Life-cycle greenhouse gas assessment of soybeans

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Abstract The main goal of this paper is to investigate the life-cycle (LC) greenhouse gas (GHG) balance of soybeans produced in Latin-America, assessing the implications of different cultivation systems and direct land use change. A LC model and inventories for soybean production in Brazil and Argentina have been developed, including land use change (LUC), plantation and transport to Europe. A comprehensive evaluation of alternative LUC scenarios (conversion of tropical forest, forest plantation, perennial crops plantations, savannahs and grasslands) and different cultivation systems (tillage, reduced-tillage and no-tillage) have been performed to analyze the impact on GHG balance. A sensitivity analysis to N_2O emission calculation is also presented. It is shown that LUC dominates soybean LC GHG emissions, but significant GHG variation has been observed for the alternative LUC and cultivation systems assessed. The original land choice is a critical issue to assure the sustainability of soybean production and degraded grassland should be preferably used for soybean cultivation.

1 Introduction

Brazil and Argentina are the second and third largest soybean producers in the world, after the United States of America (USA) [1]. The increase in soybean production in Brazil and Argentina is being stimulated by the growing demand for animal feed and biodiesel [2]. However, soybean production in these countries is creating environmental concerns that have not been fully assessed [2]. Soybean production is highly dependent on non-renewable resources (fossil fuels, fertilizers and pesticides), which together with land use change (LUC) associated with the expansion of soybean agriculture in Brazil and Argentina results in important GHG emissions. Several LC studies have been performed for soya in Brazil and Argentina. However, just a few studies have addressed alternative cultivation systems, e.g. [2-6] and even a smaller number have accounted for LUC, e.g. [4, 6].

The main aim of this paper is to present a LC GHG assessment of soybean produced in Latin-America. A comprehensive evaluation of the implications of alternative LUC scenarios and soybean production systems has been performed for Brazil and Argentina. Various previous land use scenarios have been considered (tropical forest, forest plantations, perennial crops plantations, savannahs and grasslands) for different climate regions (tropical moist, warm temperate moist and dry) and soil types (low and high activity clay soils). Alternative soybean production systems have been considered: tillage and no-tillage in Brazil and tillage, reduced- and no-tillage in Argentina. This paper is organized in 4 sections, including this introduction. Section 2 presents the LC model. Section 3 discusses the main results and section 4 draws the conclusions together.

2 Life cycle inventory and modeling

A life-cycle (LC) model for soybeans produced in Latin-America has been developed, including five alternative inventories implemented for Brazil and Argentina. The LC model addresses GHG emissions due to land use change necessary to establish soybean plantation, plantation and transport of soybeans to Europe. Indirect LUC emissions has not been addressed, since there is no consensus on how to account for this [7]. The functional unit chosen is 1 kg of soybean fresh matter produced in Brazil and Argentina and exported to Europe.

2.1 Soybean plantations

To perform our study, life-cycle inventories (LCI) of soybeans plantations in Brazil and Argentina from 5 different cultivation systems have been selected, from recent and transparent studies (with important quantitative information available) [3-5, 8]. Table 1 shows the main inputs for the 5 cultivation systems selected: no-tillage (NT) and tillage (T) in Brazil [3, 8] and no-tillage (NT), reduced- (RT) and tillage (T) in Argentina [5, 4]. It can be observed that the type and quantities of fertilizers is considerably different for the various systems and that no-tillage requires more pesticides. In general, NT systems, use less diesel, since direct seeding is performed without primary tillage, as reported in [5] and [4] (Argentina), but not for Brasil [3, 8].

Tab.1: Soybean cultivation main inputs (values per ha and year).

Plantation	Brazil		Argentina		
	No-tillage [1, 5]	Tillage [4]	No-tillage [6]	Reduced-tillage [2]	Tillage [2]
Inputs					
Pesticides	8.0 kg	1.47 kg[a]	6.75 kg[c]	3.26 kg[d]	
Limestone	375 kg	-	-	-	
Fertilizers	33.8 kg P 65.4 kg K	30 kg P_2O_5[b] 30 kg K_2O	16 kg P	5 kg MAP[e] 10.5 kg TSP[e]	
Diesel	65 L	65 L	35 L	35.6 L	62.6 L
Electricity	122 MJ	-	-	-	
Production					
Annual yield (kg soybeans/ha)	2830	2544	2630	2591	

[a] 2,4-D (51%), glyphosate (37%), monocrotofos(8%) and endosulfan (4%).

[b] Diammonium phosphate (45%), single super phosphate (29%), triple super phosphate (16%), phosphate rock (5%) and ammonium nitrate phosphate (5%).

[c] Glyphosate (81%), chlorpyrifos (12%), 2,4-D (5%) and cypermethrin (1%).

[d] Glyphosate (72%), chlorpyrifos (13%), 2,4-D (7%) and others (8%).

[e] MAP-Monoammonium phosphate and TSP-Triple super phosphate

Direct GHG emissions from plantation arise from fertilizer application and biological nitrogen fixation (N_2O) together with diesel combustion from agricultural operations (mainly CO_2, calculated based on [9]). Indirect GHG emissions associated with the production of agricultural inputs have also been accounted for, using emission factors for pesticides [9], limestone [10], fertilizers [9, 11], diesel [12] and electricity [13].

N_2O emissions are produced from nitrogen in the soil through i) nitrification and denitrification processes and volatilization of nitrogen from the soil to the air (direct emissions), and ii) leaching and runoff of nitrate into water streams (indirect emissions) [14]. The IPCC Guidelines Tier 1 methodology [15] has been used to calculate direct and indirect N_2O emissions, based in the parameters and emission factors (default values and uncertainty ranges) presented in Table 2.

Tab.2: Parameters and emission factors for the calculation of N_2O emissions [15].

		Brazil		Argentina	
		NT [1,5]	T [4]	NT [6]	RT and T [2]
Input of synthetic fertilizer: F_{SN} (kg/ha*yr)			[a]		[a]
N input from soybean residue: F_{CR} (kg/ha*yr) $F_{CR}=AG_{DM}*N_{AG}+BG_{DM}*N_{BG}$		38.7	36.3	36.6	36.2
Soybean yield (kg moist biomass/ha*yr)		2830	2544	2630	2591
Dry matter (DM) content (%)		88%	89%	87%	87%
Production of soybeans: $Crop_{BF}$ (kg dry biomass/ha*yr) $Crop_{BF}$=Crop yield*DM		2490	2264	2288	2254
Slope		0,93			
Intercept (t dry matter/ha*yr)		1,35			
Above ground residues: AG_{DM}, DM (kg DM/ha*yr) $AG_{DM}=Crop_{BF}$*Slope+Intercept		3666	3456	3478	3446
Ratio of below ground residues to above-ground biomass (R_{BG-BIO})		0,19			
Belowground residues: BG_{DM}, DM (kg DM/ha*yr) $BG_{DM}=(Crop_{BF}+AG_{DM})*R_{BG-BIO}$		1170	1087	1096	1083
N content of aboveground residues: N_{AG} (kg N/kg DM)		0,008			
N content of belowground biomass: N_{BG} (kg N/kg DM)		0,008			
$Frac_{GASF}$: NH_3- and NO_x-emissions (kg NH_3-N+NO_x-N/kg synthetic fertilizer-N)	Default value	0,1			
	Uncertainty range	0,03-0,3			
$Frac_{LEACH}$: N leaching off (kg N/kg fertilizer)	Default value	0,3			
	Uncertainty range	0,1-0,8			
EF1 (kg N_2O-N/kg fertilizer-N)	Default value	0,01			
	Uncertainty range	0,003-0,03			
EF4 (kg N_2O-N/(kg NH_3-N+ kg NO_x-N-emitted))	Default value	0,01			
	Uncertainty range	0,002-0,05			
EF5 (kg N_2O-N/kg N leaching off)	Default value	0,0075			
	Uncertainty range	0,0005-0,025			
Direct N_2O emissions (kg N_2O/ha) $=(F_{SN}+F_{CR})$*EF1*44/28	Default value	0,61	0,70	0,57	0,58
	Uncertainty range	0,18-1,8	0,21-2,1	0,17-1,7	
Indirect N_2O emissions from NH_3 and NO_x-emissions (kg N_2O/ha) $=F_{SN}*Frac_{GASF}$*EF4*44/28	Default value	0	0,013	0	0
	Uncertainty range	0	0,001-0,19	0	0
Indirect emissions form N leaching off (kg N_2O/ha) $=(F_{SN}+F_{CR})*Frac_{LEACH}$*EF5*44/28	Default value	0,14	0,16	0,13	0,13
	Uncertainty range	0,003-1,2	0,0035-1,39	0,0029-1,15	0,0028-1,16

[a] Calculated based on the % of N on phosphorus fertilizers,

2.2 Land use change

The following alternative LUC scenarios (together with one no LUC (L0) scenario) have been considered for Brazil (B) and Argentina (A): tropical rainforest (B1), forest plantations (B2, B6 and A1), perennial crops plantations (B7 and A2). Concerning savannahs and grasslands conversion, different management options have also been addressed in the LUC scenarios: improved management (B3, B8 and A3), moderately degraded (B4, B9 and A4) and severely degraded (B5, B10 and A5) savannahs/grasslands. See Table 3 for details.

Emissions from carbon stock changes caused by LUC have been calculated using Equation (1), following IPCC Tier 1 and Renewable Energy Directive [15-17]:

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

in which $\mathbf{e_l}$ are the annualized greenhouse gas (GHG) emissions from carbon stock change due to LUC (kg CO_2-eq/kg soybeans); $\mathbf{CS_R}$ is the carbon stock per unit area associated with the **R**eference land use (alternative LUC scenarios), i.e. land use 20 years before the raw material was obtained (kg CO_2-eq/ha); $\mathbf{CS_A}$ is the carbon stock per unit area associated with the **A**ctual land use, i.e., soybeans plantation (kg CO_2-eq/ha) and **P** is the productivity of the crop (kg soybeans/ha per year). For the calculation of CS_R and CS_A, Equation (2) has been applied:

$$CS_i = SOC_i + C_{veg} = (SOC_{ST} \times F_{LU} \times F_{MG} \times F_I) + C_{veg} \qquad (2)$$

Standard soil organic carbon (SOC_{ST}) values have been adopted for 2 types of climate regions in Brazil and 1 type in Argentina, as described below. Two climate regions in Brazil, with low activity clay soils, have been considered: tropical moist (Central-West) and warm temperate moist (Southern). About 83% of the Brazilian soybean production in 2009 was from these regions [18]. For Argentina, Warm temperate dry climate region (Santa Fe, Cordoba and Buenos Aires), with high activity clay soils, have been considered, since 93% of the national soybean production was from these regions [19].

Appropriate values for the factors reflecting the difference in soil organic associated with type of land use (F_{LU}), principle management practice (F_{MG}) and different levels of carbon input to soil (F_I) compared to the SOC_{ST} have been selected to calculate the Reference and Actual land use soil organic carbon (SOC_i). Table 3 presents the SOC_{ST} and the factors F_{LU}, F_{MG} and F_I for the various LUC scenarios and for the soybeans plantations (in the different climate regions and types of agriculture system). C_{veg} (also shown in Table 3) represents the above and below ground vegetation carbon stock in living biomass and in dead organic matter, [17].

Tab.3: GHG emissions from carbon stock change due to LUC - calculation of SOC and C_{veg} values adopted for the LUC scenarios in Brazil and Argentina.

	R: Reference land use		LUC scenarios	SOC: SOC_{ST} (t C/ha)	SOC: F_{LU}	SOC: F_{MG}	SOC: F_{I}	SOC: SOC_{i} (t C/ha)	C_{veg} (t C/ha)
Brazil (Central-West) Tropical (moist), low activity clay soils	Tropical rainforest (>30% canopy cover)		B1	47	1	-	-	47	198
	Forest plantation (*Eucalyptus* sp.)		B2			1	1	47	58
	Savannah (scrubland)	IM	B3			1,17	1,11	61	53
		MD	B4			0,97	1	46	
		SD	B5			0,7	1	33	
	A: Actual land use								
	Soybean plantation	NT	-	47	0,48	1,22	1	28	0
		T	-		0,48	1	1	23	0
Brazil (South) Warm temperate (moist), low activity clay soils	R: Reference land use								
	Forest plantation		B6	63	1	1	1	63	31
	Perennial crop (reduced tillage)		B7		1	1,08	1	68	43,2
	Grassland	IM	B8		1	1,14	1,11	80	6,8
		MD	B9		1	0,95	1	60	6,8
		SD	B10		1	0,7	1	44	6,8
	A: Actual land use								
	Soybean plantation	NT	-	63	0,69	1,15	1	50	0
		T	-		0,69	1	1	43	0
Argentina Warm temperate (dry), high activity clay soils	R: Reference land use								
	Forest plantation		A1	38	1	1	1	38	31
	Perennial crop (reduced tillage)		A2		1	1,02	1	39	43,2
	Grassland	IM	A3		1	1,14	1,11	48	3,1
		MD	A4		1	0,95	1	36	3,1
		SD	A5		1	0,7	1	27	3,1
	A: Actual land use								
	Soybean plantation	NT	-	38	0,8	1,1	1	33	0
		RT	-		0,8	1,02	1	31	0
		T	-		0,8	1	1	30	0

IM-Improved management; MD-Moderately degraded; SD-Severely degraded; NT-No-tillage; RT-Reduced-tillage; T-Tillage

2.3 Transportation

Transportation of soybeans from the plantations in Latin-America to the mills in Europe encompass the transport by truck to the harbors in Brazil (Paranaguá) and Argentina (Buenos Aires), by transoceanic freight ship to Portugal and by train to the mills. GHG emissions have been calculated based on average distances and emission factors [20], both presented in Table 4.

Tab.4: Average distances and GHG emission factors per type of transport.

		Transoceanic ship (50000 t)	Trucks (28 t)	Train (28 t)
Distances (km)	Brazil	8145,2	790	60
	Argentina	9555,7	394	60
Emission factors (kg $CO_{2\ eq}$/tkm)		0,011	0,193	0,039

3 Results and discussion

Life-cycle GHG emissions (kg CO_2eq/kg soybean) for soybean produced in Latin-America and exported to Europe, using different cultivation systems and alternative previous land use are comparatively assessed in this section. The GHG results have been calculated by multiplying the emissions of CO_2, CH_4 and N_2O by their corresponding global warming potentials (100-year time horizon) [21]. N_2O emissions from fertilizer application and biological nitrogen fixation have been calculated using the default parameters and emission factors presented in Table 2. Other GHG were found to be negligible and were not pursued.

Fig. 1 presents the GHG emissions calculated for the various cultivation systems and LUC scenarios assessed (a total of 35 scenarios), showing the contribution of LUC, soybean plantation and transportation. The results show a huge variation in GHG emissions: between 0,1 kg CO_2eq/kg (production with no-tillage in previous degraded grassland, Argentina) and 16,5 kg CO_2eq/kg (production with tillage in previous tropical rainforest, Brazil Central-West). LUC dominates the results, mainly due to a very high difference between the vegetation carbon stock in the reference and actual soybean plantation (C_{veg} emissions in Fig. 1). GHG emissions due to LUC represent more than 80% in 24 scenarios (all Brazil Central West scenarios, 7 out of 10 in Brazil southern and 8 out of 15 in Argentina) and represent less than 43% in 4 scenarios (3 scenarios in Argentina (conversion of severely degraded grassland) and 1 in Brazil southern (conversion of severely degraded grassland, no-tillage).

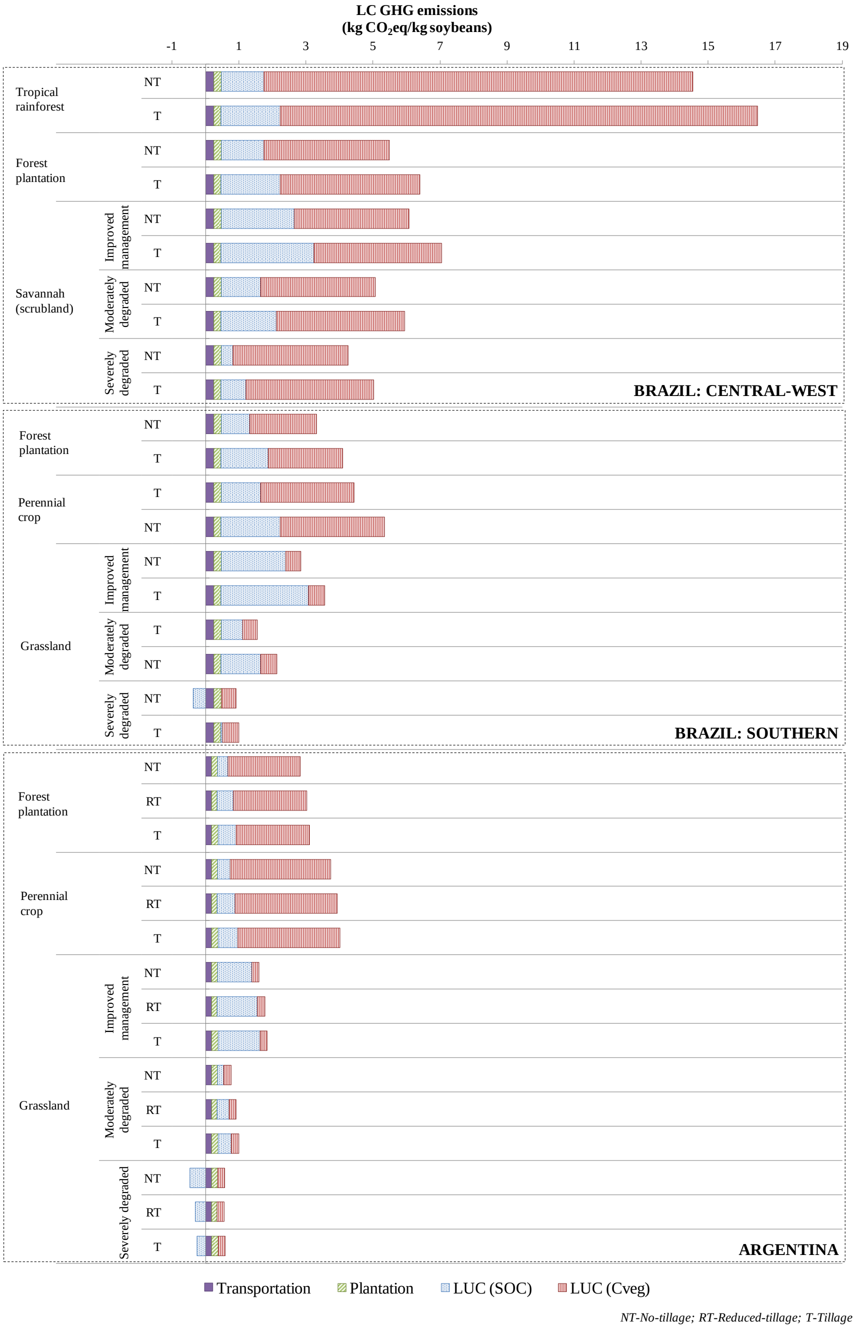

Fig.1: **LC GHG emissions of soybeans produced in Brazil and Argentina and exported to Europe: alternative LUC scenarios and production systems.**

Concerning soil management practices, it can be also observed that all the tillage systems have higher GHG emissions than the no-(reduced-)tillage corresponding systems.
Relatively low GHG emissions (less than 3 kg CO_2eq/kg) have been obtained when grassland is converted into soybean plantation (no-tillage). The lowest values have been calculated for severely degraded grasslands (0,1 to 0,5 kg CO_2eq/kg), which is due to low C_{veg} emissions and negative soil organic carbon changes, i.e. there is an increase in SOC of soybean plantation relatively to the SOC of severely degraded grassland (reference land use).
Fig. 2 compares the GHG emissions associated with plantation and transportation (excluding LUC) for the various cultivation systems. It is also presented a sensitivity analysis to N_2O emission calculation. Results with default, maximum and minimum parameters and emission factors (see Table 2) for N_2O emissions from fertilizer application and biological nitrogen fixation are also shown in Fig. 2. It can be observed that the uncertainty of N_2O emission calculation is very high and N_2O emission dominates the GHG emissions with plantation and transportation when N_2O maximum parameters and emission factors were used in the calculations.

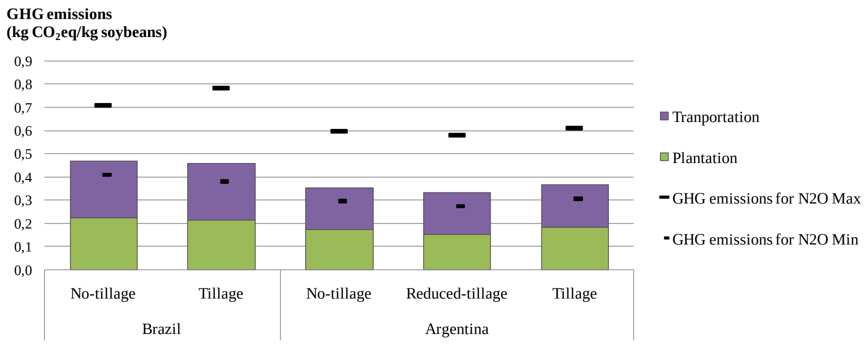

Fig.2: Soybean plantation and transport GHG emissions for various cultivation systems

The lowest GHG emissions occur for Argentina, due to reduced transport emissions (0,18 versus 0,24 kg CO_2eq/kg for Brazil) and inferior plantation emissions, mainly due to lower emission from fertilizers in Argentina.
Concerning average GHG emissions (calculated with N_2O default parameters and emission factors), the plantation is responsible for 46 to 51% of direct and indirect emissions (production of inputs). Direct emissions represent 62% to 79% of total plantation emissions.

Regarding the various production systems, the lowest LC GHG emissions have been obtained for reduced-tillage plantations in Argentina and the highest for tillage plantations in Brazil. These contradictory results for the different production systems can be explained by the use of different literature sources. For instance, for the case of plantations (no-tillage) in Brazil, a higher consumption of fertilizers, energy and pesticides have been reported in the literature, compared with the inventory for plantations with tillage, in Brazil.

4 Conclusions

This paper presents an assessement of the life-cycle (LC) greenhouse gas (GHG) emission of soybeans produced in Latin-America, addressing the implications of different cultivation systems and direct land use change. A LC model and inventories for soybean production in Brazil and Argentina have been developed, including land use change (LUC), plantation and transport to Europe. A comprehensive evaluation of 35 scenarios, resulting from a combination of LUC scenarios and cultivation systems for Brazil and Argentina has been performed.

The results show the importance of LUC on the GHG emissions of soybeans, but significant GHG variation has been observed for the alternative LUC and cultivation systems assessed. A sensitivity analysis to N_2O emission calculation has been also presented, showing a high-level uncertainty of N_2O emission calculation. Concerning soil management practices, it can be also observed that all the tillage systems have higher GHG emissions than the no-(reduced-)tillage corresponding systems. The highest GHG emissions (16,5 kg CO_2eq/kg) have been calculated for Brazil central-west when tropical rainforest is converted into soybean plantation (tillage system). On the other hand, the lowest GHG emissions have been calculated for severely degraded grasslands in Argentina (0,1 to 0,5 kg CO_2eq/kg), due to an increase in SOC of soybean plantation relatively to the SOC of severely degraded grassland (reference land use).

The original land choice is a critical issue to assure the sustainability of soybean production and degraded grassland should be preferably used for soybean cultivation. Concerning cultivation, it is important to reduce the uncertainty in N_2O emission calculations and further studies should be performed using transparent agricultural inventories in Latin-America to enable further conclusions concerning the cultivation systems assessed in this paper.

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