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Greenhouse gas assessment of soybean production: implications of land use change and different cultivation systems

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ABSTRACT

The increase in soybean production as a source of protein and oil is being stimulated by the growing demand for livestock feed, food and numerous other applications. Significant greenhouse gas (GHG) emissions can result from land use change due to the expansion and cultivation of soybean. However, this is complex to assess and the results can vary widely. The main goal of this article is to investigate the life-cycle GHG balance for soybean produced in Latin America, assessing the implications of direct land use change emissions and different cultivation systems. A life-cycle model, including inventories for soybean produced in three different climate regions, was developed, addressing land use change, cultivation and transport to Europe. A comprehensive evaluation of alternative land use change scenarios (conversion of tropical forest, forest plantations, perennial crop plantations, savannah and grasslands), cultivation (tillage, reduced tillage and no-tillage) and soybean transportation systems was undertaken. The main results show the importance of land use change in soybean GHG emissions, but significant differences were observed for the alternative scenarios, namely 0.1–17.8 kg CO_2eq kg^{-1} soybean. The original land choice is a critical issue in ensuring the lowest soybean GHG balance and degraded grassland should preferably be used for soybean cultivation. The highest GHG emissions were calculated for tropical moist regions when rainforest is converted into soybean plantations (tillage system). When land use change is not considered, the GHG intensity varies from 0.3 to 0.6 kg CO_2eq kg^{-1} soybean. It was calculated that all tillage systems have higher GHG emissions than the corresponding no-tillage and reduced tillage systems. The results also show that N_2O emissions play a major role in the GHG emissions from cultivation, although N_2O emission calculations are very sensitive to the parameters and emission factors adopted.

1. Introduction

The increase in soybean production as a source of protein and oil is being stimulated by the growing demand for livestock feed, food and numerous other applications (e.g. biodiesel, bioplastics and lubricants). The global production of soybean more than doubled in the period 1995–2011 to a new record volume of 263.8 million tonnes (2010/11). The major world soybean producers in 2010/11 were the United States of America (90.6 million tonnes), Brazil (73.8 million tonnes) and Argentina (49.5 million tonnes). There was an impressive growth in soybean production in Brazil and Argentina, mainly associated with an expansion in cultivation areas of 126% and 209% respectively during the period 1995–2011 (Product Board MVO, 2011).

Important environmental concerns have emerged regarding carbon stock changes due to the land use changes (LUC) needed for the expansion of the soybean cultivation area. LUC, together with soybean cultivation, can result in significant greenhouse gas (GHG) emissions. However, the assessment of soybean GHG intensity is complex and the results can vary widely due to several factors, namely: i) the uncertainty of soil emissions (Smeets et al., 2009), in particular nitrous oxide (N_2O) and carbon dioxide (CO_2) emissions due to LUC (Kendall and Chang, 2009); ii) the diversity of soil management practices (e.g. tillage, reduced tillage, no-tillage), material inputs, locations and yields (Kim and Dale, 2009); and iii) the different distances and types of soybean transport in question.

The life-cycle (LC) GHG balance of soybean-based products has been assessed in various publications in recent years, e.g. Alvarenga et al. (2012), Castanheira and Freire (2012), Mourad and Walter (2011), Prudêncio da Silva et al. (2010), Omni Tech International (2010), Tsoutsos et al. (2010), Panichelli et al. (2009), Lehuger

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et al. (2009), van Dam et al. (2009), Reinhard and Zah (2009), Dalgaard et al. (2008), Reijnders and Huijbregts (2008), Searchinger and Heimlich (2009), Huo et al. (2008, 2009), Kim and Dale (2009), Miller et al. (2007). However, only some studies accounted for carbon emissions from direct LUC and a wide range of results was reported (e.g. Kim and Dale, 2009; Searchinger and Heimlich, 2009; Prudêncio da Silva et al., 2010; Castanheira and Freire, 2012; van Dam et al., 2009; Panichelli et al., 2009; Reinhard and Zah, 2009; Reijnders and Huijbregts, 2008; Dalgaard et al., 2008). The differences in the results are mostly related to LUC modeling assumptions, namely: i) the LUC area, ii) previous land use (e.g. forest, savannah, grassland), iii) the duration of land use for soybean production (e.g. 10 or 25 years) and iv) LUC location (Ponsioen and Blonk, 2012). The wide range of results shows that producing general figures to quantify direct LUC in the GHG emissions balance is difficult and each case should be addressed individually (Börjesson and Tufvesson, 2011; Cherubini, 2010).

The influence of management practices on LC GHG emissions from agricultural products is a challenging issue (Flysjö et al., 2012; Hokazono and Hayashi, 2012; Chamberlain et al., 2011; Knudsen et al., 2010; Basset-Mens et al., 2007). A small number of studies have addressed alternative agricultural systems in order to assess the effects of different soybean management practices and identify the greatest source of GHG emissions in each system. In addition, N_2O emissions from nitrogen (N) additions and mineralization of soil organic matter were identified as a major contributor to the soybean GHG balance (Brandão et al., 2010; Snyder et al., 2009; Reijnders and Huijbregts, 2008; Landis et al., 2007), since N_2O has a high Global Warming Potential in relation to CO_2 (1 kg N_2O is equivalent to 298 kg CO_2eq, for a 100 year time-horizon). However, there are significant uncertainties in N_2O emission calculations (IPCC, 2006), particularly for N_2O emissions originating in the fraction of N lost via runoff, leaching and volatilization (Reijnders and Huijbregts, 2011). In addition, only a few studies have assessed how this influences the soybean GHG balance (Del Grosso et al., 2009; Smeets et al., 2009; Snyder et al., 2009; Panichelli et al., 2009; Smaling et al., 2008; Reijnders and Huijbregts, 2008; Miller, 2010; Miller et al., 2006).

The transportation of soybean can represent an important contribution to the GHG balance (Prudêncio da Silva et al., 2010). Soybean is transported long distances by road and 42% of the soybean produced in Brazil (and 25% in Argentina) was exported for processing in other countries (Product Board MVO, 2011). Although long distance transoceanic transport might increase GHG emissions slightly, Prudêncio da Silva et al. (2010) showed that the place of origin of soybean within Brazil strongly affects its environmental impact, due to the current predominance of road transport.

Alternative LUC scenarios, cultivation and transportation systems can be critical in terms of soybean LC GHG intensity. This has not been addressed comprehensively in previous research. The main purpose of this article is to present an LC GHG assessment of soybean produced in Latin America (LA) and exported to the European Union (EU). A comprehensive evaluation of the implications of 45 scenarios (a combination of alternative LUC, cultivation systems, soil types and climate regions) was undertaken. A sensitivity analysis to field N_2O emissions was implemented, since there is significant uncertainty regarding the emission factors and partitioning fractions (volatilization and leaching factors) adopted in calculations (IPCC, 2006). Default, maximum and minimum values from the IPCC (2006) for emission factors and partitioning fractions were adopted to assess the influence on field N_2O emission calculations. An analysis of the effect of soybean origins on GHG intensity was also implemented for various types of lorry and distances between plantations and ports. The article is organized in 4 sections, including this introduction. Section 2 presents the LC model and inventory for soybean, including alternative LUC scenarios, soybean cultivation and transportation systems. Section 3 discusses the main results and Section 4 draws the conclusions together.

2. Life-cycle model and inventory

A life-cycle GHG assessment of soybean was implemented, based on the principles and framework of the life cycle assessment (LCA) methodology (ISO, 2006). This assessment comprises the compilation and evaluation of the inputs, outputs and potential environmental impacts (without predicting the absolute or precise environmental impacts) of the product system throughout its life-cycle (ISO, 2006). The GHG intensity of soybean was assessed on the basis of the LC model and inventory (inputs and outputs) described in this section. The GHG intensity (GHG emissions expressed as CO_2 equivalent) was calculated by multiplying emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) by their corresponding global warming potential (100-year time horizon) (IPCC, 2007). It was found that other GHG emissions occur in negligible amounts in the soybean system analyzed and were, therefore, not pursued.

The LC model includes GHG emissions associated with direct LUC, soybean cultivation and the transport of soybean (from plantations to ports and from ports to Portugal). Emissions related to upstream manufacturing of inputs were included although the contribution from the manufacture of capital equipment was assumed to be negligible. Indirect LUC emissions were not addressed, given the lack of available data on the indirect conversion of soils and since there is no consensus on how to account for this (European Commission, 2010a).

The functional unit chosen was 1 kg of soybean produced in LA and exported to Europe. The EU consumed about 14 million tonnes of soybean in 2010 (93% imported from LA and the US) and 89% of this amount was consumed by the crushing industry (Product Board MVO, 2011). In the EU-27 imported soybean is predominately used to produce soybean meal for the livestock feed industry since, without the protein provided by soybean, Europe would not be able to maintain its current level of livestock productivity (Krautgartner et al., 2012). The EU-27 is the second largest soybean importer, surpassed only by China (USDA, 2012). Brazil is the EU's leading supplier of soybean (40–70%) and Argentina is the leading supplier of soybean meal (50–55%) (Krautgartner et al., 2012).

2.1. Land use change scenarios and carbon stock changes

Fig. 1 shows the 45 LUC scenarios. These scenarios were established on the basis of a combination of alternative previous land uses (conversion of tropical forest land, forest plantations, perennial crop plantations, savannah and grasslands), different cultivation systems (tillage, reduced tillage and no-tillage), climate (tropical moist, and warm temperate, moist and dry) and soil characteristics (low and high activity clay soils). Three climate regions and two soil types were selected because they represent the most important area in LA (Brazil and Argentina) where soybean is produced. In Brazil (2009/2010) about 83% of soybean was produced in the Central-West (tropical moist climate) and South (warm temperate moist climate) regions, which are characterized by low activity clay soils (IBGE, 2012; European Commission, 2010b). In Argentina, about 76% of soybean (2009/2010) was produced in the provinces of Buenos Aires, Córdoba and Santa Fé in the Las Pampas region, characterized by a warm temperate dry climate and high activity clay soils (Product Board MVO, 2011; European Commission, 2010b). Concerning savannahs and grasslands conversion, different management options were also included, namely

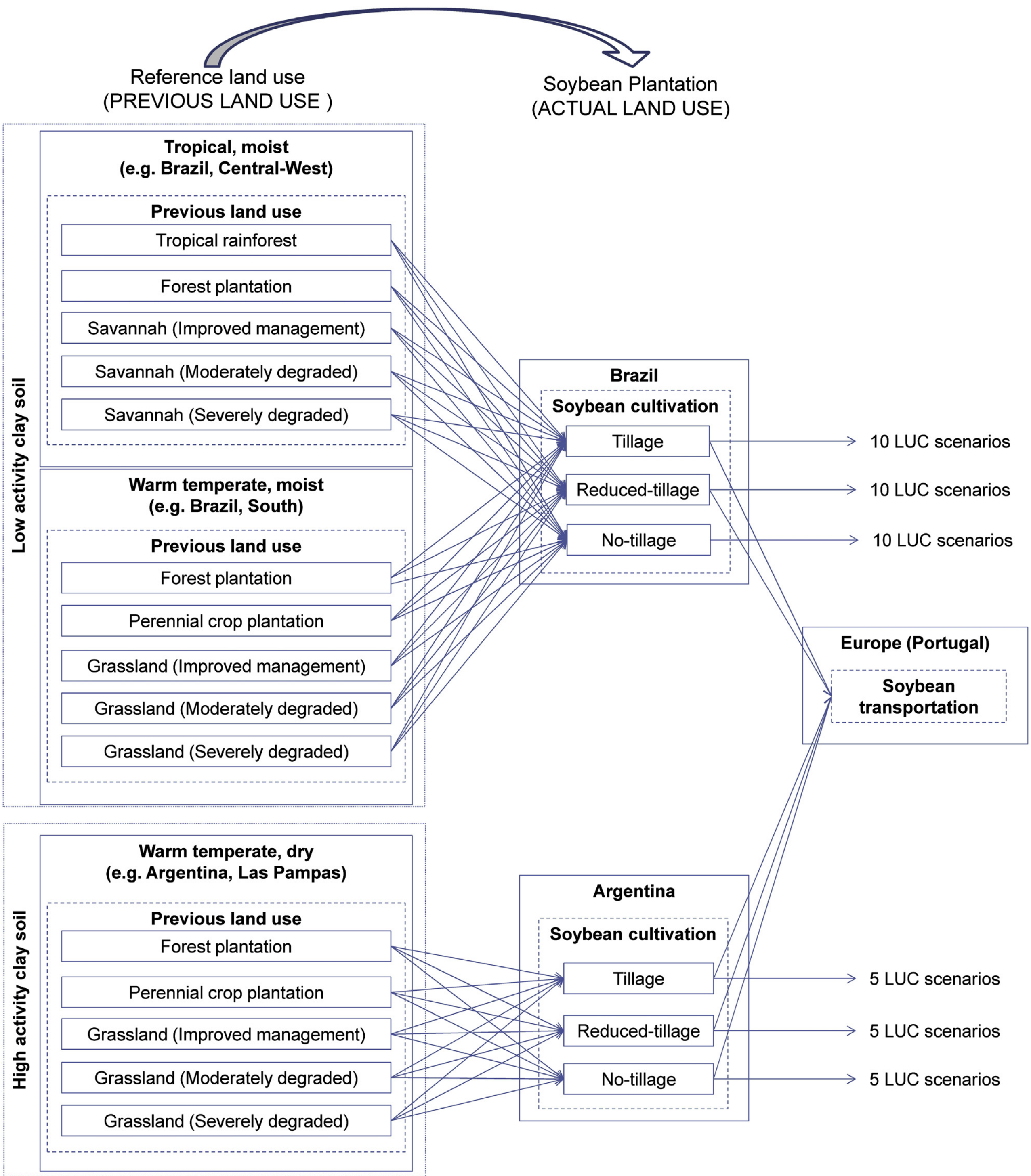

Fig. 1. The forty-five land use change (LUC) scenarios.

improved management (IM), moderately degraded (MD) and severely degraded (SD).

Forty-five scenarios were considered, since the soybean area increased significantly during the period 1991–2011 in Brazil (9.6–23.9 Mha) and Argentina (4.8–18.8 Mha) (FAO, 2012). Panichelli et al. (2009) showed that in Argentina the expansion of the soybean area from 2000 to 2005 occurred in former cropland (32%), pasture land (27%), savannahs (19%) and forests (22%). Regarding soybean expansion in Brazil, Macedo et al. (2012) showed that from 2001 to 2005 this took place in rainforest land (26%) and scrubland (74%) and from 2005 to 2009 mainly in scrubland (91%). Moreover, Dros (2004) forecasted the expansion of the soybean area in Brazil and Argentina up to 2020 as 13.2 Mha in Brazil and 5.4 Mha in Argentina.

GHG emissions from carbon stock changes caused by LUC were calculated using Eq. (1), following the IPCC Tier 1 and Renewable Energy Directive (IPCC, 2006; European Commission, 2009, 2010b). Annualized GHG emissions from carbon stock change due to LUC were found by dividing by the time period in which C pools are expected to reach equilibrium after land-use conversion (IPCC default: 20 years).

$$e_l = (CS_R - CS_A) \times 44/12 \times 1/20 \times 1/P \quad (1)$$

in which e_l (t CO_2eq t^{-1} soybean) are the annualized GHG emissions from carbon stock change due to LUC; CS_R (t C ha^{-1}) is the carbon stock associated with the reference (previous) land use; CS_A (t C ha^{-1}) is the carbon stock associated with the actual land use (soybean cultivation) and P (t soybean ha^{-1} $year^{-1}$) is the productivity. In order to calculate CS_R and CS_A, Eq. (2) was applied

$$CS_i = SOC_i + C_{vegi} = (SOC_{ST} \times F_{LUi} \times F_{MGi} \times F_{I_i}) + C_{vegi} \quad (2)$$

in which SOC_i (t Cha^{-1}) is the soil organic carbon in the reference (SOC_R) and actual land use (SOC_A), C_{vegi} (t C ha^{-1}) is the above and below ground vegetation carbon stock in living biomass and in dead organic matter in the reference (C_{vegR}) and actual land use (C_{vegA}), SOC_{ST} (t Cha^{-1}) is the standard soil organic carbon and F_{LU}, F_{MG} and F_I are factors that reflect the difference in SOC_{ST} associated with the type of land use (F_{LU}), principle management practice (F_{MG}) and different levels of carbon input to soil (F_I).

Table 1 presents the SOC_R, calculated, as well as the C_{vegR} and F_{LU}, F_{MG}, F_I factors adopted from the European Commission (2010b). Regarding actual land use, C_{vegA} is equal to zero (since soybean is harvested annually). Table 2 presents the SOC_A calculated and the F_{LU}, F_{MG}, F_I factors adopted (European Commission, 2010b). SOC_{ST} values were selected for the 3 aforementioned climate regions and 2 types of soils.

2.2. Soybean cultivation systems

Alternative life-cycle inventories (LCI) for different soybean cultivation systems in Brazil and Argentina were implemented, based on transparent studies providing important quantitative information (FNP, 2012; Cavalett and Ortega, 2009, 2010; Ortega et al. 2005; Dalgaard et al., 2008; Panichelli et al., 2009). Table 3 shows the annual production and main inputs of 3 types of cultivation in Brazil and Argentina: no-tillage (NT), reduced tillage (RT) and tillage (T). It should be noted that NT is now widespread in Brazil and Argentina (more than 70%).

The LCI for NT soybean cultivation in Brazil was based on official data for agricultural operations and inputs for transgenic Roundup Ready (RR) soybean production in Paraná state (FNP, 2012). In Paraná, more than 90% of soybean is RR produced under NT. An RT LCI was adopted from Cavalett and Ortega (2009, 2010). For soybean cultivation under tillage in Brazil, an LCI was produced based on the intensive system described by Ortega et al. (2005), characterized by the intensive use of pesticides and agricultural machinery. Pesticide use was calculated based on the input data and information on individual trade products, doses and main active ingredients. The type of fertilizers used in soybean plantations was adopted from Brazilian statistics for the fertilizers sector. The diesel consumption considered for the NT soybean system was calculated based on the specific consumption for agricultural operations provided by Romanelli et al. (2012). In all cultivation systems, a residual effect of lime application for 5 years was considered; the values shown in Table 3 are the corresponding annual values.

The main inputs of NT soybean production in Argentina were based on the LCI presented by Dalgaard et al. (2008). Concerning RT and T soybean production in Argentina, the LCI data was adopted from Panichelli et al. (2009), but adjustments were made for soybean yields and pesticides. The yields were calculated for RT (2677 kg ha^{-1}) and T (2248 kg ha^{-1}) based on the average yield of 2591 kg ha^{-1} and the respective RT and T shares in national production (79.9% and 20.1%) (Panichelli et al., 2009). It was also considered that the soybean yield is about 17%–20% higher under RT than T systems, based on information for cultivation in other countries (Opara-Nadi, 1993). Regarding pesticides, it was considered that pesticide use is higher in RT systems (Deike et al., 2008; Friedrich, 2005), in particular the use of herbicides (2,4D is typically consumed in RT) (Tosi et al., 2005). The use of glyphosate was calculated as the weighted quantity of glyphosate for both systems, considering the national shares of RT and T production systems (79.9% and 20.1%).

Table 1
Carbon stocks of previous (reference) land use (CS_R): Soil organic carbon (SOC_R) and vegetation carbon stock (C_{vegR}) for 3 climate regions (European Commission, 2010b).

Soil type	Climate region	R: Reference land use		SOC					C_{vegR} (t Cha^{-1})	CS_R (t Cha^{-1})
				SOC_{ST}[g] (t Cha^{-1})	F_{LU}[h]	F_{MG}[h]	F_I[h]	SOC_R (t Cha^{-1})		
Low activity clay soils	Tropical, moist (Brazil, Central-West)	Tropical rainforest[a]		47	1	–	–	47	198.0	245
		Forest plantation[b]				1.0	1.0	47	58.0	105
		Savannah (scrubland)	IM[c]			1.17	1.11	61	53.0	114
			MD[d]			0.97	1.0	46		99
			SD[e]			0.7	1.0	33		86
	Warm temperate, moist (Brazil, South)	Forest plantation		63	1	1.0	1.0	63	31.0	94
		Perennial crop (RT[f])			1	1.08	1.0	68	43.2	111
		Grassland	IM[c]		1	1.14	1.11	80	6.8	87
			MD[d]		1	0.95	1.0	60		67
			SD[e]		1	0.7	1.0	44		51
High activity clay soils	Warm temperate, dry (Argentina, Las Pampas)	Forest plantation		38	1	1.0	1.0	38	31.0	69
		Perennial crop (RT[f])			1	1.02	1.0	39	43.2	82
		Grassland	IM[c]		1	1.14	1.11	48	3.1	51
			MD[d]		1	0.95	1.0	36		39
			SD[e]		1	0.7	1.0	27		30

[a] >30% canopy cover.
[b] *Eucalyptus* sp.
[c] Improved management.
[d] Moderately degraded.
[e] Severely degraded.
[f] Reduced tillage.
[g] Standard soil organic carbon.
[h] Factors that reflect the difference in SOC_{ST} associated with type of land use (F_{LU}), principle management practice (F_{MG}) and different levels of carbon input to soil (F_I).

Table 2
Carbon stocks of soybean plantations, actual land use (CS_A), and soil organic carbon (SOC_A) for 3 climate regions (European Commission, 2010b).

Soil type	Climate region	Cultivation system	SOC					CS_A (t Cha^{-1})
			SOC_{ST}[d] (t Cha^{-1})	F_{LU}[e]	F_{MG}[e]	F_I[e]	SOC_A (t Cha^{-1})	
Low activity clay soils	Tropical, moist (Brazil, Central-West)	NT[a]	47	0.48	1.22	1	28	28
		RT[b]		0.48	1.15	1	26	26
		T[c]		0.48	1.0	1	23	23
	Warm temperate, moist (Brazil, South)	NT[a]	63	0.69	1.15	1	50	50
		RT[b]		0.69	1.08	1	47	47
		T[c]		0.69	1.0	1	43	43
High activity clay soils	Warm temperate, dry (Argentina, Las Pampas)	NT[a]	38	0.8	1.1	1	33	33
		RT[b]		0.8	1.02	1	31	31
		T[c]		0.8	1.0	1	30	30

[a] No-tillage.
[b] Reduced tillage.
[c] Tillage.
[d] Standard soil organic carbon.
[e] Factors that reflect the difference in SOC_{ST} associated with type of land use (F_{LU}), principle management practice (F_{MG}) and different levels of carbon input to soil (F_I).

2.2.1. GHG emissions: agricultural operations and field emissions

Regarding GHG emissions from soybean cultivation, diesel combustion from agricultural operations (mainly CO_2, calculated based on Nemecek et al. (2007)) together with field CO_2 emissions from liming (IPCC, 2006) and N_2O emissions (from N additions to soils and mineralization of N in soil organic matter following land-use change in mineral soils) were considered. GHG emissions associated with the production of agricultural inputs were also accounted for using emission factors for pesticides (Nemecek et al., 2007), limestone (Kellenberger et al., 2007), fertilizers (Patyk and Reinhardt, 1997; Nemecek et al., 2007) and diesel (Jungbluth, 2007).

The IPCC Tier 1 methodology (IPCC, 2006) was used to calculate direct and indirect N_2O emissions. Direct N_2O emissions occur directly from the soils to which the N is added/released (from anthropogenic N inputs or N mineralization). Indirect N_2O emissions occur through two pathways (IPCC, 2006): i) following volatilization of NH_3 and NO_x from the soil and the subsequent deposition of these gases and their products (NH_4^+ and NO_3^-) to soils and waters and ii) after leaching and runoff of N, mainly as NO_3^-.

Direct and indirect N_2O emissions were calculated using Eqs. (3) and (4) (IPCC, 2006) for each alternative cultivation system,

$$N_2O_{Direct} = (F_{SN} + F_{CR} + F_{SOM}) \times EF_1 \times 44/28 \quad (3)$$

$$N_2O_{Indirect} = [F_{SN} \times Frac_{GASF} \times EF_4 + ((F_{SN} + F_{CR} + F_{SOM}) \times Frac_{LEACH} \times EF_5)] \times 44/28 \quad (4)$$

in which F_{SN} is the annual amount of synthetic fertilizer N applied to soils (kg N ha^{-1}), F_{CR} is the annual amount of N in crop residues (above-ground and below-ground) returned to soils (kg N ha^{-1}), F_{SOM} is the annual amount of N in mineral soils that is mineralized (the process by which organic N in soil organic matter is converted to inorganic forms: NH_4^+ and NO_3^-), in association with loss of soil C from soil organic matter as a result of changes to land use or management (kg N ha^{-1}). Organic C and N are closely linked in soil organic matter and when soil C is lost through oxidation as a result of LUC, this loss will be accompanied by a simultaneous mineralization of N (IPCC, 2006). EF_1, EF_4 and EF_5 are the emission factors

Table 3
Main inputs and production (values per ha and year) of soybean cultivation systems in 3 climate regions: No-Tillage (NT), reduced tillage (RT) and tillage (T).

Inputs	Brazil tropical and warm temperate moist regions			Argentina warm temperate dry region		
	NT[a]	RT[b]	T[c]	NT[a]	RT[b]	T[c]
	FNP (2012)	Cavalett and Ortega (2009, 2010)	Ortega et al. (2005)	Dalgaard et al. (2008)	Panichelli et al. (2009)	
Pesticides (kg)						
Pesticides, unspecified	0.2	1.1	1.0		0.13	0.13
Sulfonyl [urea-compounds]					0.003	0.003
Organophosphorus-compounds	1.4	1.0	1.2	0.8	0.42	0.42
Pyretroid-compounds	0.01	0.01	0.01	0.02	0.11	0.11
Glyphosate solution	1.0	1.4	1.2	2.6	2.6	1.1
2,4 D	1.2	1.6	1.4	0.3	0.3	
Triazine-compounds					0.01	0.01
Cyclic N-compounds	0.1	0.02	0.02		0.01	0.01
Benzimidazole-compound	0.1	0.01	0.01			
[Thio]carbamate-compound	0.03	0.01	0.01			
Limestone (kg)	40	75	200			
Fertilizers (kg)						
Single super phosphate, as P_2O_5	30	79	30			
Triple super phosphate, as P_2O_5	30			38	5.0	5.0
Monoammonium phosphate, as P_2O_5					5.2	5.2
Potassium chloride, as K_2O	60	79	30			
Potassium sulphate, as K_2O			75			
Diesel (L)	51	54	94	35	35	62
Products						
Soybean (kg)	2940	2830	2400	2630	2677	2248

[a] No-tillage.
[b] Reduced tillage.
[c] Tillage.

Table 4
Parameters and emission factors for N_2O emission calculation (IPCC, 2006).

				Brazil			Argentina		
				NT[d]	RT[e]	T[f]	NT[d]	RT[e]	T[f]
F_{SN}: N input from synthetic fertilizer (kg N ha^{-1})				0	0	0	0	1.1	1.1
F_{CR}: N in crop residues (kg N ha^{-1})				39.7	38.7	34.8	36.6	36.6	32.8
F_{SOM}: N mineralized (kg N ha^{-1})	No LUC			0	0	0	0	0	0
	Tropical region	Tropical rainforest		65	70	81			
		Forest plantation		65	70	81			
		Savannah (scrubland)	IM[a]	112	117	128			
			MD[b]	60	65	77			
			SD[c]	18	23	34			
	Warm temperate regions	Forest plantation		43	54	65	15	23	25
		Perennial crop		60	70	82	18	26	28
		Grassland	IM[a]	99	109	121	49	57	59
			MD[b]	33	43	55	9	17	19
			SD[c]			2			
$Frac_{GASF}$[g] (kg NH_3–N + NO_x–N kg^{-1} N applied)				0.1 (0.03–0.3)					
$Frac_{LEACH}$[h] (kg N kg^{-1} N additions)				0.3 (0.1–0.8)					
EF_1[i] (kg N_2O–N kg^{-1} N)				0.01 (0.003–0.03)					
EF_4[i] (kg N_2O–N (kg NH_3–N + kg NO_x–N volatilized)$^{-1}$)				0.01 (0.002–0.05)					
EF_5[i] (kg N_2O–N kg^{-1} N leaching/runoff)				0.0075 (0.0005–0.025)					

[a] Improved management.
[b] Moderately degraded.
[c] Severely degraded.
[d] No-tillage.
[e] Reduced tillage.
[f] Tillage.
[g] Fraction of F_{SN} that volatilizes as NH_3 and NO_x.
[h] Fraction of all N added/mineralized that is lost through leaching and runoff.
[i] Emission factors adopted for N_2O emissions from N additions, from atmospheric deposition of N on soils and water surfaces and from N leaching and runoff, respectively.

adopted for N_2O emissions from N additions (kg N_2O–N kg^{-1} N input), from atmospheric deposition of N on soils and water surfaces (kg N_2O–N (kg NH_3–N + NO_x–N volatilized)$^{-1}$) and from N leaching and runoff (kg N_2O–N (kg N leached and runoff)$^{-1}$), respectively. $Frac_{GASF}$ is the fraction of F_{SN} that volatilizes as NH_3 and NO_x, kg N volatilized kg^{-1} N applied and $Frac_{LEACH}$ is the fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff (kg N kg^{-1} N additions).

The amounts of N added/released (F_{SN}, F_{CR} and F_{SOM}), default emission factors (EF_1, EF_4 and EF_5), fractions that volatilize ($Frac_{GASF}$) and are lost through leaching and runoff ($Frac_{LEACH}$) are presented in Table 4 (uncertainty ranges presented inside brackets). F_{SN} is equal to zero in all systems except RT and T in Argentina, where synthetic N is applied as monoammonium phosphate. The amount of N in crop residues (F_{CR}) was estimated on the basis of the soybean yield and default factors for above-/below-ground residue given by the IPCC (2006). The N_2O emissions from N mineralization as a result of loss of soil carbon through changes in land use and management (F_{SOM}) were estimated on the basis of the average annual loss of soil carbon for each LUC scenario and a default C:N ratio of 15. It should be noted that the 2006 IPCC guidelines included significant adjustments to the methodology previously described in the 1996 IPCC guidelines: i) biological nitrogen fixation was removed as a direct source of N_2O (after Rochette and Janzen (2005) concluded that N_2O emissions induced by the growth of legume crops may be estimated solely as a function of the above-ground and below-ground nitrogen inputs from crop residue) and ii) the release of N by mineralization of soil organic matter as a result of change of land use or management was included as an additional source.

2.3. Soybean transportation

The transportation of soybean from the plantations in Brazil and Argentina to Europe encompasses transport by lorry ("16–32t") to the ports and by transoceanic freighter to the port of Lisbon (Portugal). It was assumed that the type of lorry complies with EURO 3 (European Union emission standards for vehicles, Directive 98/69/EC). The GHG emissions from transoceanic and road transportation were calculated based on emissions factors (Spielmann et al., 2007) and distances between the different places of origin of the soybean and the port of Lisbon. The distances from Brazil and Argentina to the port in Portugal were 8371 km and 10244 km, respectively. The distances were estimated on the basis of the distances presented in Table 5 and the quantity exported from each port (the weighted average distance). In Brazil (in 2010), about 85% of soybean was exported from the ports of Santos (25%), Paranaguá (36%), Rio Grande (16%) and Vitória (8%) (Silva, 2010). In Argentina, 75% of the soybean was exported (the average for 2009–2010) from Bahia Blanca (30%), Rosario (24%) and San Lorenzo/San Martin (21%)(MAGyP, 2012).

Regarding the transport of soybean from the plantations to the ports, the distances of 1456 km and 403 km were adopted for Brazil and Argentina, respectively. These weighted average distances were calculated based on the distances between the main ports and the main soybean producing locations (IBGE, 2012; SIIA, 2012)

Table 5
Distances of transportation of soybean to Portugal from Brazilian and Argentinean ports (values in bold were used in the calculations).

	Port	Distance (km) to port of Lisbon (Portugal)
Brazil	Santos (São Paulo)	8169
	Paranaguá (Paraná)	8408
	Rio Grande (Rio Grande do Sul)	9114
	Vitória (Espírito Santo)	7347
	Weighted average	**8371**
Argentina	Bahia Blanca	10366
	Rosario	10147
	San Lorenzo/San Martin	10179
	Weighted average	**10244**

Table 6
Distances between the main soybean plantation regions and ports in Brazil (values in bold were used in the calculations).

Distances (km)	Mato Grosso – MT (26%)						Goiás – GO (11%)					Paraná – PR (20%)					Rio Grande do Sul – RS (15%)				Weighted average for each port
	Campo Novo do Parecis (5%)	Diamantino (5%)	Nova Mutum (6%)	Sapezal (6%)	Sorriso (10%)	Weighted average for MT to port	Chapadão do Céu (5%)	Cristalina (7%)	Rio Verde (11%)	Jataí (9%)	Weighted average for GO to port	Cascavel (8%)	Goioerê (7%)	Campo Mourão (7%)	Toledo (10%)	Weighted average for PR to port	Santo Ângelo (9%)	Passo Fundo (10%)	Cruz Alta (13%	Weighted average for RS to port	
Santos, São Paulo (25%)	2034	1826	1878	2119	1972	1974	1019	953	986	1034	997	923	859	788	965	892	1178	966	1125	1093	1340
Paranaguá, Paraná (36%)	2206	1998	2049	2290	2161	2151	1205	1298	1312	1239	1271	596	627	557	638	607	851	639	797	765	1299
Rio Grande, Rio Grande do Sul (16%)	2748	2540	2592	2832	2686	2688	2011	2199	2087	2098	2103	1027	1146	1202	1069	1106	565	574	479	534	1710
Vitória, Espírito Santo (8%)	2511	2303	2354	2595	2448	2450	1596	1123	1384	1473	1382	1837	1732	1661	1852	1779	2125	1913	2071	2040	2015
																					1456

presented in Table 6 (Brazil) and 7 (Argentina), as well as the percentage of soybean production and exportation (shown in brackets in Tables 6 and 7) in relation to national production. The influence of locations on soybean GHG emissions was assessed based on the use of maximum and minimum distances between plantations and ports. The effect of the type of lorry was analyzed based on the GHG emission factors for eleven types of lorry, using a combination of different capacities (in tonnes) and standards for vehicles (EURO 3, 4, 5 and fleet average): >16t (fleet average), >32t (EURO3, 4, 5), 16–32t (EURO3, 4, 5), 3,5–16t (fleet average), 7,5–16t (EURO3, 4, 5).

3. Results and discussion

The main results are presented and discussed in this section, which provides a GHG assessment of soybean for the 45 different LUC scenarios and cultivation systems, including an analysis of the contribution of each LC stage and GHG type. It also provides a sensitivity analysis of field N_2O emissions and transportation routes.

3.1. The LC GHG balance for soybean

Fig. 2 presents the GHG balance (LUC, cultivation and transportation), calculated on the basis of average soybean transportation distances, as well as default parameters and emission factors for field N_2O emissions. A huge variation can be observed, ranging from 0.06 to 17.8 kg CO_2eq kg^{-1} of soybean. The highest GHG emissions were calculated for the tropical (moist) region when tropical rainforest is converted into soybean plantations (tillage system). On the other hand, the lowest GHG emissions were calculated for severely degraded grasslands in the warm temperate (dry) region. LUC dominates the results, contributing significantly to the GHG balance in almost all scenarios. LUC represents more than 70% in 28 scenarios (all tropical region scenarios, with 9 out of 15 in warm temperate moist regions and 9 out of 15 in warm temperate dry regions). LUC amounts to less than 45% in the scenarios in which severely degraded grassland has been converted in warm temperate regions. In warm temperate dry regions, negative CO_2 emissions due to LUC were obtained (−0.06 to −0.26 kg CO_2eq kg^{-1}), due to the fact that the SOC_A in the soybean plantations is higher than the SOC_R in the severely degraded grassland in this region.

According to Dros (2004), 75% of land conversion in Brazil will take place in savannah/scrubland (Cerrado in Central-West of Brazil) and 90% of the conversion in Argentina in dry and moist savannah/grassland (Chaco). The LUC carbon stock changes obtained for all grassland conversion scenarios in the warm temperate dry region (Argentina) are lower than 1.5 kg CO_2eq kg^{-1}. In the tropical region (Brazil, Central-West), the LUC carbon stock changes calculated for savannah/scrubland (Cerrado) conversion vary between 3.5 and 7.0 kg CO_2eq kg^{-1}.

Some studies account for carbon emissions from direct LUC in the LC GHG assessment of soybean and soybean-based products, although a wide range of results has been reported. Table 8 compares the results from different articles. In order to make the comparisons, the GHG intensity of soybean obtained in this article was additionally calculated in terms of the GHG intensity of soybean-based biodiesel, assuming the following: 5 kg soybean kg^{-1} biodiesel (Panichelli et al., 2009); emissions from processing 18 g CO_2eq MJ^{-1} (European Commission, 2009); an energy allocation factor of 34% (36% for oil extraction and 95% for transesterification) (Castanheira and Freire, 2012). In general, the results from the various publications that addressed LUC showed a huge variation in GHG intensity. The lowest results were obtained

Table 7
Distances between the main soybean plantation regions and ports in Argentina (values in bold were used in the calculations).

Distances (km)	Buenos aires (32%)			Córdoba (25%)			Santa Fé (20%)	Weighted average
	General Villegas	Pergamino	Average	Union	Marcos Juarez	Average	General López	
Bahia Blanca (30%)	539	640	590	869	790	830	638	680
Rosario (24%)	357	114	236	240	143	192	186	208
San Lorenzo/San Martin (21%)	381	143	262	249	152	201	211	229
								403

for converted grassland and the highest for converted tropical forest and perennial cropland.

LUC emissions in Fig. 2 are disaggregated in ΔSOC and ΔC_{veg}, to allow for a better understanding of the contribution of soil and vegetation carbon stock changes to the overall GHG balance. More than 50% of the LUC CO_2 emissions occur due to a high carbon stock change in vegetation (ΔC_{veg}) in the following 24 scenarios: i) all LUC scenarios in the tropical region, ii) forest and perennial crop conversions in warm temperate regions, iii) severely and moderately degraded grassland conversion in warm temperate moist and dry regions. Changes in SOC (ΔSOC) contribute more than 50% to LUC CO_2 emissions in the 12 remaining scenarios.

Concerning cultivation, it can be observed that tillage systems have higher GHG emissions than the corresponding reduced or no-tillage systems in each region. The lowest GHG emissions occur when soybean is cultivated using reduced and no-tillage in former grassland in the warm temperate dry region (less than 2.2 kg CO_2eq kg^{-1}). Batlle-Bayer et al. (2010) also showed that no-till practices reduce soil organic carbon losses (0–30 cm topsoil layer) after land use conversion from conventional tillage (primary and secondary tillage). According to the Product Board MVO (2011), the main reason is that no-till farming protects the soil from erosion and structural breakdown. No-tillage offers the possibility not only of reducing carbon loss from the soil as a result of cultivation, but also of increasing soil carbon in the form of organic matter, with positive impacts on both soil productivity and GHG reductions (Cavalett and Ortega, 2009, 2010).

GHG emissions from the cultivation and transport of soybean vary between 0.3 and 0.9 kg CO_2eq kg^{-1} soybean. The contribution of cultivation ranges from 2% (rainforest conversion in the tropical region, NT soybean) to 53% (no LUC in all regions, T soybean). Transportation represents between 2% (rainforest conversion in the tropical region in all soybean cultivation systems) and 60% (no LUC in tropical and warm temperate moist regions, NT soybean) of the total GHG emissions. When LUC is not considered, the contribution of cultivation varies between 40% and 49% (no- and reduced tillage) and 53% (tillage) for the alternative systems, whereas transportation contributes 47%–60% to the total soybean GHG emissions.

3.2. GHG emissions from soybean cultivation

GHG emissions for the alternative cultivation systems (including the contribution of main inputs) are shown in Fig. 3. N_2O emissions from N mineralization (as a result of loss of soil carbon due to LUC) are not presented in Fig. 3. GHG emission ranges for cultivation obtained from the sensitivity analysis performed for field N_2O emissions (maximum and minimum parameters and emission factors) are presented in the chart as error (range) bars. GHG emissions for soybean cultivation, adopting default values in the calculation of field N_2O emissions, vary between 0.14 (reduced-tillage, Argentina) and 0.32 kg CO_2eq kg^{-1} (tillage, Brazil). These results can be justified by the higher soybean yields and lower diesel requirements (for machinery) in no- and reduced tillage, since direct seeding is performed without primary tillage.

The great variation in GHG emissions presented in Fig. 3 for the soybean cultivation systems can be explained by the variation in fertilizer, lime and diesel inputs. Soybean cultivation in tropical and warm temperate moist regions has higher GHG emissions (0.19–0.32 kg CO_2eq kg^{-1}) compared to the warm temperate dry regions (0.14–0.19 kg CO_2eq kg^{-1}). This difference is due to the use of limestone and greater quantities of fertilizer in Brazil. Field N_2O emissions (default) are the most important contributions to the GHG emissions from cultivation (between 32% and 58%) except under the tillage system in Brazil, where the emissions from the use of machinery contribute 37%. Diesel for agricultural machinery represents 25%–45% of the total emissions, with a higher contribution under tillage systems than the corresponding no- or reduced tillage systems. The main reason for the variations in GHG emissions in the cultivation systems is diesel consumption, although the reason for the different GHG results from Brazil and Argentina is the amount of fertilizer and lime applied to the soil.

Regarding the sensitivity analysis of the field N_2O emissions, it can be observed that the uncertainty in N_2O emission calculations is very high and dominates GHG cultivation emissions. When minimum parameters and emission factors are adopted, the emissions from cultivation are reduced by 19%–44%. If the maximum parameters and emission factors are adopted, cultivation emissions increase by 80%–181% and the field N_2O emissions dominate (59%–85%) the results for all cultivation systems. These results show that GHG emissions from cultivation are very sensitive to the parameters and emission factors adopted for field N_2O emissions calculations. This concurs with other studies, showing that field N_2O emissions play a major role in the GHG emissions from soybean cultivation.

An analysis of the contribution of each GHG (CO_2, N_2O and CH_4) to the overall soybean GHG emissions produced by the various cultivation systems (expressed in CO_2 equivalents) is presented in Fig. 4. When default N_2O emissions are considered, CO_2 emissions from diesel combustion and the production of fertilizers are the main factors contributing to the GHG intensity for soybean produced in tropical and warm temperate moist regions. N_2O contributes less than 41% in these regions, but more than 47% in warm temperate dry regions (due to field N_2O emissions). However, when minimum values are adopted for the field N_2O emissions, the results are significantly different and CO_2 represents a higher contribution to cultivation emissions in all regions (72–89%). It can also be observed that if maximum values are adopted 59%–85% of GHG emissions are due to N_2O. Methane emissions represent less than 3% in all the scenarios considered.

3.3. Soybean transportation

Fig. 5 shows the GHG transportation emissions, calculated on the basis of the weighted average distances for the transoceanic and road transportation of soybean. The error range bars represent the variation associated with eleven types of lorry and the maximum and minimum distances for each route. The highest emissions were calculated for the "3.5–16 t" lorry (fleet average) and the lowest for

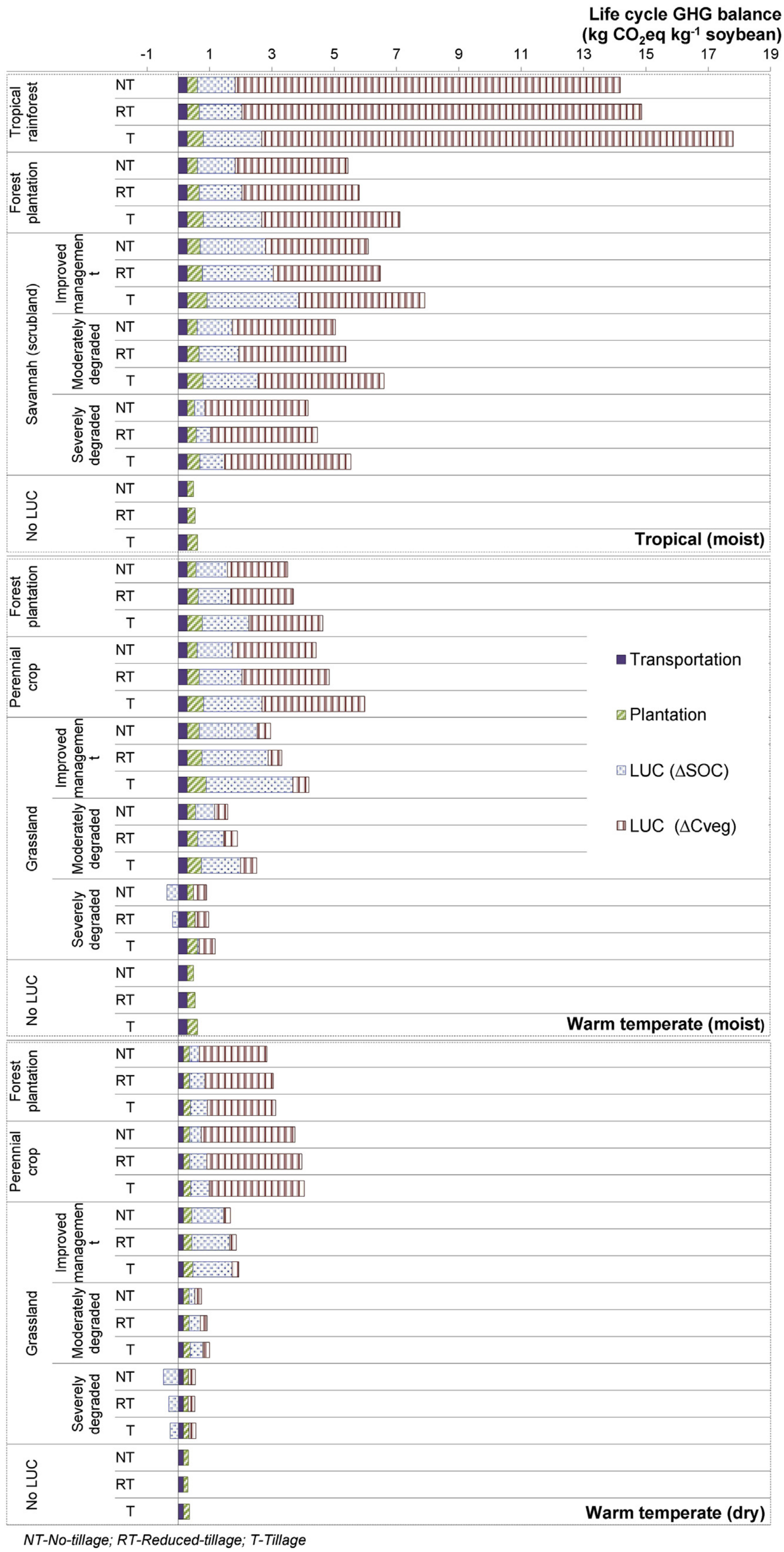

Fig. 2. The soybean LC GHG balance: alternative LUC scenarios and cultivation systems in 3 LA regions.

Table 8
GHG intensity of soybean biodiesel from Brazil and Argentina: different studies (biodiesel low-heating value: 37 MJ kg^{-1}).

Country, region (LUC type)	GHG intensity		Source
	kg kg^{-1}	g MJ^{-1}	
Brazil, Central-West (scrubland – tropical rainforest)	7.8–31.1	210–840	This article
Brazil, South (grassland – perennial cropland)	1.6–10.9	43–294	
Argentina, Las Pampas (grassland – perennial cropland)	0.8–7.6	21–205	
Brazil (degraded grassland – tropical rainforest)	2.2–24.6	59–666	Lange (2011)
Argentina (degraded grassland – scrubland)	0.4–7.5	11–202	
Brazil (cerrado – tropical rainforest)	5.4–35.2	146–951	Reijnders and Huijbregts (2008)
Argentina	0.3–3.5	8–95	van Dam et al. (2009)
Brazil (demography)	1.4	39	Reinhard and Zah (2009)
Argentina (demography)	1.7	46	Panichelli et al. (2009)

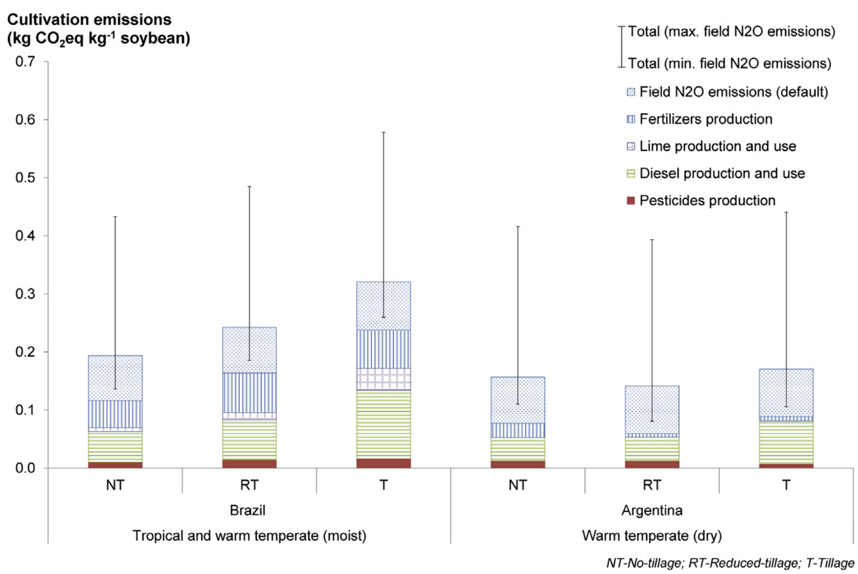

Fig. 3. GHG emissions from alternative soybean cultivation systems.

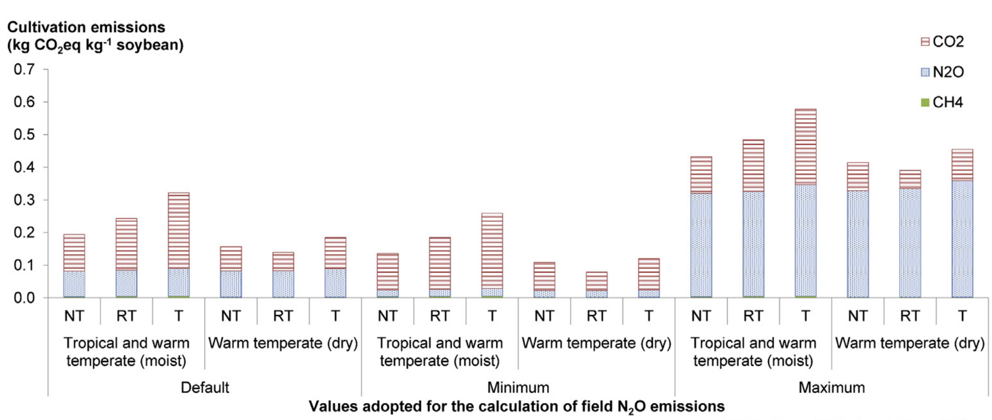

Fig. 4. Contribution of each GHG to total emissions from alternative cultivation systems.

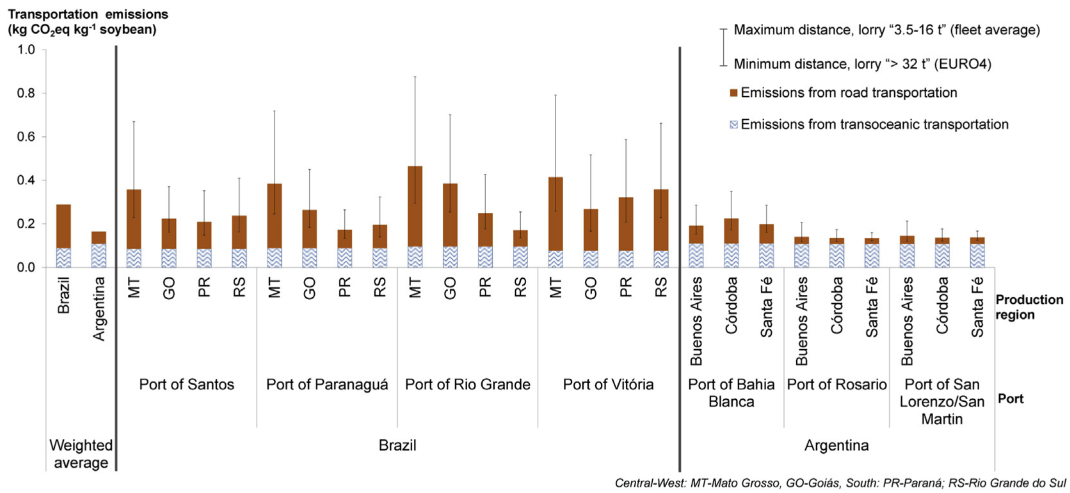

Fig. 5. GHG emissions from soybean transportation.

the ">32t" lorry (EURO4). Transportation of soybean from Brazil involves higher emissions (0.29 kg CO_2eq kg^{-1} soybean) than Argentina (0.16 kg CO_2eq kg^{-1} soybean) due to the greater road transport distances in Brazil. About 69% of the emissions in Brazil are from road transportation, whereas in Argentina this only represents 34% of the total transportation emissions. In Brazil, soybean exported from Mato Grosso has higher GHG emissions than other states. Regarding ports, it can be observed that the emissions are in general lower for soybean exported from Santos and Paranaguá. In Argentina, no significant differences in the results were observed.

4. Conclusions

This article presents an assessment of the LC GHG emissions from soybean produced in Latin America, focusing on the implications of different cultivation systems and direct LUC. An LC model and inventories for soybean produced in Brazil and Argentina was developed, addressing LUC, cultivation and transport to Europe. A comprehensive evaluation of 45 scenarios, resulting from a combination of LUC and cultivation systems for Brazil and Argentina, was undertaken. The results demonstrate the importance of LUC in the soybean GHG balance, although significant GHG variation was observed for the alternative LUC and cultivation systems assessed. The highest GHG emissions (17.8 kg CO_2eq kg^{-1}) were calculated for the tropical region when tropical rainforest is converted into soybean cultivation (the tillage system). On the other hand, the lowest GHG emissions were calculated for severely degraded grassland in Argentina (0.1–0.3 kg CO_2eq kg^{-1}), due to an increase in the SOC of soybean cultivation in relation to the SOC of severely degraded grassland (the reference land use). Concerning soil management practices, it was observed that all the tillage systems have higher GHG emissions than the corresponding reduced tillage and no-tillage systems. A sensitivity analysis for N_2O emission calculations was also presented, showing a high level of uncertainty in the calculation of N_2O emissions.

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