the low C/N ratio of this residue, high labile C contents and the more favorable WFPS verified in the NT than in the CT plot (Figure 1a). The decomposition of soybean residues was fast, even when simply left on the soil surface, as observed similarly by Campos (2006) at the same site; the decay rate was more controlled by moisture, temperature, pH and O_2, and less by residue incorporation into soil by tillage. In addition, Aita & Giacomini (2007) reported that the effect of tillage to increase the crop residue decomposition rate is inversely proportional to the N plant content.

In this study, the cumulative *or* total soil CO_2-C flux CO_2-C flux, during a 30 day period, was similar in the tillage systems, independent of the chamber type (Figure 3). Therefore, differences in CO_2-flux between treatments (Figure 2) were restricted to short-term periods, while no difference between treatments was stated in the 30 day period.

In the measurements of the dynamic chamber, the total CO_2-C flux in the NT plot was 471 kg ha^{-1} but 381 kg ha^{-1} under CT (Figure 3). These values are equivalent to approximately 28 and 18 % of the soybean crop residue input (NT=1698 kg ha^{-1} C and CT = 2072 kg ha^{-1} C in the 2006/2007 growing season), for NT and CT respectively. Results of the static chamber indicated that 24 and 21 % of aboveground C input by soybean crops evolved as CO_2–C flux under NT and CT respectively. Based on decomposition equations of soybean residues (NT $y = Co\ e^{-0.0085\ t}$ and CT $y = Co\ e^{-0.0084\ t}$) established by Campos (2006) at this site, a CO_2-C flux of 382 and 461 kg ha^{-1} from NT and CT soils, respectively, was estimated in a 30 day-period. Therefore, the source of the greatest part of the CO_2-C flux measured here was probably the soybean residue decomposition. Quincke et al. (2007) reported a cumulative *or* total soil CO_2-C flux of 327 kg ha^{-1} from CT soil and 227 kg ha^{-1} in the NT soil in a soybean/sorghum rotation in USA in a 30 day period after tillage, measured in a dynamic chamber. These results are lower than the values found here.

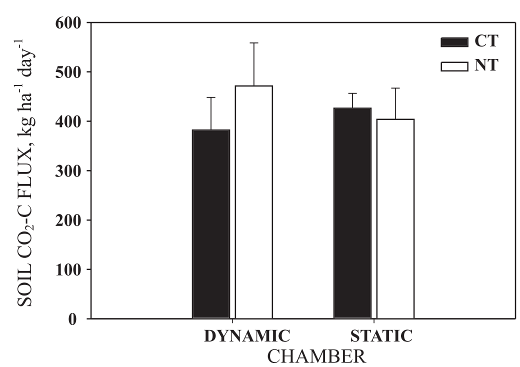

Figure 3. Total soil CO_2-C flux in 30 day period in conventional tillage (CT) and no-tillage (NT) in intensive cropping system measured in dynamic and static chambers. The vertical bars represent the mean standard error.

Relationships between soil CO_2-C flux and soil temperature and WFPS

There was an exponential increase in soil CO_2-C flux with soil temperature ($r = 0.91$; $p < 0.0001$), and a linear relationship with soil WFPS ($r = 0.79$; $p < 0.0004$) (Figure 4). These relations were significant in the NT plot only and when measured in the dynamic chamber, which was more sensitive to changes of these variables than the static chamber.

Similarly as observed in this study, Janssens et al. (2001) reported that 80 % of temporal changes in soil CO_2-C flux could be ascribed to changes in soil temperature, at adequate soil moisture. Verma et al. (2005) and Costa et al. (2008) also observed a positive correlation between soil CO_2-C flux and soil temperature. However, in a bare Oxisol, La Scala et al. (2000) found no correlation between CO_2-C flux and soil temperature. During this experiment, the NT plot maintained higher soil moisture with a mean WFPS of 37 % (Figure 1a). This is probably the reason why soil temperature was detected as the main control factor. On the other hand, higher soil moisture variation was registered in the CT plot, with a mean WFPS of only 25 % (Figure 1a), that may have influenced the relationship soil CO_2-C - soil temperature. Linn & Doran (1984) observed a higher aerobic microbial activity, measured by the soil CO_2-C flux, when the WFPS was close to 60 %. The same authors found the lowest soil CO_2-C flux when WFPS was around 30 %.

After the exponential model linearization, a model $Ln(E_{CO2\text{-}C}) = a + bT_{SOIL}$ was obtained (Figure 4a). In this study Q_{10} was calculated by the following mathematical expression: $Q_{10} = e^{10b}$, and the value found was 3.93. This result is in the range of 1.3 to 5.1 reported by Conant et al. (2004) in USA soils. These authors found higher Q_{10} values when temperatures were lower, in agreement with Lloyd & Taylor (1994).

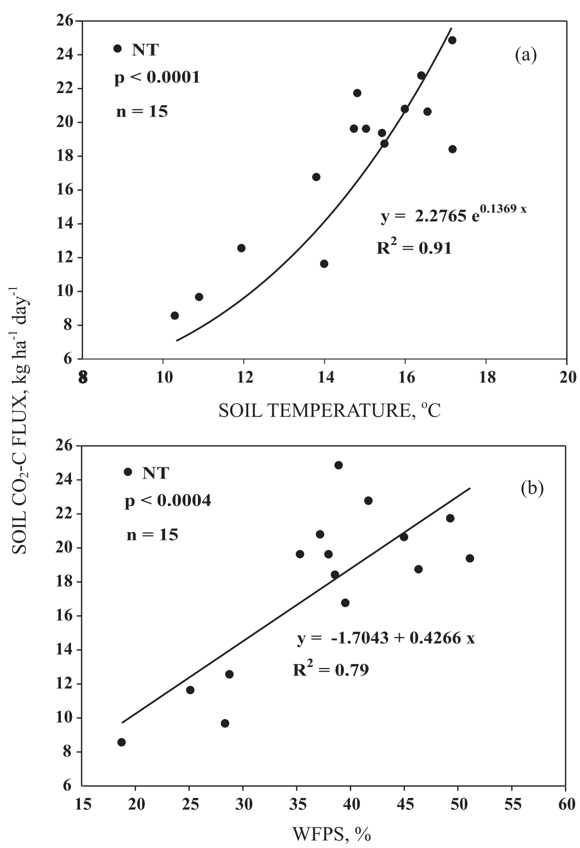

Figure 4. Relationship between CO_2-C flux and soil temperature in the 0-0.10 m layer (a) and water-filled pore space (WFPS) in the 0-0.10 m layer (b) measured in a dynamic chamber in no-tillage system (NT).

Comparison of soil CO_2-C flux measured by static and dynamic chambers

The correlation between CO_2-C flux obtained from the two chambers was linear in the NT plot ($r = 0.78$; $p < 0.02$) (Figure 5), while in the CT plot this relationship was not significant. Under NT, the static chamber underestimated the CO_2-C flux registered by the dynamic chamber, especially when flux was close or superior to 20 kg ha^{-1} day^{-1}. Jensen et al. (1996) comparing static and dynamic chambers in CT agriculture and under forest and pasture ecosystems in temperate climate found an exponential relationship ($r= 0.84$). Therefore, when soil surface CO_2-C flux rates measured by the dynamic method were above 24 kg ha^{-1} day^{-1} CO_2-C, they were up to five times higher than by the static method. Therefore, these authors also reported that when CO_2-C fluxes are high, measurements by the static chamber underestimate the ones by the dynamic chamber, as verified in this study.

When the soil CO_2-C flux is low the static chamber can overestimate the flux in relation to the dynamic

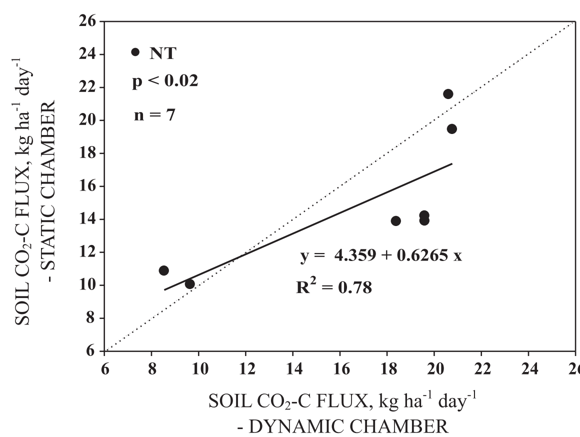

Figure 5. Relationship between CO_2-C flux measured in dynamic and static chambers in no-tillage (NT) system.

chamber (Nay et al., 1994; D'Andréa et al., 2006). Jensen et al. (1996) reported that some static chamber, are not able to full integrate CO_2–C flux in a one-day-period. Besides, the larger spatial variability observed with the dynamic chamber requires a large number of replications to obtain reliable estimates of the mean soil CO_2-C flux. This limitation was probably reduced in our study, at least during the tillage operation, when 5 and 11 measurements were performed on the days of disk plowing and harrowing, respectively, and were reduced to a frequency of 2 daily measurements (9–10 and 15–16 h) after that. However, no measurements were performed with the dynamic chamber at night.

The dynamic compared to the static chamber is more appropriate to detect spatial and temporal variability in studies that relate soil CO_2-C flux with soil temperature and WFPS. Using the dynamic chamber it is possible to sample a high number of points in a short time (La Scala et al., 2006). This fact probably helped to establish a significant relationship between CO_2-C flux and abiotic factors (temperature and WFPS) by the dynamic but not the static chamber. On the other hand, the static chamber maintained in the soil for 24 h has the advantage of integrating the daily CO_2-C flux and is probably more adequate for long-term studies, for instance, related to crop residue decomposition and labile C fraction decay in soil organic matter.

CONCLUSIONS

1. The total soil CO_2–C flux in a 30 day period was similar in no-till and conventional tillage, independent of the chamber type. The differences in CO_2-C flux between tillage systems were related to the day of observation; the differences were higher in the first weeks after tillage. The restricted impact of soil tillage in CO_2-C flux was associated to predominant climatic conditions of low soil temperature and water-filled pore space during the experimental period (autumn).

2. The dynamic chamber was more efficient than the static to detect rapid changes in soil CO_2-C flux driven by abiotic factors. Soil CO_2-C flux in the no-till plot increased exponentially with soil temperature and linearly with water-filled pore space and these properties explained most of the temporal flux variability. The CO_2-C flux was more sensitive to soil temperature than to water-filled pore space during the fall period evaluated in southern Brazil.

3. Only in the no-till system the static chamber CO_2-C flux measurements were linearly related to those of the dynamic chamber. In this case of high CO_2-C flux the static chamber underestimated the flux registered by the dynamic chamber.

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