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Greenhouse gas assessment of Brazilian soybean production and postharvest nitrous oxide emissions from crop residues decomposition

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To my beloved grandparents, Natércia and João Bosco (in memoriam), my greatest example in life. ***This is for you!***

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“The best time to plant a tree was 20 years ago. The second best time is now.”

Chinese Proverb

ABSTRACT

RAUCCI, G. S. **Greenhouse gas assessment of Brazilian soybean production and postharvest nitrous oxide emissions from crop residues decomposition.** 2015. 77 p. Dissertation (M.S.) – Center for Nuclear Energy in Agriculture, University of São Paulo, Piracicaba, 2015.

Brazil is one of the world's largest producers and exporters of soybeans. The oil and meal obtained from grains are important components of biodiesel and animal feed chains. In recent years, international standards and certifications were developed to promote sustainability in the agricultural supply chain. In this context, greenhouse gases (GHG) emissions in the products life cycle has been the main point of interest to the scientific community and consumers. Few studies have evaluated the GHG emissions in soybean cultivation with specific data for the Brazilian reality. The aim of this study was to evaluate the main sources of GHG in soybean production in the State of Mato Grosso, Brazil. We evaluated 55 farms in the crop years of 2007/08, 2008/09 and 2009/10, accounting for 180,000 hectares of soybean cultivation area and totaling 114 individual situations. The results indicated that the largest source of GHG in the soybean production is the decomposition of crop residues (36%), followed by fuel use (19%), fertilizer application (16%), liming (13%), pesticides (7%), seeds (8%) and electricity consumed at the farms (<1%). The average GHG emissions considering the three crop years were 0.186 kg of CO_2eq kg^{-1} of soybean produced. Based on these results, field experiments were conducted to quantify N_2O emissions from the decomposition of soybean crop residues in different climatic regions and harvest periods in Brazil. Our results show that, in field conditions, the contribution of N_2O emissions from senesced and desiccated residues that remain on field after soybean harvest are unlikely to represent a significant source of N_2O loss above normal background soil emissions. These results were also supported by the laboratory incubation experiment, indicating that the IPCC methodology for estimating N_2O emissions from soybean crop residues may provide overestimations for the Brazilian conditions. The results of this study provide relevant and specific information to producers, industry and scientific community regarding the environmental impacts associated with soybean production in Brazil.

Keywords: Agriculture. Sustainability. Emission factors. Global warming. Carbon footprint.

RESUMO

RAUCCI, G. S. **Emissões de gases de efeito estufa na cultura da soja e influência dos resíduos culturais nas emissões de óxido nitroso pós-colheita.** 2015. 77 p. Dissertação (Mestrado) – Centro de Energia Nuclear na Agricultura, Universidade de São Paulo, Piracicaba, 2015.

O Brasil é um dos maiores produtores e exportadores mundiais de soja. O óleo e farelo obtidos dos grãos são componentes importantes das cadeias do biodiesel e ração animal. Nos últimos anos, normas e certificações internacionais foram desenvolvidas para promover a sustentabilidade na cadeia de produção agrícola. Nesse contexto, as emissões de gases de efeito estufa (GEE) no ciclo de vida dos produtos tem sido o principal ponto de interesse para a comunidade científica e consumidores. Poucos estudos avaliaram as emissões de GEE no cultivo da soja com dados específicos para a realidade brasileira. O objetivo deste estudo foi determinar as principais fontes de GEE na produção de soja em Mato Grosso, principal estado produtor brasileiro. Foram coletados dados de 55 fazendas nos anos-safra de 2007/08, 2008/09 e 2009/10, totalizando 114 avaliações. Os resultados indicaram que a maior fonte de GEE na produção de soja é a decomposição de resíduos culturais (36%), seguido pelo uso de combustível (19%), aplicação de fertilizantes (16%), calagem (13%), pesticidas (7%), sementes (8%) e eletricidade consumida nas fazendas (<1%). A emissão média considerando os três anos-safra avaliados foi 0,186 kg de CO_2eq kg^{-1} de soja produzido. Com base nesses resultados, foram desenvolvidos experimentos em campo para quantificação das emissões de N_2O proveniente da decomposição dos resíduos culturais da soja em diferentes regiões climáticas e períodos de colheita no Brasil. Adicionalmente, foram realizadas incubações em laboratório com materiais de soja em diferentes estágios de desenvolvimento. Os resultados indicaram que resíduos culturais de soja que permanecem no campo após a colheita não representam uma fonte significativa de N_2O. Os resultados obtidos neste estudo fornecem informações relevantes para produtores, indústria e comunidade científica quanto aos impactos ambientais associados à cultura da soja no Brasil.

Palavras-chave: Agricultura. Sustentabilidade. Fatores de emissão. Aquecimento global. Pegada de carbono.

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SUMMARY

1 GENERAL INTRODUCTION

Soybean is the main oilseed crop cultivated in the world, mostly because of its high oil and protein content. In Brazil, one of the major global producers of the commodity is the crop with higher production and planted area. In 2013/2014, over 30 million hectares were cultivated with the crop, producing more than 85 million tons of grains (CONAB, 2014). The Center-West and South regions were responsible together for more than 80% of the Brazilian soybean cultivated area in the last three crop seasons (2011/2012 to 2013/2014). The states of Mato Grosso and Goiás in Center-West and Paraná and Rio Grande do Sul in South are currently the major producers of soybean in Brazil (CONAB, 2014).

The commercial cultivation of this Asian oilseed in Brazil began in the 1950's, with major expansion in the 70's when soybeans became a commodity driven by the vast commercial applications of its by-products – i.e. grain, bran and oil (EMBRAPA, 2014). Since 2001/2002, the soybean-cultivated area grew about 53% in the country and the average productivity has grown consistently over the years. Recently, Brazil has achieved a soybean yield of 2665–3000 kg ha^{-1}, an enhancement of more than 50% compared to 1976/1977 (EMBRAPA, 2014). These indicators show the improvement of agricultural practices and technological development around the crop, reflecting large investments in research in the last four decades, e.g. development of high yield varieties adapted to tropical climates, and resistant to pests and droughts (EMBRAPA, 2014; CASTANHEIRA et al., 2014).

The No-Till System is another good example of the advance of crop management and conservation technologies developed in Brazil. Within this farming technique, sowing is done without the conventional tillage steps of plowing and harrowing (FAO; IAPAR, 2012). Additionally, the system promotes permanent soil cover throughout the year with the use of crops in rotation. The crop residues are maintained on the surface of the soil, while roots improve the physical, chemical and biological characteristics belowground. Currently, almost all soybean area is cultivated in no-till system in Brazil, with significant amounts of soybean biomass left on the soil after harvest (EMBRAPA, 2011).

The use of crop residues as feedstock in biorefinery for biofuel or biomaterials production is already a reality (VENENDAAL et al., 1997; BREHMER et al., 2008; BESSOU et al., 2010). Globally, the agricultural sector generates 140 billion tons of biomass every year that could be used as feedstock for energy production (FOSTER-CARNEIRO et al., 2013). A major part of the biomass comes from agricultural and forest residues, with a growing share coming from purpose-grown energy crops (JENSEN et al., 2012; IEA, 2009). As one of the largest producers of agricultural commodities, generating large amounts of residues and wastes, Brazil has a great potential for the use of these feedstocks in biorefineries (LAL, 2005).

Soybean is seen as a potential crop for bioenergy, not only for its biomass, but also as an important source of vegetable oil. In Brazil, soybean oil is currently the main feedstock for biodiesel production. According to ABIOVE (2014), the oilseed is responsible for about 75% of biodiesel production, followed by tallow (22%) and cotton oil (2%). Foster-Carneiro et al. (2013) investigating the potential use of main agricultural residues and animal wastes for biorefinery purposes in Brazil indicated that sugarcane and soybean have the highest agronomic availability.

In the last decades, population growth in developing countries, the quest for energy security, increased demand for fuels and the claim of positive environmental benefits with the replacement of fossil fuels has accelerated the debate and investments in renewable energy sources in many countries (FAO, 2008; 2010; GBEP, 2011). At the same time, there has been growing concern regarding biofuels supply chains, and the environmental, social and economic impacts they can trigger. These include deforestation, biodiversity loss, pressure on water resources, and increasing demand for land and agricultural inputs. Furthermore, climate change and greenhouse gas (GHG) emissions have figured in the center of the debate (FOLEY et al., 2005; FARGIONE et al., 2008; SEARCHINGER et al., 2008; SCHAFFEL; LA ROVERE, 2010; GARNETT, 2008; TILMAN et al., 2011).

In response to these criticisms, various certifications standards and rules are being developed around the world in order to establish criteria and indicators that prove the sustainability of biofuels in several respects. The EU Renewable Energy Directive (RED) is of the first and most broad programs, requiring the economic operators within the EU to check the entire value chain of its products according to a clearly defined set of sustainability criteria (EUROPEAN COMMISSION, 2009). Moreover, a number of global sustainability initiatives are emerging to support the biofuel supply-chain meet the goals of regulations and help the industry towards a more sustainable direction – e.g. GBEP (Global Bioenergy Partnership*)*; ISCC (International Sustainability and Carbon Certification); 2BSvs (Biomass Biofuels voluntary scheme); RTRS (Round Table on Responsible Soy); BONSUCRO (former Better Sugarcane Initiative, BSI).

Within these standards, GHG emissions are one of the most recurring and rigorous indicators. The RED, for example, defined that for biofuels to be considered as renewable energy a proved reduction of 35% in life-cycle GHG emissions is required (EUROPEAN COMMISSION, 2009). Despite CO_2 emissions from the combustion of biofuels are considered neutral because of its biogenic origin, some studies point to only marginal GHG benefits, or even deficits, compared to their fossil fuel counterparts when the entire production chain is considered (TILMAN et al., 2006; FARGIONE et al., 2008; SEARCHINGER et al., 2008; DAVIS et al., 2009; CAVALETT; ORTEGA, 2010).

Several studies on Brazilian soybean-based products have reported the importance of environmental impacts in the agricultural production phase, from which field nitrous oxide (N_2O) emissions play a major role in the total GHG emissions (LEHUGER et al., 2009; PRUDÊNCIO DA SILVA et al., 2010; CASTANHEIRA; FREIRE, 2013; MOHAMMADI et al., 2013; LATHUILLIÈRE et al., 2014). In 2012, Brazilian GHG emissions totaled 1,488 $MtCO_2e$, with the agricultural sector accounting for almost 30% of this total. Over the last 22 years emissions from this sector grew by almost 50%, driven mainly by agricultural expansion (SEEG, 2014).

The lack of conclusive and consistent results for GHG emissions in agriculture presents a challenge for researchers and policy-makers. In this context, the use of life-cycle assessment (LCA) with a country-specific approach is needed for a more accurate evaluation of the environmental impacts of biobased products (FINNVEDEN; NILSSON, 2005; REAP et al., 2008; THORN et al., 2011).

The aim of this study was to evaluate the main sources of GHG in the life cycle of soybean production in Brazil and provide specific information about N_2O emissions following the decomposition of crop residues in field conditions. Therefore, this dissertation was prepared in phases, described in detail in the two chapters of this document.

The first chapter, entitled "GREENHOUSE GAS ASSESSMENT OF BRAZILIAN SOYBEAN PRODUCTION: A CASE STUDY OF MATO GROSSO STATE" aimed to evaluate the emissions and main sources of GHG in the soybean cultivation in Brazil using the LCA approach. A dataset of 55 different farms and 114 individual evaluations was used as a case study in the State of Mato Grosso, the largest soybean producing state in Brazil. This step is important since most studies on GHG emissions in the cultivation of soybeans in Brazil used crop management data based on national averages, extension services or public databases that often does not represent the production reality of a region. This is one of the few studies on GHG emissions in the cultivation of soybeans in Brazil with cultivation data collected directly from producers. This chapter has been accepted for publication in a special volume of the Journal of Cleaner Production (RAUCCI et al., 2014).

The second chapter, entitled "POSTHARVEST NITROUS OXIDE EMISSIONS FROM SOYBEAN CROP RESIDUES IN BRAZIL" aimed to quantify postharvest N_2O emissions from soybean crop residues decomposition in different climate regions and harvest periods. Field experiments were conducted in the South Central region of Brazil in which N_2O emissions from known volumes of soybean residues applied to the soil were measured using the static chamber method. Additionally, laboratory incubations with soybean plant materials in different growth stages were also performed. This chapter has already been prepared to publication in an internationally recognized peer reviewed journal.

The results generated by this research project may be used as a basis for other scientific studies where soybeans produced in Brazil are part of the system. Additionally, it is expected that the results generated by this study provide relevant and specific information to producers, industry and scientific community regarding the environmental impacts associated with soybean production in Brazil. Decision makers and other stakeholders in the production chain can use this set of information in order to assist them on the adoption of appropriate measures to the expansion of soybean cultivation in the country.

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2 GREENHOUSE GAS ASSESSMENT OF BRAZILIAN SOYBEAN PRODUCTION: A CASE STUDY OF MATO GROSSO STATE

Abstract

In recent years, the debate about environmental impacts and the sustainability of agricultural products has increased. Environmental impact indicators are increasingly being demanded for policy and decision-making processes. Consumers are more and more concerned about the quality of food products and now looking for those with a low environmental impact, with a particular attention to greenhouse gas (GHG) emissions. There are few studies regarding the GHG emissions associated with the Brazilian soybean production. The aim of this study was to evaluate the main sources of GHG in soybean production in the State of Mato Grosso, Brazil. Our analysis considered the Life Cycle Assessment (LCA) from cradle to farm gate. We evaluated 55 farms in the crop years of 2007/08, 2008/09 and 2009/10, accounting for 180,000 hectares of soybean cultivation area and totaling 114 individual situations. The results indicated that the largest source of GHG in the soybean production is the decomposition of crop residues (36%), followed by fuel use (19%), fertilizer application (16%), liming (13%), pesticides (7%), seeds (8%) and electricity consumed at the farms (<1%). The average GHG emissions considering the three crop years were 0.186 kg of CO2eq kg-1 of soybean produced. We also categorized the results based on land use intensity and production areas. This study contributed to identify the main sources of GHG in the soybean production and indicate mitigation priorities associated to the soybean cultivation in Brazil. Further studies, including field experiments, should contribute to a better understanding of the profile of emissions from crop residues in Brazil.

Keywords: carbon footprint; crop residues; nitrous oxide; emission factors; agriculture; global warming.

2.1 Introduction

In recent decades, the agricultural sector has been included in the discussions about environmental impacts of production systems (TILMAN et al., 2001; FOLEY et al., 2005; BUTLER et al., 2007; GARNETT, 2008; TILMAN et al., 2011). The international market is looking for products resulting from processes with minimal environmental impacts, especially regarding the greenhouse gas emissions (GHG) to the atmosphere (FINKBEINER, 2009; HERTWICH; PETERS, 2009). The increasing demand for grains, fiber, meat and renewable energy sources requires a new kind of knowledge about the production systems to make them more acceptable within the new sustainability criteria (RUVIARO et al., 2012).

Brazil is a leading global producer of agricultural commodities, especially soybean. In 2012, 50.9 million hectares were destined for the cultivation of grains, 49.2% of this area was planted with soybeans, producing 66.4 million tons of the grain. For 2013, production is estimated at 82.1 million tons, 23.6% higher than 2012. The soybean acreage has increased in 2.6 million hectares, resulting in 27.6 million hectares cultivated with the grain in Brazil (CONAB, 2013).

The central-west region of the country, comprising the states of Mato Grosso, Mato Grosso do Sul and Goiás, was responsible for 53% of the Brazilian production (34.9 million tons). The state of Mato Grosso is the largest national producer of the grain. For 2013, it is expected an increase of 837,700 hectares with soybean in the state, increasing from 6.98 to 7.82 Mha (CONAB, 2013).

Soybean is the primary grain exported in Brazil. Estimates for 2013 indicate increase in the exports due to growing international demand, mainly to China. In the last year, 32.5 million tons have been exported, and for 2013 the country is expected to export 36.8 million tons (CONAB, 2013). Estimates for 2013 show that Brazil is going to lead the ranking of largest exporter of soybeans, overcoming the U.S. in 4.9% (USDA, 2013). In relation to other products of the soybean complex, in 2012 Brazil exported 14.3 million tons of soy meal, almost 55% of the total production, and 1.8 million tons of oil, about 27.7% of the total volume. For 2013, are expected increments of approximately 14% in the production of soy meal and soy oil (CONAB, 2013).

Soybean is the main feedstock for biodiesel production in Brazil (above 80% of the total), complemented by tallow (around 19%) and other oilseeds (NOGUEIRA, 2011; CONAB, 2011). The increasing development of international standards and guidelines with criteria related to GHG balance may restrict the potential for export the Brazilian biodiesel (e.g. EU Renewable Energy Directive - European Commission, 2009).

In recent years, the productive sector have promoted various efforts to reduce the environmental impact related to soybean cultivation, reducing the deforestation, adopting the no-tillage system and creating the Soy Moratorium (PRUDÊNCIO DA SILVA et al., 2010). However, soybean production is highly dependent on inputs such as fertilizers, fuels, machinery, and pesticides, contributing to increasing GHG emissions to the atmosphere and the carbon footprint of the final product.

Several studies have reported the importance of environmental impacts in the agricultural production phase of soybeans, even when steps related to transportation and biodiesel production are considered (DALGAARD et al., 2007; PANICHELLI et al., 2009; LEHUGER et al., 2009; KNUDSEN et al., 2010; ÖZILGEN; SORGÜVEN, 2011). However, there is a very high discrepancy between the results, related mainly to differences in the methodologies used in the evaluations, climate and soil conditions, and diversity of production systems adopted in different producer regions in the world.

Soybeans produced in Brazil and its by-products (e.g. soymeal and pallets for animal feed, soybean oil, biodiesel and glycerin) have high international demand and are important components of the supply chain of various products. Therefore, the GHG intensity of Brazilian soybean-based products has been assessed in some publications in recent years, e.g. Castanheira and Freire (2012; 2013), Alvarenga et al. (2012), Cavalett and Ortega (2010), Prudêncio da Silva et al. (2010), Lehuger et al. (2009).

In studies about Life Cycle Assessment (LCA) in Brazil soybean is treated as a product from a single source, regardless of differences in relation to climate, soil type and cultivation systems (PRUDÊNCIO DA SILVA et al., 2010). Moreover, in most of these studies crop management data is based on national averages, extension services or public databases that often does not represent the production reality of a region. Data quality is a key issue for reducing the uncertainty in the results of studies on GHG emissions of agricultural products (BJÖRKLUND, 2002; FINNVEDEN; NILSSON, 2005; REAP et al., 2008; THORN et al., 2011). This is one of the few studies on GHG emissions in the cultivation of soybeans in Brazil with cultivation data collected directly from producers.

Therefore, the aim of this study was to evaluate the emissions and main sources of GHG in the soybean cultivation using a LCA approach on a dataset of 55 different farms and 114 individual evaluations in the State of Mato Grosso, Brazil.

2.2 Materials and methods

2.2.1 System boundaries and delimitations

In the agricultural production of soybean several processes are involved, including site preparation, crop sowing, agricultural operations and harvesting. The soybeans life cycle was assumed to start upon the harvest of the previous crop, and to end upon the harvest of the soybeans. Emissions related to transportation and processing of soybeans outside of the farm gates were not considered.

The stages included in the cradle to farm gate analysis of soybean production were: i) production of agricultural inputs (including transportation to the farm); and ii) farm stage, including operations such as soil tillage, pH correction with limestone application, sowing, fertilizer application, crop protection and harvest. Soybean irrigation is not a common practice in Mato Grosso, therefore it was not considered in this study (Figure 2.1).

Agricultural inputs comprise fuels, fertilizers, lime, pesticides, seeds and electricity. The functional unit chosen was 1 kg of soybean (grain) produced. This approach allows results to be compared with those by other authors or applied in developing studies where Brazilian soybeans are part of the system.

The international standards ISO 14040 and ISO 14044 were used to guide the allocation criteria. For the most part of the evaluation, the allocation of emissions was avoided by analyzing separately the production systems of the products obtained (i.e. other crops) in the same area. When it was not possible to analyze the inputs applied separately to each crop, such as lime application in the soil, electricity use on the farm, among others, we used the allocation criteria based on the production area for each crop in the same agricultural year.

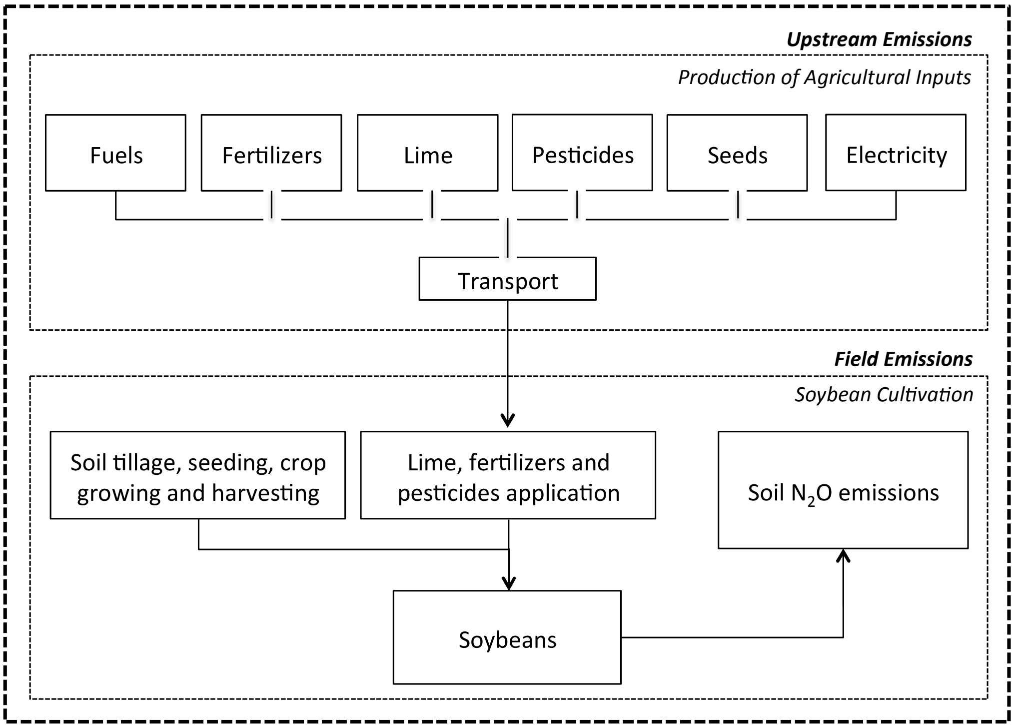

Figure 2.1 - Involved processes, system boundaries and main inputs in the soybean production.

2.2.2 Description of the case study and data collection

The study was carried out in the State of Mato Grosso, located in the Center West region of Brazil. We selected 55 different farms located at East, North, West and South of Mato Grosso, accounting for 180,000 hectares of soybean cultivation area (Figure 2.2).

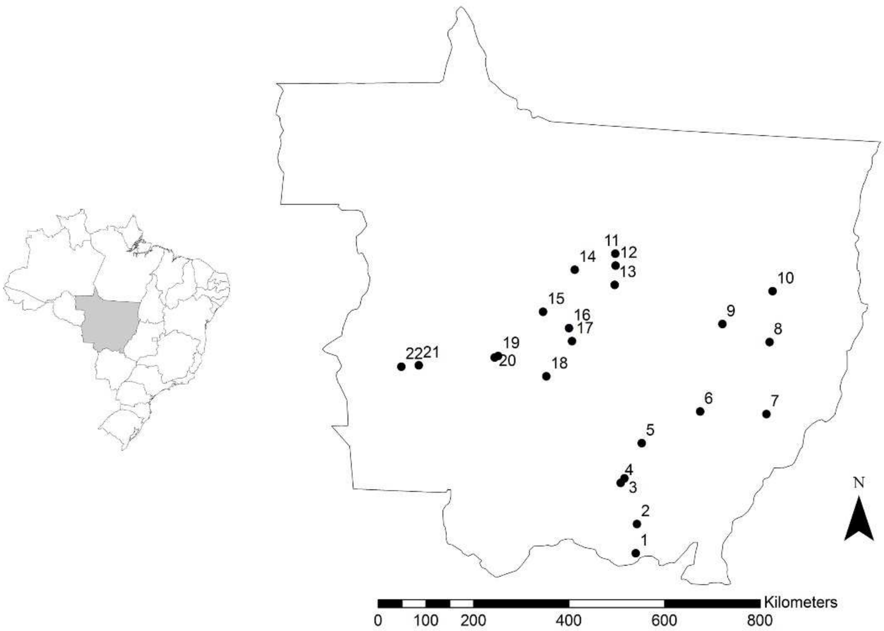

Figure 2.2 - Location map of the main municipalities where soybean farms were evaluated in Mato Grosso, Brazil.

In 2007/2008, 2008/2009 and 2009/2010 crop years, 36, 32 and 46 farms were evaluated, respectively, totaling 114 individual situations. Some of the studied farms had overlapping and were sampled for two or three crop years. The soybean farms were selected with the support of the largest soybean growers association in Mato Grosso, in order to comprise farms with different areas and scattered throughout the state. Table 2.1 shows the location of the study farms and number of evaluations in each crop year.

Table 2.1 - Location of the study farms and number of evaluations in each crop year in Mato Grosso, Brazil.

Number	**Region**	**Municipality**	**Crop Year**[a]		
			2007/08	**2008/09**	**2009/10**
1	South	Itiquira	x	x	x
2	South	Rondonópolis	x x	x	x
3	South	Campo Verde	x x	x x	x x x
4	South	Jaciara	x x	x x	x x x
5	South	Dom Aquino			x x
6	South	Santo Antônio do Leste	x	x	x
7	East	Nova Xavantina	x x	x x	x x
8	East	Canarana	x x x	x x x	x x x
9	East	Gaúcha do Norte	x	x	x x x
10	East	Querência	x x x x	x x	x
11	North	Santa Carmem			x
12	North	Vera	x	x	x x
13	North	Sorriso			x x x
14	North	Ipiranga do Norte	x	x	x
15	North	Tapurah	x	x	x x
16	North	Lucas do Rio Verde	x x x x	x x x	x x x x
17	North	Nova Mutum	x	x	x
18	North	Diamantino			x
19	West	Tangará da Serra	x	x	x
20	West	Campo Novo do Parecis	x x x x x	x x x x x	x x x x
21	West	Sapezal	x x	x x	x x
22	West	Campos de Júlio	x x	x x	x x x x

[a] Study farms are represented by “x”.

Data from soybean cultivation (e.g. farming practices, agricultural inputs, yields etc.) was obtained from the official database of the soybean growers association in Mato Grosso, which develops a monitoring and annual registration of all inputs used in the fields of its members to better estimate the production costs. Table 2.2 presents the production characteristics of the case study farms.

Table 2.2 - Production characteristics of the case study soybean farms in Mato Grosso, Brazil.

Crop year	**2007/08**		**2008/09**		**2009/10**	
Number of studied farms	36		32		46	
	Mean	Range	Mean	Range	Mean	Range
Soybean area (ha)	1710	325 - 6500	1568	350 - 5288	1479	446 - 4000
Second crop area[a] (ha)	933	0 - 6000	693	0 - 2938	627	0 - 2034
Second crop area/soybean area (%)	49	0 – 100	41	0 – 100	42	0 – 100

[a] Maize, rice, cotton, sorghum.

In the Center West region of Brazil, soybean cultivation occurs in large growing areas. In Mato Grosso, over half of the farms have more than 1,000 ha (IBGE, 2006). Table 1 shows that soybean farms with different cultivation areas were comprised in this study, ranging from 325 ha to 6,500 ha, with an average soybean area of 1,686 ha. Most of soybean areas in Brazil are cultivated under the no-tillage system, with a second-season production known as *Safrinha*. With this farming strategy growers can take advantage of a long tropical growing season to produce two crops in a single year. In this study, soybeans were closely followed by the production of maize (most common second crop), cotton, rice or sorghum. Thus, the ratio between the second crop area and the soybean area can be used as an indicator of land use efficiency and was in average 49%, 41% and 42%, respectively for 2007/08, 2008/09 and 2009/10.

Table 2.3 shows the main inputs for soybean cultivation in the case study farms. The average diesel oil consumption was similar in all crop years evaluated. We also considered the mandatory blending of diesel oil with biodiesel in Brazil, with the percentages established in the Brazilian legislation of 2%, 3% and 5%, respectively, for the harvests of 2007/08, 2008/09 and 2009/10. The percentage of ethanol blended in gasoline was considered 25% for all three years.

Despite the conditions of low natural fertility, soils in the Center West of Brazil have the highest agricultural potential of the country. The use of modern agricultural techniques and the development of adapted soybean varieties have resulted in the higher national average yields for the state of Mato Grosso. The mean soybean yield for the period evaluated was 3,200 kg ha^{-1}.

In practice, very little nitrogen is applied in soybean cultivation via nitrogen fertilization. The low nitrogen input through fertilizers is possible since 70-85% of the nitrogen requirement is supplied by biological fixation (ALVES et al., 2003). On average, 14% of the farms assessed applied some source of nitrogen in the three crop years evaluated.

Calcium and magnesium are supplied on lime application. On average, 43% of the farms applied lime on each of the years evaluated. Liming usually presents residual effect on the soil and it is not an agricultural practice recommended annually (OLIVEIRA; PAVAN, 1996; PÖTTKER; BEN, 1998; MIRANDA et al., 2005).

The low availability of phosphorus (P) and potassium (K) in the soils of center west of Brazil can be major constraints to soybean growth and production. Therefore, fertilization with these nutrients is also crucial for the good development of the crop. P and K are usually supplied in formulated fertilizers, with potassium chloride (KCl) being the most commonly used source of potash. The fertilization rates were very similar among the three crop years evaluated.

The use of pesticides is necessary to protect the crop against pests and weeds. The average use of the major groups of pesticides, i.e. herbicides, fungicides and insecticides, was very similar in all crop years evaluated.

Electricity consumption in the agricultural stage of soybean production was very low and usually used for lighting. In Brazil, about 85% of electricity is derived from renewable sources (76.9% hydro power, 6.8% biomass and 0.9% wind) which leads to low CO_2 emissions compared to other countries where electricity is based on fossil fuels (BRASIL, 2013).

Table 2.3 - Main inputs and yield for 1 ha of soybean in the State of Mato Grosso, Brazil (crop years of 2007/08, 2008/09 and 2009/10).

Crop year	**2007/08**		**2008/09**		**2009/10**	
	Mean	Range	Mean	Range	Mean	Range
Inputs						
Diesel oil (L)	30	15.7 - 45.8	36	22.2 - 58.0	27	20.0 - 41.9
Fertilizers (kg)						
N	8	0.2 - 16.1	5	2.7 - 8.3	7	2.0 - 13.4
P_2O_5	84	64.4 - 161.2	82	49.2 - 131.6	78	37.3 - 141.8
K_2O	90	52.6 - 145.1	89	57.2 - 131.6	83	37.3 - 125.0
Limestone (kg)	333	102.0 - 610.8	489	178.4 - 722.9	439	101.5 - 1,319.0
Seeds (kg)	46	30.6 - 67.3	53	36.0 - 88.6	48	31.2 - 94.5
Electricity (kWh)	18	1.8 - 104.0	23	3.9 - 72.4	28	3.4 - 136.6
Pesticides (kg)						
Herbicides	3.85	0.12 - 10.91	3.94	0.22 - 7.31	5.85	0.18 - 11.29
Fungicides	0.95	0.03 - 2.37	1.11	0.17 - 2.68	1.40	0.02 - 3.76
Insecticides	1.61	0.04 - 8.13	2.00	0.18 - 5.31	1.83	0.04 - 6.45
Output						
Soybean yield (kg)	3,316	2,783 - 3,805	3,157	2,331 - 3,670	3,129	2,413 - 3,672

2.2.3 GHG emissions calculation: production of agricultural inputs, agricultural operations and field emissions

The GHG emissions calculations were individually made for each farm included in the study in each crop year, considering all the cultivation and input data reported.

Upstream GHG emissions associated with the production and transport of agricultural inputs were accounted for using emission factors for fertilizers and seeds (WEST; MARLAND, 2002), limestone (ECOINVENT CENTRE, 2009), fuels (MACEDO et al., 2008; ALMEIDA et al., 2008) and electricity (BRASIL, 2010). Emissions from the production of pesticides were estimated using specific emission factors to each active ingredient (ECOINVENT CENTRE, 2009). When a specific emission factor was not available, we used a generic emission factor based on the product type, e.g. herbicide, fungicide or insecticide (WEST; MARLAND, 2002).

Direct GHG emissions from cultivation arise from lime and fertilizer application and the diesel oil combustion from these agricultural operations. The direct and indirect N_2O emissions and CO_2 emissions related to urea and lime application were estimated using the methodology proposed by the "2006 IPCC Guidelines for National Greenhouse Gas Inventories" (IPCC, 2006). Indirect N_2O emissions included volatilization, leaching and run-off. We considered nitrogen (N) inputs from the annual amount of synthetic fertilizer N applied, as well as N from the mineralization of crop residues (above and below ground). The calculation procedures, parameters and emission factors for N_2O emissions are well documented and described in detail by Castanheira and Freire (2013). It’s important to note that N_2O emissions from N mineralization (as a result of soil carbon loss due to land use changes) were not included in this study.

Emissions of N_2O and CH_4 were compared based on their global warming potential (GWP), since CH_4 and N_2O have a GWP 25 and 298 times higher than CO_2 (IPCC, 2007), respectively, and then expressed in terms of equivalent CO_2 (CO_2eq).

2.3 Results and discussion

2.3.1 GHG emissions from soybean cultivation in Mato Grosso

The total GHG emissions for all farms evaluated in the three crop years showed a strong correlation with the total soybean production area, a good indicator of the quality of the data used for the calculations (Figure 2.3). This was also true for the other main GHG sources in the soybean production, i.e. crop residues, fuel and fertilizers use.

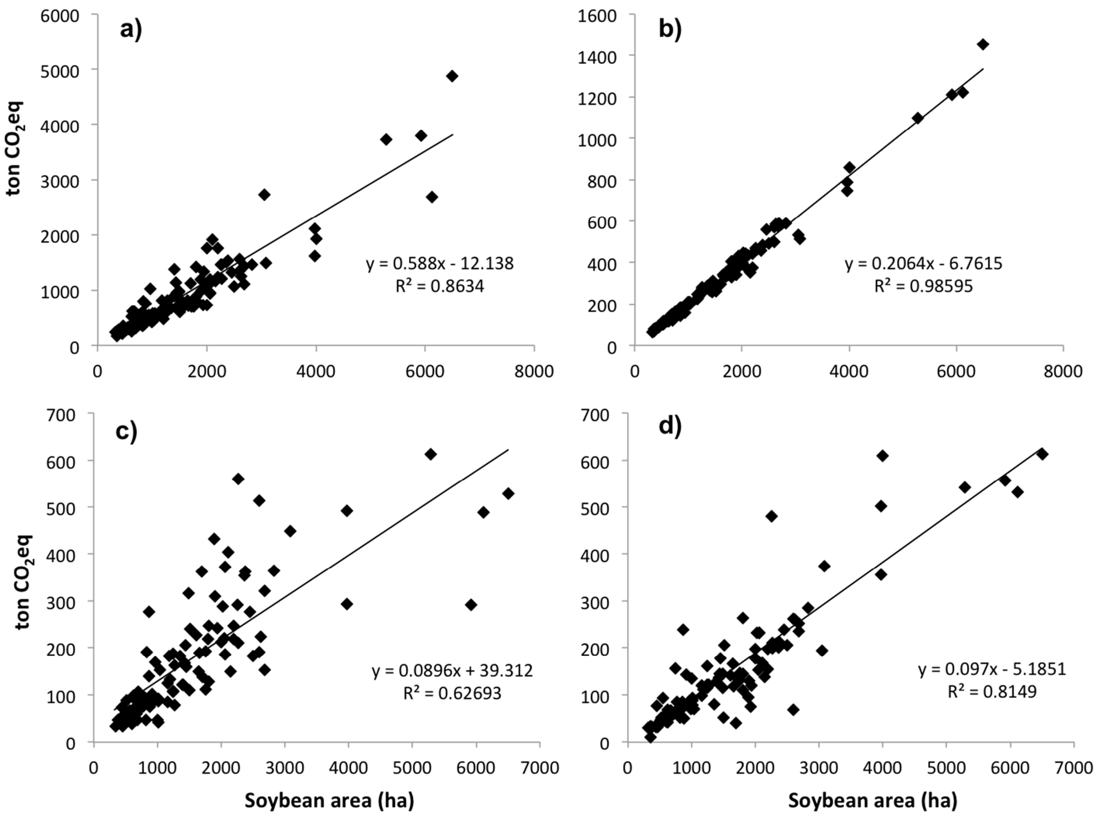

Figure 2.3 - (a) Total GHG emissions and (b) GHG emissions for the main sources, i.e. crop residues, (c) fuel and (d) fertilizers, according to soybean cultivation areas of all situations evaluated in Mato Grosso, Brazil.

Overall, the main differences between the GHG emissions were due to fuel and fertilizer consumption, but were also related to lime application in some cases.

Nevertheless, the total GHG emissions of the studied farms should be evaluated with caution and should not be used as sole indicators of sustainability in the soybean production. For example, farms with larger cultivation areas and greater intensity of crops generally have larger GHG emissions due to higher use of diesel, lime and fertilizers.

In order to make a more accurate comparison between farms with different characteristics, the emissions were weighted by total soybean production. Considering the average emissions of all farms evaluated, the GHG intensity of the soybean produced in the State of Mato Grosso was 0.164, 0.190 and 0.202 kg CO_2eq kg^{-1} soybeans, respectively for 2007/08, 2008/09 e 2009/10 crop years (Figure 2.4). Considering the global average of the period evaluated, the GHG intensity for the State of Mato Grosso was 0.186 kg CO_2eq kg^{-1} soybeans.

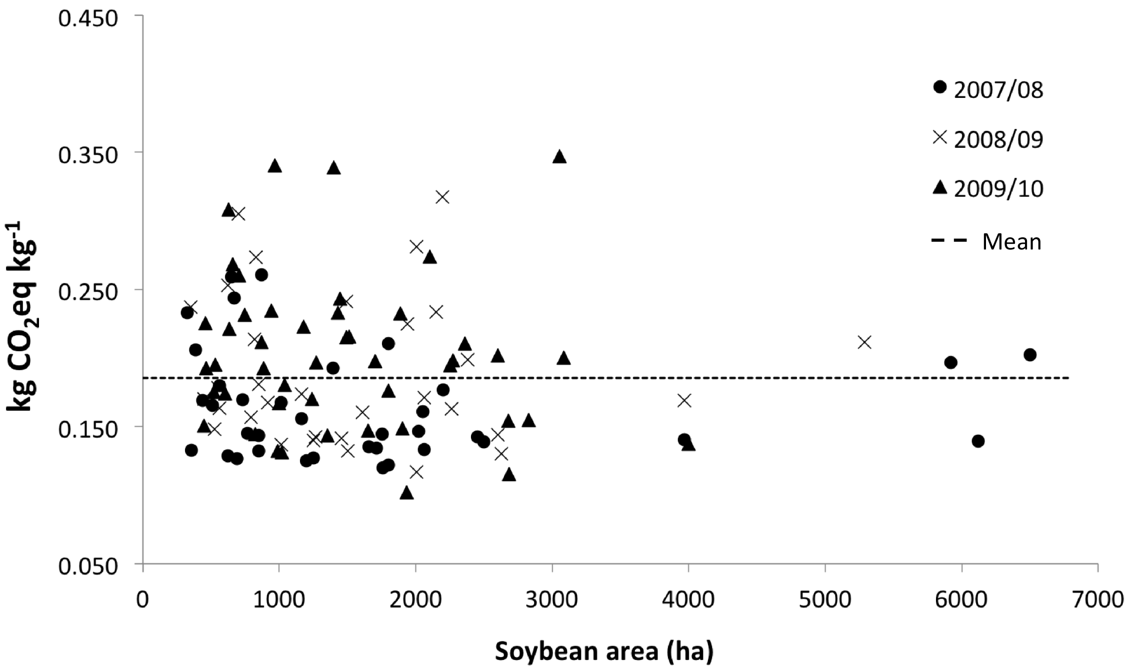

Figure 2.4 - GHG emissions (kg CO_2eq kg^{-1} soybeans) for 114 situations evaluated in the crop years of 2007/08, 2008/09 and 2009/10 and average emission (line) for the soybean cultivated in Mato Grosso, Brazil.

Once again, the great variation in GHG emissions can be partially explained by the variation in fertilizer, lime and diesel consumption in the farms evaluated. Moreover, it is interesting to note that GHG emissions vary regardless of soybean cultivation area. Less variation in the results was observed for the 2007/08 crop year.

The relative GHG emissions, expressed as a percentage, indicate the participation of the several sources evaluated in the total GHG emissions in the soybean production. In all farms and crop years evaluated, the main source of GHG was associated with the decomposition of crop residues, which represented 33 to 40% of total emissions (Figure 2.5). These results are in agreement with several other studies, showing that field N_2O emissions, especially from crop residues, play a major role in the GHG emissions from soybean cultivation (CASTANHEIRA; FREIRE, 2013; MOHAMMADI et al., 2013; PRUDÊNCIO DA SILVA et al., 2010; LEHUGER et al., 2009).

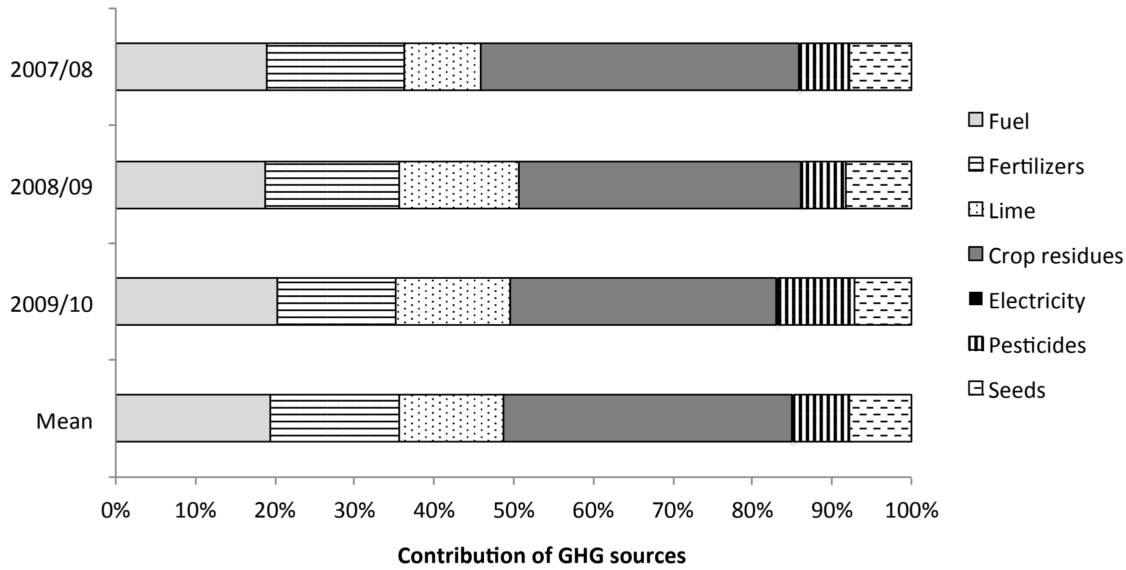

Figure 2.5 - Contribution of GHG emission sources in the soybean production in Mato Grosso, Brazil.

Crop residues left or incorporated in the soil are known as important sources of N_2O emissions to the atmosphere (CHEN et al., 2013; SIGNOR; CERRI, 2013; SHAN; YAN, 2013; HÉNAULT et al., 2012; VELTHOF et al., 2002; BOUWMAN, 1996). However, it is still a challenge to predict the magnitude and drivers of N_2O emissions following crop residues addition in the soil (CHEN et al., 2013). Limited, variable and often contradictory information concerning N_2O emissions from crop residues was found in a literature review by Novoa and Tejeda (2006). This variability of N_2O emissions can be partly explained due to differences in environmental factors (e.g. climate and soil conditions), crop factors (e.g. crop type and crop residues) and management factors (e.g. no tillage practices, harvesting).

Additionally, N_2O emissions from soil, crop residues, fertilizer and manure are often estimated using a default emission factor (EF). In the IPCC 2006 guidelines this EF is 1% (IPCC, 2006), i.e. the direct fertilizer-derived N_2O soil emission is equal to 1% of the amount of N applied. Still, a large variation in EFs for crop residues can be found in literature (MILLAR et al., 2004; VINTHER et al., 2004; STEHFEST; BOUWMAN, 2006; FLECHARD et al., 2007).

Chen et al. (2013) performed a meta-analysis of various publications to assess the impacts of crop residue amendment on soil N_2O emissions and the relation to soil and residue attributes, e.g. soil pH, soil texture, soil water content and residue C:N ratio. The results revealed that the stimulatory residue effects on N_2O emission are comparable with the effects of synthetic N fertilizers. They also stressed the importance of connecting the quality and quantity of crop residues with soil properties for predicting soil N_2O emissions.

Lesschen et al. (2011) developed an approach to determine N_2O EFs that depend on N-input sources and environmental factors for agricultural lands in temperate zones. Based on Velthof et al. (2002), Harrison et al. (2002) and Novoa and Tejeda (2006), the authors assumed the following N_2O EFs for different crop residues of arable crops: 0.2% for crop residues of cereals, 2% for crop residues of vegetables and 1% for crop residues. Despite high uncertainties in N_2O emissions, the authors considered that the use of differentiated EFs could perform better than a single default EF shown in IPCC (2006). Furthermore, using differentiated EFs allows accounting for the effects of accurate mitigation measures and offers a possibility to develop a Tier 2 approach. This increment allows the development of specific information for the agriculture system or management practice evaluated, resulting in less uncertainty of EFs.

The second largest source of GHG was associated with the use of fossil fuels for agricultural operations, representing 20% of total emissions. Fertilizers application accounted for the third largest source of GHG and showed no significant variation along the crop years. The upstream emissions associated with the production and transport to the farms represented about 15 to 17% of the total. Soil N_2O emissions due to the application of fertilizers were very low, representing less than 1% of total emissions. This is in agreement with the low nitrogen application rates in the soybean cultivation. Lime application was another source of GHG to the atmosphere, ranging from 10 to 15%.

The use of pesticides (herbicides, fungicides and insecticides) accounted for 6 to 10% of GHG emissions. The production phase of pesticides has little contribution in the total emissions. However, it does not mean that other environmental impacts are not important (FOLEY et al., 2005; TSCHARNTKE et al., 2012). The production and transport of soybean seeds accounted for only 7 to 8%. The electricity used by farms was not a significant source of GHG, accounting for less than 1%.

2.3.2 GHG emissions in different production intensities and farm areas

In order to compare different production realities in Mato Grosso, we created a specific classification based on the intensity of land use. This classification was based on the ratio between the second-season crop area and the soybean area in the same agricultural year: i) low intensity: < 30% of soybean area cultivated with others crops; ii) medium intensity: 30-60% of soybean area cultivated with other crops; iii) high intensity: > 60% of soybean area cultivated with other crops.

This classification was created under the premise that the intensity of land use or the inclusion of other crops in rotation/succession with soybean can affect the GHG intensity of the entire production system. The number of farms in each category and the emissions for each source are presented in Table 4.

Table 2.4 - GHG emissions in different land use intensities and farm areas in Mato Grosso, Brazil.

	Farm size[a]			**Land use intensity**[b]		
	Small	*Medium*	*Large*	*Low*	*Medium*	*High*
Number of farms	9	73	32	38	47	29
	kg CO_2eq ha^{-1}					
Fuel	101.0	107.8	130.7	107.3	120.4	111.4
Fertilizers	87.8	92.4	89.8	97.4	93.5	79.7
Lime	130.9	90.5	99.4	130.7	77.7	81.0
Crop residues	204.5	202.0	199.3	202.0	199.8	203.5
Electricity	0.7	0.8	0.6	0.7	0.7	1.0
Pesticides	50.2	38.6	51.9	42.3	43.6	43.9
Seeds	44.8	43.5	41.7	41.5	45.2	41.8
Soybean yield (kg ha^{-1})	3294	3179	3207	3208	3157	3242
Soybean area (ha)	408	1108	2976	1244	1792	1666
kg CO_2eq kg^{-1}	0.191	0.187	0.184	0.196	0.186	0.176

[a] Small size: 50 - 500 ha; Medium size: 500 - 2,000 ha; Large size: 2,000 - 10,000 ha;
[b] Low intensity: < 30%; Medium intensity: 30-60%; High intensity: > 60% of soybean area cultivated with others crops.

By comparing the contributions of the main GHG sources among the different land use intensities it was possible to verify some trends. The carbon footprint under different intensities of land use shows a tendency of lower values in areas with improved land use (high intensity) and incidence of second crop in the same agricultural year. The higher use of lime and the lowest average yields may have contributed to greater GHG emission on properties with “low intensity”.

Taking into account the wide variation in terms of the area cultivated with soybean in the farms evaluated in the three crop seasons, we also compared the results based on this parameter. The classification adopted is the same of the National Institute for Colonization and Agrarian Reform (in the Portuguese acronym, *INCRA*), i.e. i) small size: 50 - 500 ha; ii) medium size: 500 - 2,000 ha; iii) large size: 2,000 - 10,000 ha.

Most farms evaluated were classified as "medium size", followed by farms in "large size" category and only a few classified as "small size". The use of limestone was also higher in the smaller properties. In contrast, the emissions associated with fuel consumption were higher for larger farms. Still, there is a tendency to lower emissions in larger soybean cultivation areas.

2.3.3 Comparison with other studies

There are several studies and databases worldwide that assessed the GHG intensity of soybean production or soybean-based products recently (MOHAMMADI et al., 2013; KNUDSEN et al., 2010; TSOUTSOS et al., 2010; REINHARD; ZAH, 2009; KIM; DALE, 2009; PANICHELLI et al., 2009; SEARCHINGER; HEIMLICH, 2009; DALGAARD et al., 2008; PELLETIER et al., 2008; MILLER et al., 2007). There are also studies aimed at assessing the impacts of products (mainly biodiesel and soy meal) based on soybeans cultivated in Brazil (CASTANHEIRA; FREIRE, 2012; 2013; ALVARENGA et al., 2012; MOURAD; WALTER, 2011; CAVALETT; ORTEGA, 2010; PRUDÊNCIO DA SILVA et al., 2010; LEHUGER et al., 2009; REINHARD; ZAH, 2009). A few of them presented values of the GHG emissions at farm stage (i.e. soybean production) allowing the comparison of some of the results. However, there are few studies focusing specifically on the agricultural stage of soybean production for the Brazilian reality (Figure 2.5).

Table 2.5 - Studies reporting GHG emissions of soybean cultivation or soybean-based products from Brazilian cultivation.

Target product	Functional Unit (FU)	kg CO_{2eq}/FU	Author(s)	Comments
Soybeans	1 kg of soybeans	0.102 - 0.347	This study	GHG emissions; farm stage; 55 different farms; 114 evaluations; three crop years
Soybeans	1 kg of soybeans	0.100 - 17.8	Castanheira and Freire, 2013	GHG emissions; farm stage and transport to Europe; data from national reports or other studies; includes LUC
Broiler feed	1000 kg of feed	513 - 751	Alvarenga et al., 2012	Ecological footprint vs. LCA methodologies; data from public databases
Biodiesel	1 liter of biodiesel	0.860	Cavalett and Ortega, 2010	Emergy Accounting (EA), Embodied Energy Analysis (EEA) and Material Flow Accounting (MFA); data from field work scientific literature
Soybeans	1000 kg of soybeans	510 - 959	Prudêncio da Silva et al., 2010	GHG emissions; farm stage and transport to Europe; data from public databases; includes LUC
Soybean meal	1000 kg of feed	391	Lehuger et al., 2009	Environmental impacts using LCA; data from public databases

The results reported show large variability on the GHG emissions of Brazilian soybean cultivation. This variation can be mainly explained by the different scopes considered, the methods used for the GHG calculations, and the variations associated with the production regions and cultivation techniques. Still, our results are consistent with the range of values and emission sources presented in these studies.

Prudêncio da Silva et al. (2010) performed a LCA of soybeans produced in South and Center West regions of Brazil and exported to Europe, including land use change (LUC) and several other environmental impacts. Castanheira and Freire (2013) investigated the life cycle GHG balance of soybeans produced in Brazil and Argentina, also considering the implications of LUC and different cultivation systems. A great point of divergence in the assessment of the soybean GHG emissions, especially that produced in Brazil, is the inclusion or not of LUC in the final accounting. In this study, we did not consider GHG emissions due to LUC.

The high yields of the soybean produced in Mato Grosso may also explain the lower values for the emissions per kg of soybean produced in Brazil. For example, in the studies with soybeans produced both in Argentina and Brazil, an average yield of 2,700 kg of soybeans per hectare was considered in the calculations, which is much inferior than the average yield of 3,200 kg ha^{-1} in this study.

Nevertheless, the data for agricultural inputs and operations used in most of the studies is based on national reports or global databases with great uncertainty embedded in the results, and sometimes based on a restricted or not representative sample group. Moreover, none of those studies conducted a survey of inputs (fuel, fertilizers, pesticides etc.) and outputs of products (e.g. soybeans, crop residues) in property level, as it was done in this study.

2.4 Conclusions

This paper presents an evaluation of GHG emissions from soybean produced in Mato Grosso, Brazil. We performed 114 individual evaluations in the crop years of 2007/08, 2008/09 and 2009/10. This is one of the few studies in Brazil with data for agricultural inputs and cultivation operations assessed at farm level.

The results indicated that the largest source of GHG in the soybean production is the decomposition of crop residues (36%), followed by fuel use (19%), fertilizer application (16%), liming (13%), pesticides (7%), seeds (8%) and electricity consumed at the farms (<1%). The average GHG emissions considering the three crop years were 0.186 kg of CO_2eq kg^{-1} of soybean produced. We found no significant differences when the results were categorized by land use intensity and production areas.

It is still a challenge for the scientific community to predict the magnitude and drivers of N_2O emissions following crop residues addition in soils. In recent years, several attempts have been made to develop emissions factors for different crop residues. However, variable and contradictory information concerning N_2O emissions from crop residues was found in literature. Besides, the use of default emission factors on the calculations may not represent the reality of N_2O emissions by soybean residues in tropical conditions. Thus, further studies, including field experiments, should contribute to a better understanding of the profile of emissions from crop residues in Brazil.

Nevertheless, the results of this study appear as good indicators of the main sources of greenhouse gases in the soybean production in Mato Grosso, Brazil and can be applied in developing studies where Brazilian soybeans are part of the system.

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3 POSTHARVEST NITROUS OXIDE EMISSIONS FROM SOYBEAN CROP RESIDUES IN BRAZIL

Abstract

Crop residues left or incorporated in the soil can provide a series of environmental benefits, including soil conservation, nutrient cycling and soil carbon sequestration. However, crop residues remaining on field after harvest have been pointed as a potential source of N_2O to the atmosphere and could offset the C sequestration in cropping systems. The magnitude of N_2O emissions is mainly dependable on environmental conditions and crop residues characteristics. Soybean is one of the main grain crops in Brazil, with most of its area cultivated under no-tillage system. There are few studies in literature that evaluated N_2O emissions from soybean crop residues in the postharvest period. The aim of this study was to quantify the postharvest N_2O emissions from soybean crop residues decomposition in different climate regions and harvest periods. Hence, field experiments were conducted in which N_2O emissions from known volumes of soybean residues applied to the soil were measured using the static chamber method. Measurements continued for one month after application. Additionally, laboratory incubations with soybean plant materials in different growth stages were also performed. Our results show that, in field conditions, the contribution of N_2O emissions from senesced and desiccated residues that remain on field after soybean harvest is unlikely to represent a significant source of N_2O loss above normal background soil emissions. These results were also supported by the laboratory incubation experiment. Our results indicate that the IPCC methodology for estimating N_2O emissions from soybean crop residues may provide overestimations for the Brazilian conditions. Further studies, including field and laboratory experiments in all soybean development stages, should contribute to a better understanding of the profile of emissions from crop residues in Brazil.

Keywords: agriculture; straw; nitrogen; decomposition; emission factor; global warming.

3.1 Introduction

Soybean (*Glycine max* (L.) Merr.) is the main oilseed crop cultivated in the world, mostly because of its high oil and protein content. In Brazil, one of the major global producers of the commodity is the crop with higher production and planted area. In 2013/2014, over 30 million hectares were cultivated with the crop, producing more than 85 million tons of grains (CONAB, 2014). Currently almost all soybean area is cultivated in no-till system in Brazil, with large amounts of soybean crop residues left on the soil after harvest (EMBRAPA, 2011).

Crop residues left or incorporated in the soil provide a series of environmental benefits, including soil conservation, and improvement in soil chemical, physical and biological attributes (LAL, 1995; LAL; PIMENTEL, 2007). In addition, crop residues decrease temperature and moisture variations in the soil, increasing soil microbial activity and nutrient cycling (LAL, 2005). The adoption of no-till system with the use of cover crops has also been identified as potential source for C sequestration in the soil (LAL, 2004; CARVALHO et al., 2010; CERRI et al., 2010).

Soybean is seen as a potential crop for bioenergy, not only for its biomass, but also as an important source of vegetable oil. In Brazil, soybean oil is currently the main feedstock for biodiesel production. According to ABIOVE (2014), the oilseed is responsible for about 75% of biodiesel production, followed by tallow (22%) and cotton oil (2%). Foster-Carneiro et al. (2013) investigating the potential use of main agricultural residues and animal wastes for biorefinery purposes in Brazil indicated that sugarcane and soybean have the highest agronomic availability.

However, crop residues remaining on field after harvest have been pointed as an important source of nitrous oxide (N_2O) to the atmosphere (BOUWMAN, 1996; VELTHOF et al., 2002; CHEN et al., 2013; SHAN; YAN, 2013). Although emitted in small quantities, N_2O is a potent greenhouse gas with an estimated global warming potential up to 300 times higher than carbon dioxide (CO_2). Agriculture, mainly through animal and crop production is the main anthropogenic source of N_2O, representing 60% to 70% of the annual global N_2O emissions (IPCC, 2007). In Brazil, agriculture and livestock production are responsible for 64% of total GHG emissions (SEEG, 2014).

Nitrous oxide is generated in agricultural soils mainly by nitrification and denitrification processes (DUXBURY et al., 1982; SIGNOR; CERRI, 2013). Nitrification requires aerobic conditions and the presence of NH_4^+ to occur, whereas denitrification is favored under anaerobic conditions, with the presence of NO_3^- and mineralizable organic C

(BEAUCHAMP, 1997). In general, denitrification is considered to be the predominant process in most agricultural systems (PEOPLES et al., 2004).

There are multiple mechanisms by which crop residue returning may mediate soil N_2O emissions. Overall, residues recently added to the soil release large amounts of mineral N that can be subject to N_2O loss during nitrification and denitrification processes (AOYAMA; NOZAWA, 1993; BAGGS et al., 2000; HUANG et al., 2004; ROCHETTE et al., 2004). Besides, crop residue addition also provides organic C for microbial growth, increasing the consumption of O_2 and generating anaerobic conditions necessary for denitrification. In a recent review Chen et al. (2013) suggested that microsite anaerobicity induced by microbial growth could be a major driver for enhanced soil N_2O emissions following residue amendment.

Recent studies have shown that field N_2O plays a major role in the GHG emissions from soybean cultivation (LEHUGER et al., 2009; PRUDÊNCIO DA SILVA et al., 2010; CASTANHEIRA; FREIRE, 2013; MOHAMMADI et al., 2013). In agreement, Raucci et al. (2014) reported that crop residues could represent up to 36% of total on-farm GHG emissions in soybean cultivation in Brazil. GHG emissions in the production of soybeans and other feedstocks for biodiesel production are one of the main indicators in various certification programs for sustainable biofuels, e.g. EU Renewable Energy Directive (RED) and Global Bioenergy Partnership (GBEP).

In the IPCC 2006 guidelines, direct N_2O emissions from crop residues are estimated using a default direct emission factor (EF) of 1% of the total N added to the soil by this source (IPCC, 2006). In recent years, several studies were performed to evaluate the emissions from crop residues in field conditions. Still, a large variation in EFs can be found in literature (KAISER et al., 1998; HARRISON et al., 2002; MILLAR et al., 2004; VINTHER et al., 2004; NOVOA; TEJEDA, 2006; FLECHARD et al., 2007). N_2O emissions are dependent on several parameters, such as crop characteristics, and climate and soil conditions, requiring measurements at the regional level.

Few studies have evaluated the postharvest N_2O emissions from soybean crop residues decomposition in Brazil, especially in field conditions. The aim of this study was to quantify N_2O emissions from soybean crop residues in the major production regions of Brazil, considering different harvest periods and climatic conditions. Additionally, laboratory incubations with soybean plant materials in different growth stages were also performed.

3.2 Materials and Methods

3.2.1 Field experiment

3.2.1.1 Site description

The experiments were performed in areas located in the states of Paraná (PR) and Mato Grosso (MT) in the year of 2013. These areas represent contrasting environmental conditions and were chosen as the main areas of soybean production in the South Central region of Brazil (Figure 3.1).

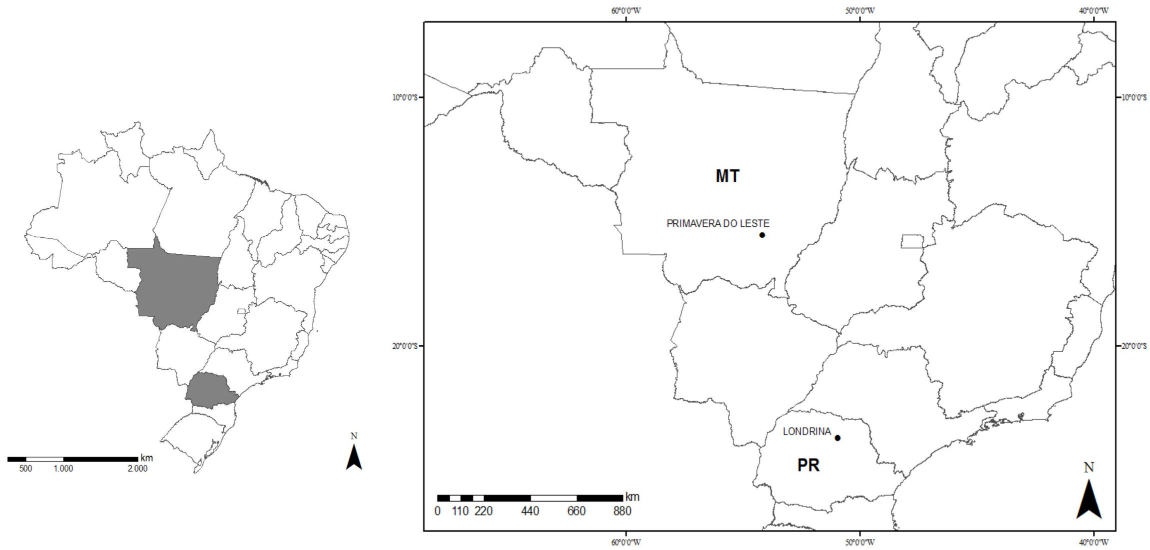

Figure 3.1 - Location of the experimental sites in the municipalities of Primavera do Leste (MT) and Londrina (PR).

In Mato Grosso, the experiments were carried out in the experimental fields of the Mato Grosso Cotton Institute (in the Brazilian acronym, IMA) in the municipality of Primavera do Leste (15˚32’23”S; 54˚11’39”W). The local climate is classified as tropical wet and dry (Aw - Köppen Climate Classification), with mean annual temperature of 18 - 24°C and rainfall of 1560 mm. The area has been cultivated under the soybean/corn crop succession for at least 15 years. The soybean variety harvested was TMG132, medium cycle variety most cultivated in the state.

In the state of Paraná, the experiments were conducted in agricultural production areas of Fazenda Figueira (23˚33’57”S; 50˚58’19”W), near the municipality of Londrina. According to the Köppen classification, the local climate is humid subtropical (Cfa), with rainfall in all seasons and eventual dry winter periods. The average annual rainfall ranges from 1400 to 1600 mm, and the annual average temperature is 21°C. The area has been used for agriculture for more than 15 years. Initially, it was exclusively cultivated with corn, but for at least the past 8 years has been cultivated in a soybean/corn succession.

3.2.1.2 Experimental design

The experiments proposed were designed to address the different climatic conditions in which decomposition of crop residues after harvest can occur. These are directly related to different periods of maturation and harvest of the cultivars, i.e. early cycle soybeans harvested in February, medium cycle harvested in March and late cycle harvested in April. Thus, the experiments were conducted according to the date of soybean maturity/harvest in each region.

Five chambers with the full equivalent amount of soybean crop residues left on the field and five chambers without any (Control) were installed. Two other treatments were installed in order to assess likely N_2O mitigating actions. These treatments consisted of 1/3 and 2/3 of the total amount that is deposited in the soil after harvest. Thus, other ten chambers were installed in the same manner previously described (Figure 3.2). Therefore, the following treatments were evaluated: full amount, 2/3, 1/3 and no straw (Control).

In the Mato Grosso case study, a medium cycle cultivar was harvested in February. Since IMA is a research institution, they had on their premises experimental plots with other soybean varieties, enabling the installation of a new experiment harvested in April (late maturity). The crop residues were then applied in chambers located in the same sampling site of the first experiment. However, only the emissions of the total amount of straw deposited on the soil were evaluated.

In Paraná case study, soybeans were harvested in March due to the prolonged rainy season. In this location the same treatments were installed, but it was not possible to assess N_2O emissions from crop residues of soybeans harvested in other months.

3.2.1.3 Crop residues characterization

The amount of soybean crop residues deposited on the soil surface after harvest was quantified in different months. In order to determine the amount of crop residues to be introduced in each chamber, a square frame of 0.25 m^2 was randomly thrown over the soil immediately after harvest (Figure 3.3). Following, a known amount of residues collected was placed in the static chambers installed in the field. This procedure was repeated and ten samples were taken for an average value of the amount deposited per square meter. The fresh crop residues without pre-drying were then introduced into the chambers in a quantity equivalent to an area of approximately 615.75 cm^2 (chamber area).

A complete description of the sampling locations, period of assessment and treatments are shown in Table 3.1. In all locations, emissions were assessed daily for a period of one month after the soybean harvest.

Table 3.1 - Description of sampling locations, period of assessment and treatments applied.

Location	**Months**	**Sampling Period**	**Crops**	**Residues**	**Dose**	**ID**
		Days		*Mg ha^{-1}*	*g chamber^{-1} DM*	
Primavera do Leste/MT	Feb/Mar	29	Soybean/corn	7.29	0 (Control)	PL1T0
					15 (1/3)	PL1T1
					30 (2/3)	PL1T2
					45 (Full amount)	PL1T3
	Apr/May	29	Soybean	4.12	0 (Control)	PL2T0
					25 (Full amount)	PL2T1
Londrina/PR	Mar/Apr	28	Soybean/corn	10.45	0 (Control)	LDT0
					21 (1/3)	LDT1
					43 (2/3)	LDT2
					64 (Full amount)	LDT3

Values are mean of ten replicates (n=10).

The residues were also taken for chemical analysis for the determination of carbon (C) and nitrogen (N) contents, and analysis of stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) (Table 3.2).

Table 3.2 - Chemical characteristics of crop residues left on field after soybean harvest.

Location	**Months**	**C**	**N**	**C/N**	**$\delta^{13}C$**	**$\delta^{15}N$**
		g kg^{-1} DM			*(‰)*	
Primavera do Leste/MT	Feb/Mar	378.29 ± 40.42	13.41 ± 3.38	28 ± 8.34	-26.68 ± 0.17	-0.54 ± 0.54
	Apr/May	347.68 ± 42.77	11.34 ± 2.59	32 ± 9.83	-28.46 ± 0.20	-0.35 ± 0.48
Londrina/PR	Mar/Apr	331.45 ± 44.51	9.40 ± 0.41	35 ± 5.19	-25.88 ± 0.66	1.92 ± 0.40

Values are mean of five replicates (n=5) ± standard error.

Figure 3.2 - Chambers installed in the field after soybean harvest with different amounts of crop residues in Paraná/PR. Full amount, 2/3, 1/3 and zero straw (control).

Figure 3.3 - Procedures for characterization of soybean crop residues deposited in the soil after harvest in Primavera do Leste/MT.

3.2.1.4 Nitrous oxide measurement

The manual static chamber method was used for measurements of N_2O fluxes (HENAULT et al., 2012; CHADWICK et al., 2014; CERRI et al., 2013). The two-piece chamber consisted of a metal base partially buried in the ground (3 cm) and a PVC cover with a septum through which gas samples were collected with the use of syringes.

Fluxes were daily measured in the middle of the morning (08:30 – 10:30 a.m.) by collecting samples in polypropylene syringes (20 mL) of each chamber at pre-defined time intervals (Figure 3.4). Immediately after closing a chamber, the first gas sample was taken (T0); after 20, 40 and 60 minutes later the remaining samples were taken (T20, T40 and T60). After each sampling period the samples in the syringes were transferred to hermetically sealed and pre-evacuated glass vials, which were able to preserve samples until the analysis in laboratory.

During the sampling period soil moisture at a layer of 0-10 cm, atmospheric pressure and soil temperature at a depth of 5 cm were also evaluated. Meteorological data for rainfall and air temperature were taken from meteorological stations located in the evaluated sites.

Nitrous oxide concentrations were determined through a gas chromatograph Shimadzu GC-2014® fitted with an electron capture device (ECD), packed columns and N_2 as a carrier gas. The molar gas volume was corrected for the temperature inside the chambers, and N_2O fluxes were calculated considering a linear increase in gas concentration inside the chambers headspace between the time intervals, chamber volume and area occupied by the chamber.

Daily N_2O fluxes were estimated by linear interpolation (USSIRI; LAL; JARECKI, 2009) assuming that the samples taken in the morning period provided a well-founded estimation of GHG emissions in agricultural experiments in Brazil (JANTALIA et al., 2008). Cumulative N_2O emissions during the sampling period were calculated by linear interpolation of mean N_2O fluxes between consecutive measurements and aggregating the results over the total period.

An overall view of the experimental sites following soybean harvest and after 30 days of gas samplings are shown in Figure 3.5.

Figure 3.4 - Example of gas sampling procedures with static chamber in field conditions.

Figure 3.5 - Field conditions after soybean harvest and after one month of sampling in a) Primavera do Leste/MT and b) Londrina/PR.

3.2.2 Laboratory experiment

A laboratory incubation experiment under controlled conditions was performed in order to identify the main factors that control N_2O emissions by soybean crop residues maintained in the soil after harvest. Such factors are often difficult to correlate in evaluations performed directly in the field. Therefore, laboratory experiments were conducted by incubation of soybean plant material in the final stages of development and after harvest.

3.2.2.1 Experimental design

The plant material was obtained from soybeans grown in experimental plots of the Department of Plant Production, at Escola Superior de Agricultura "Luiz de Queiroz" (ESALQ/USP), in Piracicaba, São Paulo state, Brazil.

The experiment consisted of five treatments with five replicates. The treatments were: control (CT), green leaves (GL), senescent leaves (SL), desiccated leaves (DL) and crop residues (CR). Green leaves were collected in R5 growth stage when the plant attains its maximum height, node number, and leaf area. In this stage, the N fixation rates peak and the plant begins to move N from the vegetative parts to the grains. Senescent yellow leaves falling off the plant naturally were manually collected around the R7 stage, when nutrient accumulation maximizes in the seed. Reminiscent dry leaves after desiccation with herbicide where also manually collected. Crop residues left on the plots after harvest consisted mostly in dry husks and branches.

Soil was taken from the 0-10 cm layer on the same site, dried and sieved at 2 mm. It was later added to 1.5 L Kilner jars with the equivalent of 0.3 kg dry soil per jar. Before the beginning of the experiment, deionized water was applied to the soil in order to bring the moisture content to 60% water-filled pore space (WFPS).

The incubation was carried out in a controlled air temperature laboratory at a constant temperature of 23°C. During the whole experiment, soils were maintained at 60% WFPS by the daily application of deionized water. The amount of water to be applied was checked daily through the weighing of the jars.

The jars were left open between sampling dates to ensure aerobic conditions and development of a uniform headspace above the soil surfaces.

3.2.2.2 Nitrous oxide measurement

For each N_2O measurement the Kilner jars were hermetically sealed for pre defined time intervals. Gas samples were collected with syringes through septa connections in the bottle caps in the intervals of T0 (right after closure), T10 (ten minutes after closure) and T30 (thirty minutes after closure). After sampling the covers were removed and the bottles kept open for at least 24 hours.

Nitrous oxide concentrations in the syringes were immediately analyzed using a SRI Gas Chromatograph 8610C. The N_2O fluxes were calculated from the increase in headspace concentration between T0 and T30 times, assuming linear increase and corrected for temperature. Cumulative emissions were calculated as the product of the mean flux rate between two successive sampling dates and the time interval between them. General procedures used for the laboratory experiment are presented in Figure 3.6.

Figure 3.6 - a) Soybean cultivated in experimental plots; b) Daily weighting of jars for moisture control; c) Soybean plant material incubated in jars; d) Gas sampling for N_2O emissions.

3.2.2.3 Statistical analysis for field and laboratory experiments

Significant differences in daily N_2O fluxes and cumulative fluxes among treatments over the sampling periods were determined by analysis of variance (ANOVA). The Tukey test ($p<0.05$) was used to determine the least significant difference (LSD) between treatments in each sampling site. The statistical analysis was performed using the Statistical Analysis System (SAS), version 9.

3.3 Results

3.3.1 Field Experiment

3.3.1.1 Nitrous Oxide Emissions

A. Primavera do Leste/MT

The daily N_2O-N fluxes and environmental conditions during the assessment period for the experiment performed in Primavera do Leste, between the months of February and March, are show in Figure 3.7. The air and soil temperature ranged from 22 to 33°C and 19 to 27°C, respectively (Figure 3.7(a)). Average temperatures were high because of the summer season in which the samples were taken, respectively 26°C and 22°C for air and soil. Rain events were distributed throughout the 29 days of evaluation, resulting in a high cumulative precipitation of 398.8 mm. There were three peak rainfall events between 17-25 days after soybean harvest, with a maximum daily rainfall of 51.6 mm on day 23 (Figure 3.7(b)).

The N_2O-N fluxes followed the same trend in all treatments evaluated, ranging on average from 15.69 to 210.24 μg N_2O-N m^{-2} h^{-1} (Figure 3.7(c)). The highest N_2O emission peak occurred on the 21st day for all the treatments, with a maximum emission rate of 210.24 (± 147.56) μg N_2O-N m^{-2} h^{-1} for PL1T0. In general, greater N_2O–N emissions were observed in PL1T0, while lower emissions were obtained in PL1T1. The area under PL1T1 had the smallest range in N_2O–N fluxes across the study period, ranging from 22.20 to 106.14 μg N_2O-N m^{-2} h^{-1}. The N_2O–N fluxes resulted in average emissions of 65.85; 51.24; 42.02 and 55.18 μg N_2O-N m^{-2} h^{-1} for PL1T0, PL1T1, PL1T2 and PL1T3, respectively.

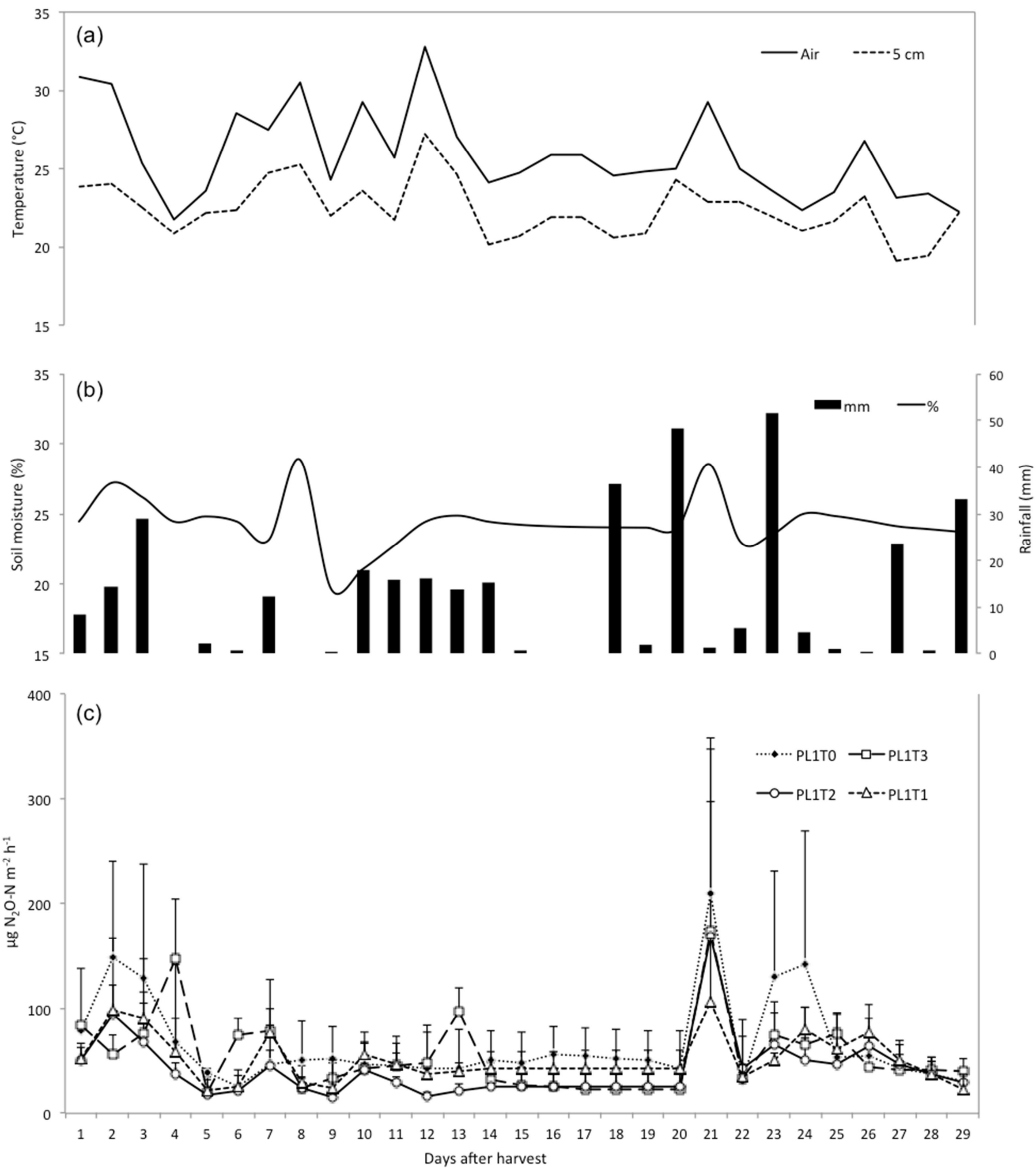

Figure 3.7 - (a) mean daily air temperature and mean soil temperature at 5 cm; (b) daily rainfall and soil moisture; (c) N_2O-N fluxes after soybean harvest. Values are mean of five replicates. Vertical bars show the standard error. PL1T0 (Control), PL1T1 (1/3), PL1T2 (2/3), PL1T3 (Full amount). Primavera do Leste/MT, Brazil. 2013.

In the second experiment in Primavera do Leste, over the following months of April and May, the cumulative rainfall in the 29 days of measurements was 15.8 mm, much lower than previously observed (Figure 3.8(a)). The average temperature for the period was also slightly lower, on average 22.7˚C.

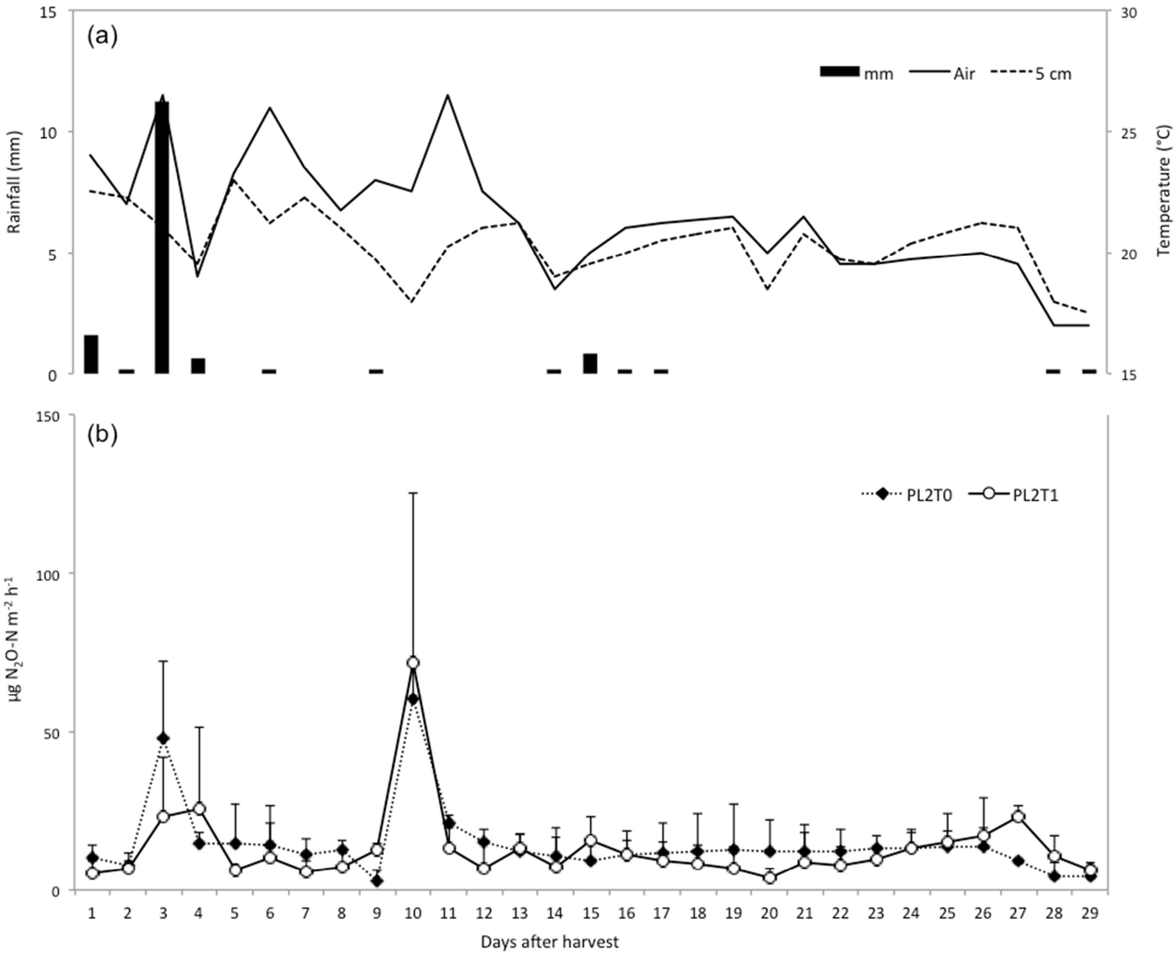

Figure 3.8 - (a) mean daily air temperature, mean soil temperature at 5 cm and daily rainfall; (b) N_2O-N fluxes after soybean harvest. Values are mean of five replicates. Vertical bars show the standard error. PL2T0 (Control), PL2T1 (Full amount). Primavera do Leste/MT, Brazil. 2013.

The intensity of N_2O-N emissions was also much lower than what previously observed in the first experiment (Figure 3.8(b)). The N_2O-N fluxes followed the same trend for the two treatments, ranging on average from 2.77 to 71.83 µg N_2O-N m^{-2} h^{-1}. The highest N_2O emission peak occurred on the 10^{th} day for both treatments, with a maximum emission rate of 71.83 (± 53.29) µg N_2O-N m^{-2} h^{-1} for PL2T1. The N_2O–N fluxes resulted in average emissions of 14.53 and 13.18 µg N_2O-N m^{-2} h^{-1} respectively for PL2T0 and PL2T1.

B. Londrina/PR

The daily N_2O-N fluxes and environmental conditions for the experiment performed in Londrina/PR, between the months of March and April, are shown in Figure 3.9.

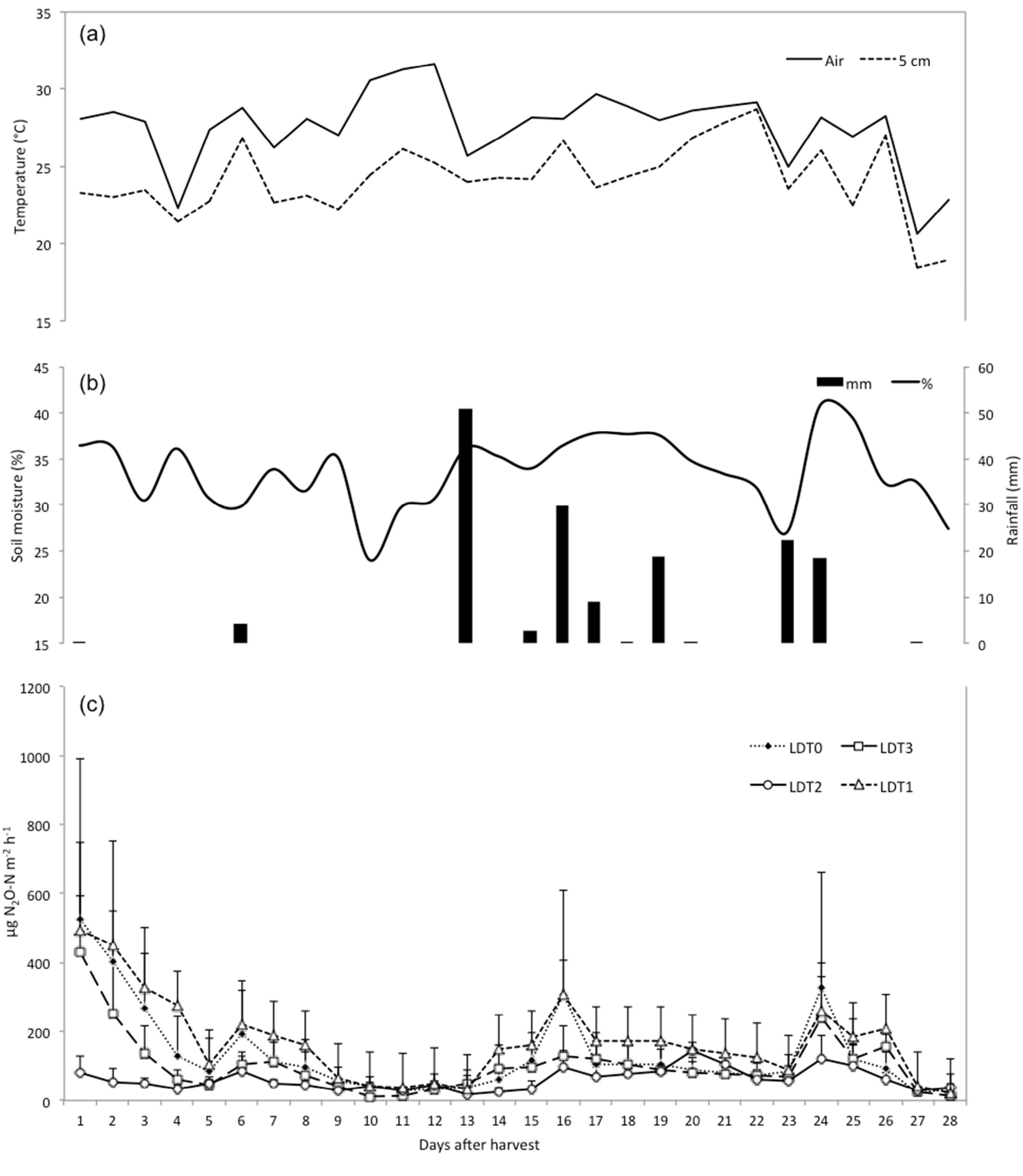

Figure 3.9 - (a) mean daily air temperature and mean soil temperature at 5 cm (a); (b) daily rainfall and soil moisture; (c) N_2O-N fluxes after soybean harvest. Values are mean of five replicates. Vertical bars show the standard error. LDT0 (Control), LDT1 (1/3), LDT2 (2/3), LDT3 (Full amount). Londrina/PR, Brazil. 2013.

The average temperature during the 28 days of evaluation was 28˚C, ranging from 20˚C to 32˚C (Figure 3.9(a)). Rain events were concentrated between the 12^{nd} and 24^{th} days of the experiment, with cumulative rainfall of 157.8 mm and maximum daily rainfall of 51 mm on day 13 (Figure 3.9(b)).

The intensity of N_2O-N emissions in Londrina was the largest among the evaluations performed in this study, ranging on average from 11.60 to 526.64 μg N_2O-N m^{-2} h^{-1} (Figure 3.9(c)). In general, N_2O emissions had the same trend for all treatments evaluated, with highest N_2O-N fluxes observed on the first days following soybean harvest, and later on days 16 and 24. Greater N_2O–N emissions were observed in LDT1, while lower emissions and smallest range were observed in LDT2. The N_2O–N fluxes resulted in average emissions of 133.25, 171.07, 61.48 and 101.97 μg N_2O-N m^{-2} h^{-1} for LDT0, LDT1, LDT2 and LDT3, respectively.

3.3.1.2 Cumulative emissions

The cumulative N_2O-N emissions were calculated for all evaluated treatments considering the whole evaluation period at each site (Figure 3.10). There were no significant differences ($p<0.05$) between crop residue treatments and control in any of the sites evaluated. Therefore, it was not possible to derive an emissions factor for soybean crop residues in any of the treatments and sites evaluated.

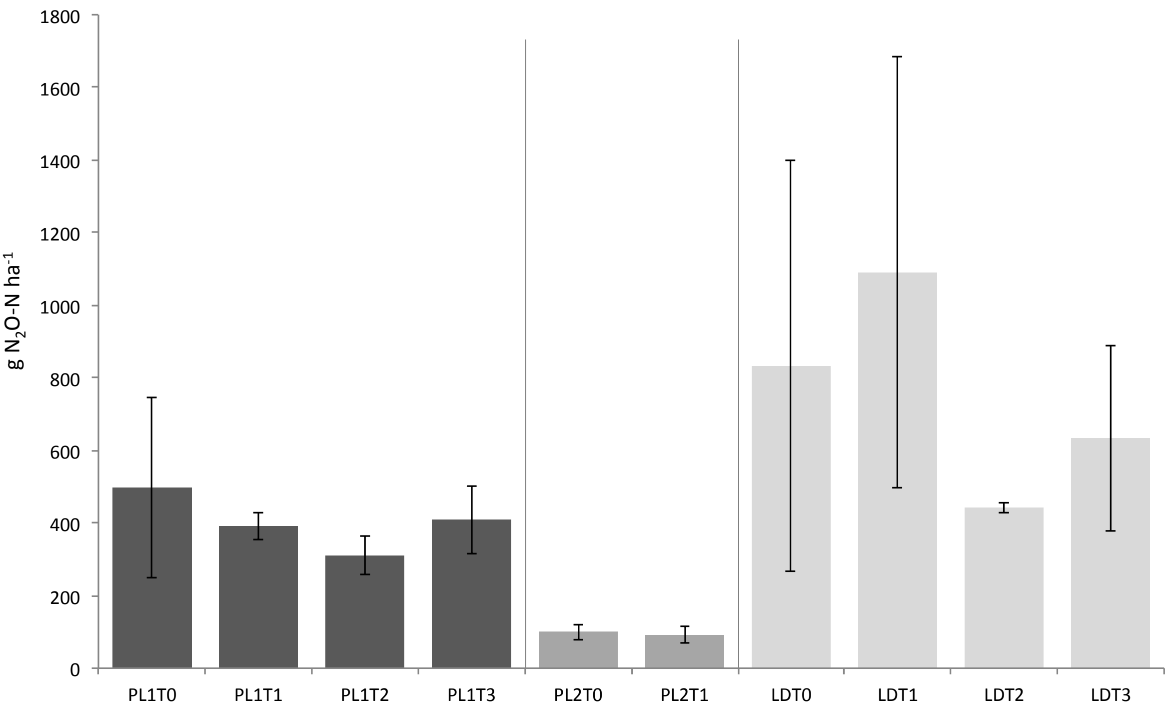

Figure 3.10 - Cumulative N_2O-N emissions and for each treatment in the field experiments after soybean harvest in Primavera do Leste/MT (PL) and Londrina/PR (LD). Values are mean of five replicates. Vertical bars show the standard error. PL1T0 (Control), PL1T1 (1/3), PL1T2 (2/3), PL1T3 (Full amount); PL2T0 (Control), PL2T1 (Full amount); LDT0 (Control), LDT1 (1/3), LDT2 (2/3), LDT3 (Full amount).

Overall, in the experiments in Primavera do Leste/MT differences between treatments, as well as the standard deviation were smaller. As for the field experiment in Londrina/PR, there was a more intense variation in the range of emissions resulting in greater standard errors, especially in LDT0 and LDT1.

3.3.2 Laboratory Incubation

3.3.2.1 Nitrous oxide emissions

An increase in N_2O fluxes was observed in the first days of incubation for all treatments, except for crop residues (Figure 3.11). In general, greater emissions were observed for GL and SL treatments, with emission peaks on the third day after incubation. N_2O fluxes then declined rapidly after day 6 for all treatments. As observed in the field experiments, N_2O fluxes from crop residues were similar to the control treatment.

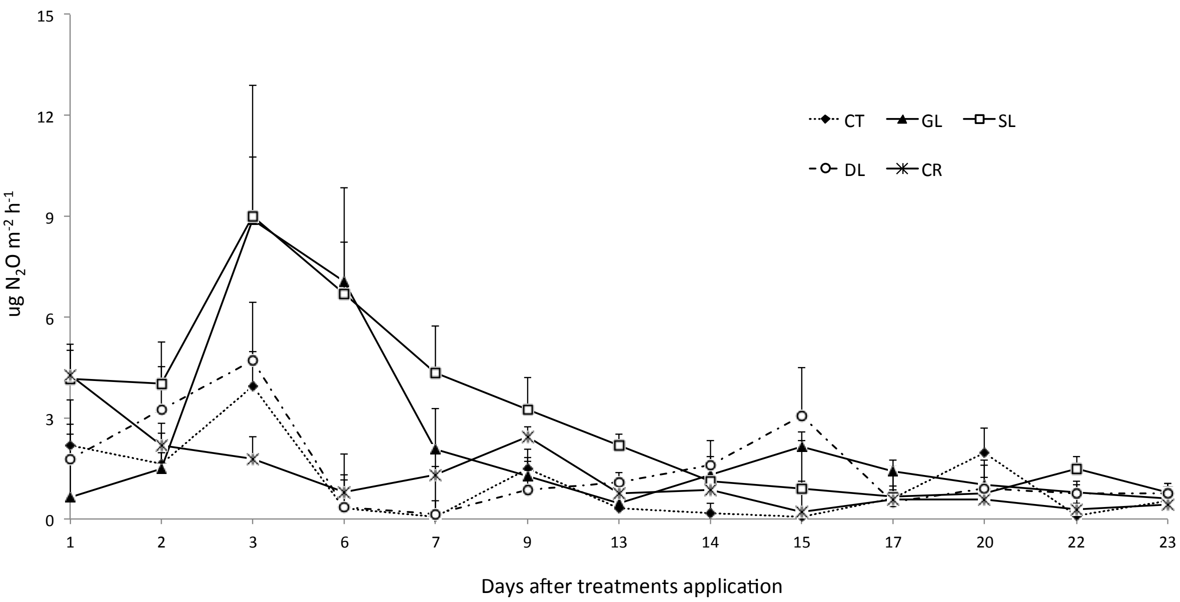

Figure 3.11 - N_2O-N emissions from the soil following treatment application in the laboratory incubation experiment. Values are mean of five replicates. Vertical bars show the standard error. CT (control), GL (green leaves), SL (senescent leaves), DL (desiccated leaves), CR (crop residues).

3.3.2.2 Cumulative emissions

Cumulative N_2O emissions for each incubation treatment in 23 days of laboratory experiment are shown in Figure 3.12. Both treatments with soybean leaves (GL and SL) followed the same trend and increased N_2O emissions in the first days of incubation. CR and DL presented very similar N_2O emissions. CT presented the lowest cumulative emissions during the whole evaluation period.

Similarly to the results in field conditions, N_2O emissions from crop residues did not differ statistically ($p<0.05$) from the control treatment (Figure 3.13). Still, soybean leaves collected before harvest resulted in significant average N_2O emissions in comparison to the other treatments.

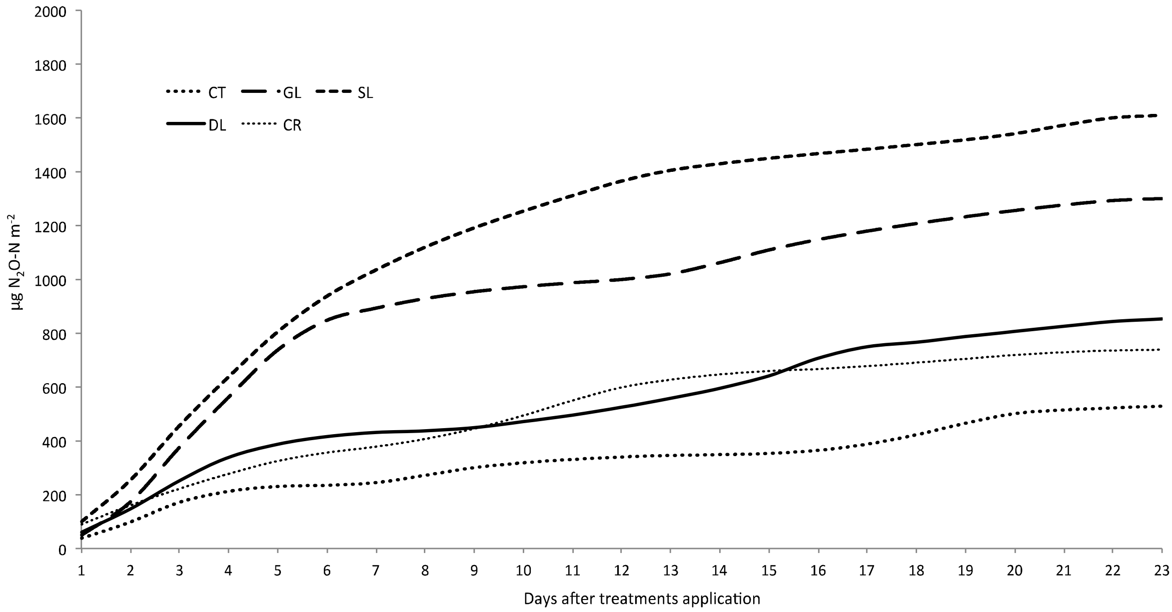

Figure 3.12 - Cumulative N-N_2O emissions for the different treatments in 23 days of the laboratory incubation experiment. CT (control), GL (green leaves), SL (senescent leaves), DL (desiccated leaves), CR (crop residues).

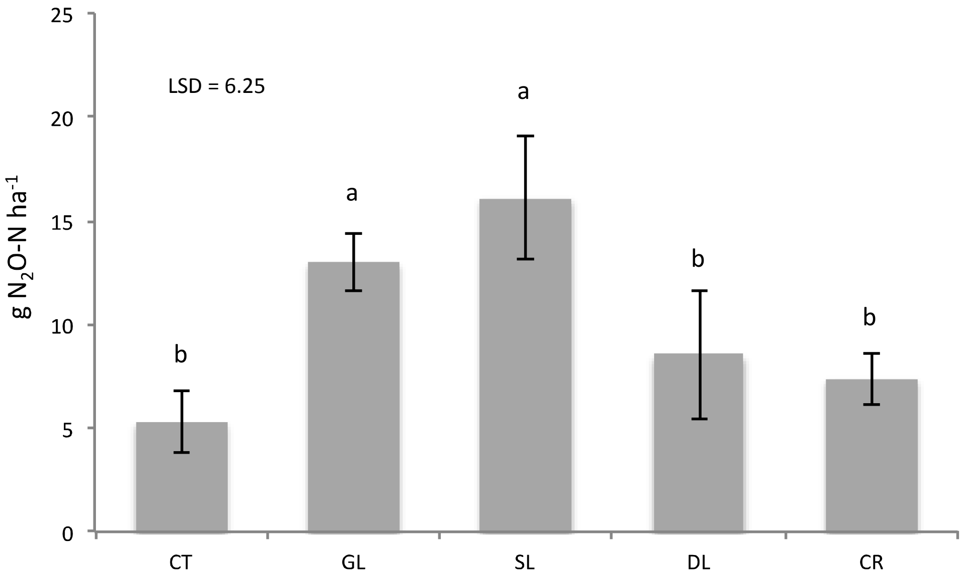

Figure 3.13 - Average N-N_2O emissions for the different treatments in 23 days of the laboratory incubation experiment. Values are mean of five replicates. Vertical bars show the standard error.

Treatments with the same letter do not differ among themselves by Turkey test at 5%. CT (control), GL (green leaves), SL (senescent leaves), DL (desiccated leaves), CR (crop residues)

3.4 Discussion

In both our field and laboratory incubation experiments, N_2O emissions from soybean crop residues did not show significant differences from control treatments. Shan and Yan (2013) performed a meta-analysis with 112 observations of N_2O emissions following crop residue returning on field conditions and also found no statistically significant effect of crop residues on N_2O release compared with control treatments.

Soil N_2O emissions following crop residue returned or left in soil after harvest have been investigated extensively in laboratory and field conditions (HUANG et al., 2004; STEHFEST; BOUWMAN, 2006; NOVOA; TEJEDA, 2006; TOMA; HATANO, 2007; DELGADO et al., 2010; MITCHELL et al., 2013). At the present, postharvest N_2O emissions from soybean crop residues are lacking, especially in tropical conditions.

The influence of legume crops on N_2O emissions has been the focus of many studies in the past, mainly because of the biological N fixation in these species (O'HARA; DANIEL, 1985; VAN BERKUM; KEYSER, 1985; GARCIA-PLAZAOLA et al., 1993; ROSEN et al., 1996; YANG; CAI, 2005). In the 1997 IPCC guidelines biological N fixation by legume crops was considered as one of the sources of N_2O in agricultural systems (IPCC, 1997). However, after a literature review by Rochette and Janzen (2005), analyzing data of N_2O flux from legume crops in field conditions, N_2O emissions from biological N fixation were shown to be minor. Therefore, biological N fixation is not listed anymore as a direct source of N_2O in the latest IPCC guidelines for N_2O inventories (IPCC, 2006). Still, the 1% default emission factor for the decomposition of legume crop residues is considered the same as that for non-legume crop residues.

There are multiple mechanisms by which soybean crop residues can influence soil postharvest N_2O emissions. At first, soil microbial population can quickly assimilate the readily available soluble organic N and C from the residues. The rapid consumption of these nutrients can increase the O_2 consumption in the rhizosphere and result in anaerobic zones (VELTHOF et al., 2002). Then, the facultative anaerobic bacteria utilize the NO_3^- available on the soil as a final electron acceptor and may result in high rates of N_2O emissions (BEAUCHAMP, 1997; WRAGE et al., 2001; BATEMAN; BAGGS, 2005).

Furthermore, the intensity by which crop residues influence nitrification and denitrification process is also dependable on several parameters, including crop characteristics and environmental conditions. Chen et al. (2013) performed a meta-analysis of various publications to assess the impacts of crop residue amendment on soil N_2O emissions and found significant relations to soil and residue attributes, e.g. soil water content, residue C:N ratio, pH, temperature and soil texture.

Soil moisture has a strong influence on soil N_2O emissions because it determines the degree of aeration (SMITH et al., 2003). In our field experiments, maximum N_2O fluxes for all treatments coincided with rainfall events. High WFPS and reduced availability of O_2 favor the formation of anaerobic zones in soil aggregates and the reduction process of NO_3^- via anaerobic respiration increases. The effect of rainfall on N_2O emissions is observed in several other studies during decomposition of crop residues under field conditions (BAGGS et al., 2003; BAGGS; BLUM, 2004). Dobbie and Smith (2001) reported that increasing the WFPS to above 50% reduces the diffusivity of oxygen in soil aggregates and, combined with soil respiration, quickly increase the fraction of the soil under anaerobic conditions. In laboratory incubation studies, higher N_2O emissions from soybean residues were observed when soil moisture conditions were above 50% WFPS (AULAKH et al., 1991; CIARLO et al., 2009).

Crop residues characteristics are another important aspect that influences the decomposition dynamics and consequently the emissions of N_2O. Crop residues with low C/N ratio like soybean are often correlated with increased N_2O emissions in soil by increasing the dissolved organic carbon concentration. In contrast, application of high C/N ratio crop residue stimulates microbial N immobilization during residue decomposition, thus leading to lower N_2O emissions (KAISER et al., 1998; BAGGS et al., 2000; MILLAR; BAGGS, 2004).

In Brazil, soybean desiccation prior harvest has become a common practice. Herbicide application is used in order to anticipate sowing of the following crop, and desiccate weeds and green soybean tissue that can hinder harvest. Desiccation is recommended when soybean reaches its physiological maturity (around R7 stage), when practically all nitrogen has been translocated to the beans. This might explain why we didn’t observe differences between treatments in our field experiments.

The senesced and desiccated residue that remains on field after soybean harvest is unlikely to represent a significant source of N_2O loss above normal background soil emissions (LEMKE et al., 2007). The amount of organic C and N returned to the soil by stalks and husks tend to be relatively small since C/N ratio of these residues are less favorable for rapid mineralization (KUMAR; GOH, 2000; PEOPLES et al., 2009).

This hypothesis was further supported by our incubation experiment. In laboratory conditions, N_2O emissions increased in the first days of incubation when green leaves and senescent leaves where added to the soil. The same did no occur when desiccated leaves or crop residues were incubated. Leaves have a higher N content, less lignin and decomposes rapidly resulting in a net N mineralization in soil, while the stalks during decomposition immobilize N (QUEMADA; CABRERA, 1995; ISAAC et al., 2000; COBO et al., 2002; THIPPAYARUGS et al., 2008).

Uchida and Akiyama (2013) compiled a list of studies that measured soybean postharvest N_2O emissions in field conditions. The authors estimated the percentage of N in crop residues emitted as N_2O to calculate the emission factors (EFs). As a result, they found an average EF of 1.3 ± 2.7%, slightly higher than the IPCC default Tier 1 value. However, the median value was 0.2%, indicating relatively low emission factors for soybean crop residues. Nevertheless, values ranged from 0.0% up to 10.0%, showing a great variation in the results.

In most of these studies emissions from soybean residues where analyzed in the context of a crop rotation or different crop management systems (e.g. conventional or zero tillage), thus making it difficult to attribute the reported N_2O emissions only to the residues remaining on the field. Nevertheless, our results are in accordance with the studies reported for Brazilian conditions, showing that the effects of soybean residues on N_2O emissions are minimal (JANTALIA et al., 2008; ESCOBAR et al., 2010).

Another aspect that can affect N_2O emissions, but has not been directly quantified in this study, is the decomposition of soybean roots and nodules belowground. Since the chambers were installed immediately after harvest, these compartments may have affected the N_2O emissions. Most of the studies that examined effects of crop residues on N_2O emissions focused on aboveground residues (HUANG et al., 2004; MILLAR; BAGGS, 2004; GARCIA-RUIZ; MUHAMMAD et al., 2011; ZHU et al., 2013). Root residues are important in terms of their total N and C contents and impacts on nutrient cycling (MCNEILL; FILLERY, 2008), and their different biochemical compositions may influence different patterns of decomposition and N_2O emissions (PUGET; DRINKWATER, 2001)

Although nodule and roots remain belowground after soybean harvest, some studies have reported that decomposition of these compartments has grater effect on N_2O emissions in the pre-harvest period. In a pot experiment conducted by Yang and Cai (2005), about 94% of total N_2O emissions during soybean growth were concentrated in the final development stages. The authors concluded that, during soybean ripening stage, available nitrogen was released into the soil from the decaying of senescent roots and nodules, resulting in increased N_2O emissions. Additionally, stimulatory effect on N_2O emissions was observed when the aerial parts of soybean plants were harvested in different stages. Ciampitti et al. (2008) observed similar results in a field experiment evaluating soil N_2O emissions during soybean phonological stages. The authors reported that only 28% of total N_2O emissions could be attributed to the postharvest period.

Further field experiments in tropical conditions are necessary to assess the specific contribution of senescent roots and nodules in the total postharvest N_2O emissions in soybean cultivation systems.

3.5 Conclusions

This is one of the first studies to evaluate the specific effect of different amounts of soybean crop residues on postharvest N_2O emissions in Brazilian conditions. Our findings show that N_2O emissions from the senesced and desiccated residue that remains on field after soybean harvest are unlikely to represent a significant direct source of N_2O to the atmosphere.

Despite the wide differences in the magnitude of N_2O emissions, our results indicate that the IPCC methodology for estimating N_2O emissions from soybean crop residues may provide overestimations for the Brazilian conditions.

More studies in different soil, climate and management conditions are necessary to better understand the profile of N_2O emissions during the soybean phenological cycle and after harvest.

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4 FINAL CONSIDERATIONS

The main objective of this research project was to evaluate the sources of GHG in the life cycle of soybean production in Brazil and provide specific information on N_2O emissions following the decomposition of crop residues in field conditions. This is one of the few studies in Brazil with soybean cultivation data assessed at farm level and to evaluate the specific effect of different amounts of soybean crop residues on postharvest N_2O emissions in Brazilian conditions.

The evaluation of emissions and main sources of GHG in soybean cultivation in the State of Mato Grosso indicated that the largest source of GHG in the soybean production is the decomposition of crop residues (36%), followed by fuel use (19%), fertilizer application (16%), liming (13%), pesticides (7%), seeds (8%) and electricity consumed at the farms (<1%). The average GHG emissions considering the three crop years were 0.186 kg of CO_2eq kg^{-1} of soybean produced. No significant differences were found when the results were categorized by land use intensity and production areas.

The quantification of postharvest N_2O emissions from soybean crop residues decomposition in different climate regions and harvest periods in the South Central region of Brazil, indicated that N_2O emissions from the senesced and desiccated residue that remains on field after soybean harvest are unlikely to represent a significant direct source of N_2O to the atmosphere. Besides, despite wide differences in the magnitude of N_2O emissions, our results indicate that the IPCC methodology for estimating N_2O emissions from soybean crop residues may provide overestimations for the Brazilian conditions.

The growing concerns with global warming and the emergence of international policies and regulations regarding the sustainability of supply chains, demand a more precise quantification of GHG emissions in the life cycle of agricultural products and the determination of specific emission factors within the production reality of a country. The lack of conclusive and consistent results for GHG emissions in agriculture presents a challenge for researchers and policy-makers. Moreover, the use of life-cycle assessment with a country-specific approach is needed for a more accurate evaluation of the environmental impacts of biobased products.

In this context, the results presented in this research indicate that GHG emissions associated with the Brazilian soybean production could be significantly lower than those estimated with the use of default emission factors proposed by the IPCC. This is even more relevant for the biodiesel sector, since a reduction in the life cycle GHG emissions could make possible to meet some of the environmental criteria in international policies, and therefore enable exports and access to new markets. However, more studies in different soil, climate and management conditions are necessary to better understand the profile of N_2O emissions in other regions of Brazil.

Finally, the results generated by this research project can be used as a basis for other scientific studies where soybeans produced in Brazil are part of the system. Additionally, the results provide relevant and specific information to producers, industry and scientific community regarding GHG emissions in soybean production in Brazil. Decision makers and other stakeholders in the production chain can use this set of information in order to assist them on the design of appropriate measures for the sustainable development of soybean cultivation in the country.