Second International Symposium on Integrated Crop-Livestock Systems
Porto Alegre, Brazil - 8-12 October 2012

Soil organic matter regulating greenhouse gases in tropical and subtropical environments: A comparison between integrated crop-livestock and annual cropping systems

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Abstract

Carbon and nitrogen cycles in grassland, annual cropping and integrated crop-livestock (ICL) systems control soil quality and regulate greenhouse gas emissions. The aim of this study was to review the knowledge on driving factors controlling soil organic carbon (OC) accumulation and greenhouse gas emissions in tropical and subtropical Brazilian ecosystems under ICL and annual cropping systems. The ICL system has a significant potential to promote soil OC sequestration, mainly due to biomass addition but also because stabilization by physical protection and organo-mineral associations. The soil OC accumulation in ICL, compared to annual cropping, can extend up to 100 cm depth. In general, emission of nitrous oxide (N_2O) from soil is higher in ICL than in annual cropping, although the opposite may also occur. The N_2O emission in ICL, however, can be offset by soil OC accumulation, although not always. Strategies to further increase soil OC sequestration and curb N_2O emissions must be developed for ICL, which is a system that is being encouraged in Brazil because of the many ecosystem services and economical benefits that it provides.

Key words: nitrous oxide, carbon sequestration, pastures, no-tillage

Introduction

Integrated crop-livestock (ICL) associated with no-tillage is an innovative soil use strategy that improves food production (grain, milk and beef) and economical gains (Moraes *et al.*, 2007), but information should be obtained to better understand the effects that this system has on soil organic matter dynamics and on greenhouse gases emissions, particularly for subtropical and tropical regions.

Worldwide, Milchunas and Lauenroth (1993) indicated that in 40% of the study-cases grazing increased soil OC stocks, while in 60% the stocks were maintained or decreased. Guo and Gifford (2002), in a meta-analysis study, concluded that conversion of cropland to pastureland increased soil OC stocks by 20%.

Fertilizer application to crop or pasture, biological fixation by legumes, and animal excreta deposition (urine and dung) are the main forms that nitrogen (N) enters to the soil-plant system in ICL. Nitrogen fertilizer application significantly increases N_2O emissions in pasturelands, as reported for the Great Plains of USA (Liebig *et al.*, 2006) and grasslands in Europe (Velthof and Oenema, 1995); but animal excreta (urine and dung) deposited onto soil are also an important N_2O contributor (Oenema *et al.*, 1997; Yamulki and Jarvis, 1997). Animal treading (de Klein and van Logtestijn, 1994; Oenema *et al.*, 1997) and the machinery traffic (Ball *et al.*, 1999) may compact the soil and favour the denitrification and N_2O emission during wet periods.

Aerobic soils of pasturelands are regarded as small methane (CH_4) sinks due to the prevailing of methanotrophy (Saggar *et al.*, 2008) and that would be the case for Brazilian pasturelands, considering that most of the soils there are free-drained Ferralsols. Hütsch (2001), in a summary of results of methane emission from grassland soils, estimated an average net emission of 0.58 mg CH_4 m^{-2} day^{-1}. However, pastoral soils may become CH_4 source if methanogenesis under anaerobic conditions surpasses methanotrophy process (Saggar *et al.*, 2008).

This paper aimed to review knowledge on driven factors controlling soil organic matter accumulation and greenhouse gas emission (N_2O and CH_4) under integrated-crop livestock systems and annual cropping systems focusing mainly on subtropical and tropical environments of Brazil.

Experimental sites, soil organic carbon and greenhouse gases measurements

We considered a set of 6 experimental sites and 3 chronosequences distributed over the Cerrado biome (tropical) and South region (subtropical) of Brazil, comparing the traditional annual cropland farming based on no-tillage (mainly with soybean or maize) with integrated crop-livestock (ICL) system. Detailed information about the experimental areas or chronosequences is presented in Table 1.

Soil OC stocks were assessed up to 20 or 100 cm depth, depending on the experiment. Soil analysis for OC was carried out by using dry combustion method. Stocks were corrected by the equivalent soil mass approach, which normalizes the effect of management on soil bulk density.

Soil N_2O and CH_4 emissions from soil or excreta (enteric fermentation was not considered in this paper) were assessed by the closed static chamber method (Mosier, 1989). After chamber closure over a metal circular base, air samples were taken during 20 to 45 minutes. Samples were analyzed by gas chromatography and the N_2O or CH_4 fluxes ($\mu g\ m^{-2}\ h^{-1}$) were calculated considering the slope of the linear increase of gas concentration during the chamber enclosure. The net greenhouse gas was obtained by considering soil OC sequestration in 0-100 cm, soil CH_4 and N_2O emission. The net emission was expressed in CO_2-C equivalent by considering the global warning potential of 25 and 298 for CH_4 and N_2O, respectively.

Soil organic carbon stocks and mechanisms of stabilization in ICL system

In all experimental sites or chronosequences, the ICL increased OC retention in soil at rates varying from almost zero to 1.57 Mg ha^{-1} $year^{-1}$ (Table 2). Higher rates occurred in the tropical environment of Cerrado (from 0.19 to 1.57 Mg ha^{-1} $year^{-1}$), in contrast with subtropical region of Southern Brazil (0.03 to 0.19 Mg ha^{-1} $year^{-1}$). The effect of ICL system on OC retention in soil organic matter is probably due to two factors: (i) carbon input as crop and pasture biomass (shoot plus root), and (ii) carbon stabilization by the physical protection mechanism enhanced by better aggregation, as an effect of no-tillage and pasture root.

The beneficial impact of ICL in terms of carbon addition (crop plus pasture) is possibly more significant in Cerrado, where C addition is more difficulty when farming system is based only on annual crops, compared to the Southern region of Brazil where two crops per year are possible. The dry season in Cerrado makes the establishment of cover crops more difficult, and even when possible, the C additions are small. On the other hand, the inclusion of brachiaria pasture in ICL system allows an enhancement of biomass C addition, either by aboveground or roots, compared do annual-based cropping systems.

Brachiaria pasture in ICL systems in Cerrado has an expressive effect on soil aggregation (Table 2). Compared to annual cropping systems based on no-tillage, the soil under ICL showed a better aggregate stability as evidenced by the increment in aggregate size from 1.80-2.60 mm in annual cropping to 3.60-4.40 in ILC (Table 2). The beneficial effect of ICL over aggregation was particularly evident on the proportion of large macroaggregates (>2 mm) and macroaggregates (>0.25 mm), which represented respectively 25-39% and 81-85% of the soil mass in annual systems but 53-68% and 85-90% in ICL.

As a result of the better soil aggregation, physical stabilization of soil organic matter inside aggregates was increased in pasture-affected soils. In three long term experiments, physical fractionation of soil organic matter was carried out and results are presented in the Table 2. In comparison to annual cropped soils, 22-34% of soil OC accumulation in soil under ICL system was due to physical-protection inside aggregates. The physical barriers and the low O_2 diffusion imposed by stable aggregates reduce the decomposing action of microorganisms and their enzymes over organic matter. Thus, higher is the probability of those organic substances to interact with soil mineral surfaces (organo-mineral interaction), mainly of iron oxides that are abundantly rich in the highly weathered Ferralsols of the tropics. This organo-mineral interaction then further increases the OC stability and turnover time in soil. The OC retention by organo-mineral interaction depends previously upon physical protection of the organic matter by soil aggregates. Studies conducted by our research team in pasture-affected soils have focused on the retention of OC, because of its environmental implications as global warming, climate change and others; but certainly the same processes also relates to N, which is another important element in environmental cycles.

The only soil where no significant increment of OC occurs after adoption of ICL was the Umbric Ferralsol of Castro (Table 2), maybe due to the short-term period of the experiment (3.5 years), but also to the originally high OC stock. Additional increments of OC in originally C-rich soils is potentially more difficult than in C-depleted soils, as concluded by Campbell *et al.* (1991) after studying a black Chernozem under various management practices.

Carbon storage at deep soil layers

In the Rhodic Ferralsol of Dourados, management systems affected OC in layers deeper than 20 cm so that the whole stock in 0-100 cm was higher in ICL than in cropland (115.83 vs. 104.03 Mg C ha^{-1}) (Table 3). The annual OC sequestration rate in ICL compared to cropland in 15 years was 0.78 Mg ha^{-1}. The C addition by roots of brachiaria pasture was certainly the main reason for this C accumulation in deep soil layers of ICL, but residue incorporation by organisms of soil macro and mesofauna and leaching of dissolved organic matter could also have played relevant roles. Grazing/re-growing cycles of pasture may increase the addition of belowground biomass as fine roots (Richards, 1993), which are more likely to be physically protected within macro and microaggregates.

Deep OC accumulation has been reported for no-tillage soils under legume-based cropping systems (Sisti *et al.*, 2004; Diekow *et al.*, 2005; Boddey *et al.*, 2010) as well as for pasturelands (Corazza *et al.*, 1999; Omonode and Vyn, 2006). The main advantage of this deeper accumulation is that C becomes more stabilized by physical protection (lower O_2 diffusion).

However, in the Umbric Ferralsol of Castro, no increment in OC stock below 20 cm depth was observed after adoption of ICL compared do annual cropland. This lack of OC increment might be associated to the short duration of this experiment (3.5 years) and to the originally high OC stock of this Umbric Ferralsol. Additionally, the winter ryegrass pasture employed in this experiment possibly had a lower root-C input if compared to the input by the perennial brachiaria pasture employed in the experiment of Dourados.

Nitrous oxide and methane emissions

The annual emission of N_2O in Castro reached 4.26 kg N_2O-N ha^{-1} year^{-1} in ICL, which was at least threefold higher than in annual cropland system (1.26 kg N_2O-N ha^{-1} year^{-1}) (Table 3). Emission of N_2O was closely associated with sidedress urea-N application to maize. In general, N_2O fluxes during the 21-day period following N application were in average 53% higher in ICL system (data not shown). Results suggested that urea-N application to maize or ryegrass was the primary factor that triggered higher N_2O emission, and the effect of grazing on further increasing N_2O fluxes was regarded as secondary. The higher N_2O fluxes after urea-N application in ICL system might be related to more anaerobic soil conditions favoring denitrification as a consequence of soil surface compaction due to animal treading (Oenema *et al.,* 1997; Luo *et al.,* 2010).

As N fertilization was the main factor that triggered N_2O peaks in ICL, the management of this nutrient, like splitting application or using urease and nitrification inhibitors (Di and Cameron, 2002; Zanatta *et al.,* 2010), should be crucial in a mitigation plan. Management of animal grazing, however, is equally important.

Methane fluxes in Castro were negative during most of the year either in crop-livestock or cropland, but an unexpected peak that occurred in April and May (not shown) turned the soil into a net source of 1.65 kg CH_4-C ha^{-1} $year^{-1}$ in crop-livestock and 1.08 kg CH_4-C ha^{-1} $year^{-1}$ in cropland (Table 1). But the difference between systems was not significant.

In Ponta Grossa, however, the cumulative annual emission of N_2O was lower in ICL than in cropland (1.09 vs. 1.77 kg N_2O-N ha^{-1} $year^{-1}$) (Table 3). The highest emission in cropland soil was related to higher water-filled pore space, possible because of higher soil residue cover during winter (oat was not grazed and used only for cover crop), and nitrate and ammonium concentrations than in ICL soil (data not shown). The N fertilizer application to oat pasture and maize crop was also the major factor that triggered the N_2O emission in both systems. The soil CH_4 fluxes in Ponta Grossa were similar between cropland and ICL, with a cumulative consumption of -0.84 and -0.90 kg CH_4-C ha^{-1} $year^{-1}$, respectively (Table 3).

In Dourados, like in Castro, the average annual N_2O emission was higher in ICL than in cropland (0.88 vs. 0.72 kg N_2O-N ha^{-1} $year^{-1}$) (Table 3), but the difference not as large as in Castro. The emission peaks occurred basically during the leaf fall stage of soybean, a period that coincided with high soil moisture and inorganic nitrogen availability (not shown). Likewise, Carvalho (2010) in the experiment of Montividiu-GO showed higher emission of N_2O and minor consumption of CH_4 in ICL than in cropland system (Table 3).

About N_2O emission factor (EF) for urine and dung of ruminants, the main finding of the two conducted studies was a considerable low emission factors for those excreta compared to the default values proposed by IPCC (Table 4). The EF for sheep urine was 0.27% and similar to the 0.26% for cattle urine, while the default factors proposed by IPCC are 1.00% and 2.00%, for sheep and cattle urine, respectively. The EFs were very similar between sheep dung (0.10%) and cattle dung (0.15%), but also lower than IPCC's default of 1.00% and 2.00%, for sheep and cattle dung, respectively.

The lower EFs for urine found in those studies was possibly the free-drained condition of the tested subtropical soils, which allows a deeper flow of urine as well as a higher O_2 diffusion. Another indication of those studies is that dung and urine should be accounted separately in inventories or communications, because dung showed a lower EF than urine. Finally, it seems that the 1% and 2% proposed in IPCC Guidelines as emission factor for sheep and cattle excreta, respectively, are overestimated for subtropical Brazilian conditions.

Net emissions of greenhouse gases from soil

Considering the overall emission of greenhouse gases in CO_2-C equivalent, the ICL in Dourados represented a sink of 0.757 Mg CO_2-C ha^{-1} year^{-1} (Table 3), and most of that was driven mainly by soil OC sequestration in the 0-100 cm (0.780 Mg C ha^{-1} year^{-1}), once soil was only a small sink of CH_4 (-1 kg CH_4-C ha^{-1} year^{-1}). The emission of soil N_2O was totally offset, but no information was obtained yet about enteric CH_4, so that a full GHG accounting in ICL system cannot be done.

Differently, in Castro, the ICL relative to cropland represented a net source of 0.351 Mg CO_2-C ha^{-1} year^{-1}, and most of that was due to the higher soil N_2O emission (Table 3). The offset of this N_2O emission did not occur, once the soil OC sequestration rate in the 0-100 cm layer of the soil under ICL was negligible. Moreover, the CH_4 from enteric fermentation was not considered here, what would further increase the net GHG emission in ICL.

However, the assessment approach of GHG used in this paper was based on a per-hectare bases but an assessment based on food production (considering the extra milk and meat production of ICL) would be more appropriate.

Concluding remarks

The ICL system has a significant potential to promote soil OC accumulation, and this accumulation can extend up to 100 cm depth. Soil emission of N_2O is generally higher in ICL than in annual cropping, but the opposite may occurs. However, the N_2O emission in ICL can be offset by soil OC accumulation. Strategies to further increase soil OC sequestration and curb N_2O emissions in ICL must be developed, for this is a system that provides many ecosystem services and economical benefits in Brazilian tropical and subtropical regions.

References

Ball, B.C., Scott, A., Parker, J.P., 1999. Field N_2O, CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. Soil Till. Res. 53, 29-39.

Boddey, R.M., Jantalia, C.P., Conceição, P.C., Zanatta, J.A., Bayer, C., Mielniczuk, J., Dieckow, J., Santos, H.P., Denardin, J.E., Aita, C., Giacomini, S.J., Alves, B.J.R., Urquiaga, S., 2010. Carbon accumulation at depth in Ferralsols under zero-till subtropical agriculture. Glob. Change Biol. 16, 784–795.

Boeni, M., 2007. Proteção física da matéria orgânica em Latossolos sob sistemas com pastagens na região do Cerrado Brasileiro. Programa de Pós Graduação em Ciência do Solo. Universidade Federal do Rio Grande do Sul, Porto Alegre.

Campbell, C.A., Bowren, K.E., Schnitzer, M., Zentner, R.P., Townley-Smith, L., 1991. Effect of crop rotations and fertilization on soil organic matter and some biochemical properties of a thick Black Chernozem. Can. J. Soil Sci. 71, 377-387.

Carvalho, J.L.N., 2010. Dinâmica do carbono e fluxo de gases do efeito estufa em sistemas de integração lavoura-pecuária na Amazônia e no Cerrado. Escola Superior de Agricultura “Luiz de Queiroz”. Universidade de São Paulo, Piracicaba, p. 141.

Carvalho, J.L.N., Raucci, G.S., Cerri, C.E.P., Bernoux, M., Feigl, B.J., Wruck, F.J., Cerri, C.C., 2010. Impact of pasture, agriculture and crop-livestock systems on soil C stocks in Brazil. Soil Till. Res. 110, 175-186.

Corazza, E.J., Silva, J.E., Resck, D.V.S., Gomes, A.C., 1999. Comportamento de diferentes sistemas de manejo como fonte ou depósito de carbono em relação à vegetação de Cerrado. Rev. Bras. Ci. Solo 23, 425-432.

de Klein, C.A.M., van Logtestijn, R.S.P., 1994. Denitrification and N_2O emission from urine-affected grassland soil. Plant Soil 163, 235-241.

Di, H.J., Cameron, K.C., 2002. The use of a nitrification inhibitor, dicyandiamide (DCD), to decrease nitrate leaching and nitrous oxide emissions in a simulated grazed and irrigated grassland. Soil Use Manage. 18, 395-403.

Diekow, J., Mielniczuk, J., Knicker, H., Bayer, C., Dick, D.P., Kogel-Knabner, I., 2005. Soil C and N stocks as affected by cropping systems and nitrogen fertilisation in a southern Brazil Acrisol managed under no-tillage for 17 years. Soil Till. Res. 81, 87-95.

Gomes, J., 2006. Emissão de Gases do Efeito Estufa e Mitigação do Potencial de Aquecimento Global por Sistemas Conservacionistas de Manejo do Solo (Fluxes of greenhouse gases and mitigation of the global warming potential by conservation soil management systems in the Southern Brazil). Programa de Pós-Graduação em Ciência do Solo. Universidade Federal do Rio Grande do Sul, Porto Alegre, p. 127.

Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Glob. Change Biol. 8, 345-360.

Hütsch, B.W., 2001. Methane oxidation in non-flooded soils as affected by crop production - invited paper. Eur. J. Agron. 14, 237-260.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). IGES, Japan.

Liebig, M.A., Gross, J., Kronberg, S.L., Hanson, J.D., Frank, A.B., Phillips, R.L., 2006. Soil response to long-term grazing in the northern Great Plains of North America. Agric. Ecosyst. Environ. 115, 270-276.

Luo, J., de Klein, C.A.M., Ledgard, S.F., Saggar, S., 2010. Management options to reduce nitrous oxide emissions from intensively grazed pastures: A review. Agric. Ecosyst. Environ. 136, 282-291.

Magiero, E.C., 2012. Fluxos de N_2O provenientes de fontes nitrogenadas em sistema de integração lavoura-pecuária no Sul do Brasil Resultados parciais de Exame de Qualificação de Doutorado (Nitrous oxide fluxes from nitrogen sources in integrated crop-livestock system in Southern Brazil - Partial results of PhD Qualify Exam). Programa de Pós-Graduação em Ciência do Solo. Universidade Federal do Rio Grande do Sul, Porto Alegre, p. 50.

Milchunas, D.G., Lauenroth, W.K., 1993. Quantitative effects of grazing on vegetation and soils over a global range of environments. Ecol. Monogr. 63, 327-366.

Moraes, A., Carvalho, P.C.F., Pelissari, A., Alves, S.J., Lang, C.R., 2007. Sistemas de integração lavoura-pecuária no Subtrópico da América do Sul: Exemplos do Sul do Brasil. In: Moraes, A., Carvalho, P.C.F., Sulc, R.M. (Eds.), Simpósio Internacional em Integração Lavoura-Pecuária. Universidade Federal do Paraná, Curitiba, pp. 1-27.

Mosier, A.R., 1989. Chamber and isotope techniques. In: ANDREAE, M.O., SCHIMEL, D.S. (Eds.), Exchange of traces gases between terrestrial ecosystems and the atmosphere: report of the Dahlem Workshop. Wiley, Berlin, pp. 175-187.

Oenema, O., Velthof, G.L., Yamulki, S., Jarvis, S.C., 1997. Nitrous oxide emissions from grazed grassland. Soil Use Manage. 13, 288-295.

Omonode, R.A., Vyn, T.J., 2006. Vertical distribution of soil organic carbon and nitrogen under warm-season native grasses relative to croplands in west-central Indiana, USA. Agric. Ecosyst. Environ. 117, 159-170.

Piva, J.T., 2010. Emissão de óxido nitroso e metano em um Latossolo Bruno submetido a sistemas de preparo e integração lavoura-pecuária (MSc dissertation). Programa de Pós-Graduação em Ciência do Solo. universidade Federal do Paraná, Curitiba, p. 57.

Piva, J.T., 2012. Fluxo de gases de efeito estufa e estoque de carbono do solo em sistemas integrados de produção no Subtrópico Brasileiro. Programa de Pós-Graduação em Agronomia: Produção Vegetal. Universidade Federal do Paraná, Curitiba, p. 96.

Richards, J.H., 1993. Physiology of plants recovering from defoliation. XVII International Grassland Congress, New Zealand & Australia, pp. 85-93.

Saggar, S., Tate, K.R., Giltrap, D.L., Singh, J., 2008. Soil-atmosphere exchange of nitrous oxide and methane in New Zealand terrestrial ecosystems and their mitigation options: a review. Plant Soil 309, 25-42.

Salton, J.C., 2005. Matéria orgânica e agregação do solo na rotação lavoura-pastagem em ambiente tropical. Programa de Pós Graduação em Ciência do Solo. Universidade Federal do Rio Grande do Sul, Porto Alegre, p. 158.

Sisti, C.P.J., Santos, H.P., Kohhann, R., Alves, B.J.R., Urquiaga, S., Boddey, R.M., 2004. Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. Soil Till. Res. 76, 39-58.

Sordi, A., 2012. Emissão de óxido nitroso a partir de urina e esterco de bovinos a pasto. PPG Ciência do Solo. Universidade Federal do Paraná, Curitiba, p. 39.

Souza, E.D., 2008. Evolução da matéria orgânica, do fósforo e da agregação do solo em sistema de integração agricultura-pecuária em plantio direto, submetido a intensidades de pastejo (Evolution in organic matter and phosphorus content and in soil aggregation on an integrated crop-livestock system under no-tillage and different grazing intensities). Programa de Pós-Graduação em Ciência do Solo. Universidade Federal do Rio Grande do Sul, Porto Alegre, p. 163.

Velthof, G.L., Oenema, O., 1995. Nitrous oxide fluxes from grassland in the Netherlands: II. Effects of soil type, nitrogen fertilizer application and grazing. Eur. J. Soil Sci. 46, 541-549.

Yamulki, S., Jarvis, S.C., 1997. Nitrous oxide emissions from excreta from a simulated grazing pattern and fertilizer application to grassland. In: Jarvis, S.C., Pain, B.F. (Eds.), Gaseous Nitrogen Emissions from Grassland. CAB International, Oxon, pp. 195-199.

Zanatta, J.A., Bayer, C., Vieira, F.C.B., Gomes, J., Tomazi, M., 2010. Nitrous oxide and methane fluxes in South Brazilian Gleysol as affected by nitrogen fertilizers. Rev. Bras. Ci. Solo 34, 1653-1665.

Zanatta, J.A., Salton, J.C., 2010. Soil carbon sequestration affected by no-tillage and integrated crop-livestock systems in Midwestern Brazil. 19th World Congress of Soil Science, Soil Solutions for a Changing World. IUSS, Brisbane, pp. 210-212.

Table 1
Characterization of experimental sites or chronosequences considered in this study, and which include annual crops (reference system) and integrated crop-livestock production systems in tropical (Cerrado region) and subtropical region (South of Brazil).

Site	Soil type	Particle distribution			Mean annual		Time of experiments	Characteristics of production systems		Reference of data
		Clay	Silt	Sand	Temp.	Rainfall		Reference	ICL	
		------- g kg^{-1} soil -------			-- °C --	- mm --	--- years ---			
Tropical Soils (Cerrado region) [1]										
Dourados, MS	Rhodic Ferralsol	633	215	155	23	1635	9	No-tillage [2]	2-years annual crop (black oat/soybean) 2-years pasture (*Brachiaria decumbens*)	Salton (2005) and Zanatta and Salton (2010)
Maracaju, MS	Humic Ferralsol	530	200	270	23	1545	11	No-tillage [3]	2-years annual crop (black oat/soybean) 2-years pasture (*Brachiaria decumbens*)	Salton (2005) and Boeni (2007)
Campo Grande, MS	Rhodic Ferralsol	360	130	510	23	1527	11	No-tillage [4]	1-year annual crop (pearl millet/soybean) 3-years pasture (*Brachiaria brizantha*)	Salton (2005) Boeni (2007)
Chupinguaia, RO	Ferralsol	610			26	2200		No-tillage[5]	Soybean/*Brachiaria ruziziensis*	Carvalho (2010)
Santa Carmen, MT	Ferralsol	520			28	2000		No-tillage[6]	Soybean/Sorghum+*Brachiaria ruzisiensis*	Carvalho (2010) and Carvalho *et al.* (2010)
Montividiu, GO	Ferralsol	560			23	1650	10	No-tillage[7]	Soybean/Maize+*Brachiaria ruzisiensis*	Carvalho (2010) and Carvalho *et al.* (2010)
Subtropical Soils (Southern region)										
Castro, PR	Umbric Ferralsol	439	177	384	18	1400	3.5	No-tillage[8]	Winter pasture (ryegrass) and corn for silage at summer	Piva (2010)
Ponta Grossa, PR	Umbric Ferralsol + Haplic Cambisol	250	100	650	18	1500	4	No-tillage[9]	Winter pasture (black oat) and soybean or maize at summer	Piva (2012)
Tupanciretã, RS	Rhodic Ferralsol	540	270	190	21	1822	6	No-tillage [10]	Winter pasture (black oat+ryegrass) and soybean at summer	Souza (2008)

[1] Chupinguaia, Santa Carmen and Montividio sites are cronosequences and not designed experiments.

[2-9] Crop successions: (1) radish (*Raphanus sativus*)/corn (*Zea mays*)-black oat (*Avena sativa*)/soybean (*Glycine Max*)-wheat (*Triticum aestivum*)/soybean; (2) black oat/soybean; (3) pearl millet (*Pennisetum specatum*) or sorghum (*Sorghum bicolor*)/soybean; (4) sorghum/soybean; (5) maize (*Zea mays*)/soybean; (6) soybean/millet or maize; (7) ryegrass/corn (for silage); (8) black oat/soybean or maize; (9) black oat+ryegrass (*Lolium multiflorum*)/soybean.

Table 2
Integrated crop-livestock (ICL) system effects on soil organic matter, soil aggregation and organic carbon (OC) sequestration in comparison to no-tillage (NT) annual cropping systems in tropical and subtropical soils of Brazil. For original references, see Table 1.

Site/Soil Management		Soil OC		Annual OC sequestration	Soil aggregates (0-5 cm) [1]			Physical SOM fractions (0-5 cm) [2]			Δ C fraction / Δ OC (0-5 cm) [3]		
		0-5cm	0-20cm		MWD	Large-Macro >2 mm	Macro >0,25 mm	LFF	LOF	HF	LFF	LOF	HF
		---- Mg ha^{-1} ----		-Mg ha^{-1}-	- mm -	--- % of soil mass-----		--------- Mg ha^{-1} ---------			----------- % --------------		
Tropical Soils (Cerrado region)													
Dourados, MS	NT	9.57	36.31	-	2.60	39	83	0.61	2.04	6.92	-	-	-
	ICL	12.85	41.03	0.52	4.40	68	90	0.67	3.17	9.01	2	34	64
Maracaju, MS	NT	15.13	56.57	-	2.25	34	85	0.63	2.79	11.70	-	-	-
	ICL	20.25	64.17	0.96	3.90	60	93	0.84	3.94	15.46	4	22	74
Campo Grande, MS	NT	11.70	47.00	-	1.80	25	81						
	ICL	14.80	50,50	0.32	3.60	53	85						
Chupinguaia, RO	NT	12.10	42.90	-									
	ICL	14.80	48.00	1,21									
Santa Carmen, MT	NT	14.90	48.40	-									
	ICL	16.15	53,25	1,57									
Montividio, GO	NT	15.70	50.10	-									
	ICL	15.50	52.00	0.19									
Subtropical Soils (South region)													
Castro, PR	NT		67.20	-									
	ICL		67.88	0.19									
Tupanciretà, RS	NT		59.30	-	3.33	54	87						
	ICL		59.50	0.03	4.37	67	90						

[1] MWD = mean weight diameter of aggregates; large macroaggregates are >2 mm and macroaggregates are > 0.25 mm.
[2] LFF = light free fraction, between aggregates (density < 2.00 Mg m^{-3}); LOF = light occluded fraction, inside aggregates (density < 2.00 Mg m^{-3}); HF = heavy fraction (density > 2.00 Mg m^{-3}).
[3] Percentage that a physical fraction represents in the overall OC accumulation in ICL.

Table 3

Nitrous oxide (N_2O) and methane (CH_4) emissions, soil organic carbon (OC) stocks and net greenhouse gases emission from soil in integrated crop-livestock (ICL) system compared to annual cropland. For original references, see Table 1.

System	N_2O (kg N_2O-N ha^{-1} $year^{-1}$)	CH_4 (kg CH_4-C ha^{-1} $year^{-1}$)	Soil OC stock (Mg C ha^{-1})		C sequestration in ICL[a] (Mg C ha^{-1} $year^{-1}$)		Net emission ICL[b] (Mg CO_2-C_{eq} ha^{-1} $year^{-1}$)
			0-20 cm	0-100 cm	0-20 cm	0-100 cm	
Castro-PR							
Cropland	1.26 a[c]	1.08 ns	67.20 ns	234.61 ns			
ICLS	4.26 b	1.65	67.88	234.74	0.194	0.037	0.351
Ponta Grossa-PR							
Cropland	1.77 b	-0.84 ns		n.d.[e]			
ICLS	1.09 a	-0.90		n.d.			
Dourados-MS							
Cropland	0.72 ns	-1.17 ns	41.50 a	104.03 a			
ICLS	0.88	-0.86	44.30 b	115.83 b	0.187	-0.780	-0.757
Montividiu-GO							
Cropland	0.57 ns	-0.94 ns					
ICLS	2.00	-0.77					

[a] Soil OC sequestration in ICL compared to cropland.

[b] Considering the N_2O and CH_4 emission and soil C sequestration in 0-100 cm, relative to cropland. All data was converted into CO_2-C equivalent.

[c] Letters compare cropland and ICLS treatments within each experiment, according to Tukey test ($p<0.10$).

[d] N_2O emission assessed during 450 days, but data was normalized to 365 days of a year. Soil C not assessed yet.

[e] Not determined.

[f] Average of two years. The ICL is a rotation of two years cropland plus two years of pasture (Brachiaria), and data refer only to the cropland phase.

Table 4
Emission factors (EF) of nitrous oxide for nitrogen sources applied in annual crop and integrated crop-livestock (ICL) systems, as recommended by IPCC (Intergovernmental Panel on Climate Change) and as obtained in regional studies conducted in Southern Brazil.

N source	IPCC-EF (1)	Regional-EF	Reference (2)
	---------- % of applied N----------		
Annual crop systems			
Fertilizer (urea)	1.00	0.44	Gomes (2006)
Legume cover-crops	1.00	0.11	
Integrated crop-livestock systems			
Sheep urine	1.00	0.27	Magiero (2012)
Sheep dung	1.00	0.10	
Cattle urine	2.00	0.26	Sordi (2012)
Cattle dung	2.00	0.15	

(1) IPCC (2006).
(2) Source of Regional-EF.