Assessing GHG mitigation options for crops at regional level using ecosystem modelling and LCA

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ABSTRACT

Soil, climate and management practices make greenhouse gas (GHG) emission estimates associated with crop production highly uncertain. Biophysical modelling provides reliable reactive nitrogen (Nr) estimates for environmental assessment. In this paper LCA and ecosystem modelling are combined to improve GHG estimation from cropping systems in the Paris (France) area, and to compare environmental impacts of two cropping systems at regional level. A cropping system aimed at productivity with high environmental performance (PHEP), while the other one aimed to reduce (GHG) emissions by half (50%GHG). Model-derived GHG estimates for crop production were at least 7% lower than estimates from the standard methodology applied to LCA, emphasizing the importance of regional factors in agricultural LCAs. The 50%GHG cropping system appears promising (184% reduction in the life-cycle GHG emissions) for climate mitigation of arable crops, pending trade-offs with other impact categories.

Keywords: LCA, GHG, regional level, CERES-EGC model, cropping systems.

1. Introduction

Modern agriculture contributes a large share of the anthropogenic emission of greenhouse gases (GHGs), in particular in the form of nitrous oxide (N_2O), a potent GHG driven by the application of fertilizer nitrogen (N) inputs (Saggar 2010). Agriculture can be a sink for CO_2 through soil C sequestration, by fixing carbon from the atmosphere and storing it on the short term with residues and soil organic matter (Brady and Weil 2002). Life-cycle assessment provides a relevant means of balancing these effects to estimate the carbon footprint of agriculture, and exploring mitigation strategies. However it has to date mostly been applied on a crop-specific basis (Brentrup et al. 2004a; Charles et al. 2006; JRC et al. 2007), whereas environmental impacts are better assessed with a cropping systems approach taking into account the interactions between successive crops and their environment (Goglio et al. 2014; Goglio et al. 2012). Also, most of the previous work on the LCA of crops involved short-term durations (one to a few years), too short to capture variations of soil organic carbon (SOC) stocks, and relied on simple models to estimate N_2O emissions (Brentrup et al. 2004b; MacWilliam et al. 2014; Nemecek et al. 2011a; Nemecek et al. 2011b). Since soil carbon and nitrogen (N) dynamics are highly influenced by farm management such as tillage, fertilizer application, residues management and their interaction with soil and climate (Brady and Weil 2002), local conditions should be considered to improve the estimation of GHG emissions. Direct measurements, especially for N_2O and NO, are often costly and time consuming, while the IPCC methodology, commonly used for N_2O estimations, does not account for local conditions. Agroecosystem models on the other hand are sensitive to these factors but require large amount of data (Gabrielle and Gagnaire 2008).

Despite this advantage in principle, only a few studies have integrated LCA with agroecosystem modelling to estimate GHG and other impacts during long term cultivation (Adler et al. 2007; Gabrielle and Gagnaire 2008; Goglio et al. 2014; JRC et al. 2007). However, all these studies were based outside Europe or involved a limited set of crops; for example, JRC et al. (2007) evaluated only biofuels crops for one year. Thus, the aim of the present work is to evaluate field emissions of CO_2 and reactive N (Nr) from contrasted cropping systems using the agro-ecosystem model CERES-EGC for the Ile de France region. The cropping systems were specifically designed with an *ex ante* evaluation to estimate the possible reduction in soil borne emissions using specific crop management. CERES-EGC model was run to simulate Nr emissions (as N_2O, NO, NH_3 and nitrate), along with soil C variations for 20 years. These fluxes were included in a cradle-to-farm-gate LCA of the biomass produced by the two cropping systems.

2. Methods

2.1. Cropping systems

The two cropping systems assessed over the Ile the France region were established in the ICC (Innovative cropping systems with constraints) trial in Grignon (40 km west of Paris) on a silty loam soil with the following aims: (1) to attain altogether High Environmental Performances and Productivity for the reference system (PHEP), and (2) to reduce by half the GHG emissions from the 50%GHG system compared to the PHEP system, while achieving the same environmental criteria (other than GHG emissions) as the PHEP system (Colnenne David et al. 2011).

The PHEP cropping system involved the following crop rotation: faba bean (*Vicia faba* var *minor* (Harz) Beck), winter wheat (*Triticum aestivum* L.), rapeseed (*Brassica napus* L.), winter wheat (*Triticum aestivum* L.), white mustard (*Sinapis arvensis* L.) or black mustard *(Brassica nigra* L.) as catch crop and spring barley (*Hordeum vulgare* L.). Main crop management characteristics of the PHEP system are given in Table 1.

Table 1. Selected characteristics of crop management for the cropping systems analysed on the Ile the France region (PHEP, 50%GHG), crop yields recorded during the 2009-2012 seasons.

System	Crop	Tillage	N fertiliser application[a] (kg ha^{-1})	Yield (Mg of dry grain ha^{-1})
50% GHG	**Spring Faba bean**	No tillage		0.63
	Rapeseed	No tillage	N 10	3.66
	Winter wheat	No tillage	N 70+43	7.52
	Winter Barley	No tillage	N 70+49	5.64
	Maize	No tillage	N 60+45	8.12
	Triticale	No tillage	N 72	6.48
PHEP	**Winter Faba bean**	Minimum tillage		1.37
	Winter wheat	Minimum tillage	N 50+37	7.34
	Rapeseed	Minimum tillage	N 50+60	3.74
	Winter wheat	Minimum tillage	N 70+58	7.34
	Spring Barley	Ploughing	N 65	5.70

[a]granular ammonium nitrate with no retarders

The 50%GHG cropping system maximizes the accumulation of soil organic carbon with the use of high biomass yielding cereals and by increasing the rate of crop residue return to soils. This is achieved with no tillage. Nitrous oxide emissions are mitigated by reducing mineral nitrogen fertilizer inputs with the introduction of legumes both as main crops in the rotation and as cover crops. Cover crops were also introduced to decrease the accumulation of soil nitrate and the subsequent emissions of N_2O from nitrate denitrification. Rapeseed was introduced to reduce nitrate leaching and the ensuing emissions of N_2O. The rotation is: (cover crop) faba bean, rapeseed, (cover crop) winter wheat, (cover crop) winter barley, (cover crop) maize (*Zea mays* L.), triticale (*XTriticosecale* (Camus) Wittm.). Main crop management details are given in Table 1 (Colnenne David et al. 2011).

2.2. Regional modelling

Crop yields, soil C dynamics and emissions of reactive N (Nr), including N_2O in particular were simulated with the agro-ecosystem model CERES-EGC over the Ile de France region, following the methodology of Gabrielle et al. (2014). The region is a 150 km x 150 km square area surrounding Paris, with 55% cropland. A GIS database was constructed with available geo-referenced data on this region, including administrative borders, land-cover type, crop management practices, soil properties and climate. The corresponding layers of spatial information were mostly in vector format, and overlaid to delineate elementary spatial units representing unique combinations of soil types, weather data, and agricultural management. These units were subsequently used in the CERES-EGC simulations at the field-scale, in a bottom-up approach to map the emissions. We used weather data predicted for the 2010-2030 time slice by the DRIAS project in France (Lémond et al. 2011), using the IPSL-CM4 model with the A1B GHG emission scenario from IPCC, which appeared as an intermediate scenario for air temperature and rainfall among the range of models and forcings tested by this project. Compared to the 1961-1990 period, air temperature would rise by 1.35 °C, with an average of 11.7 °C for the 2010-2031 time slice, and rainfall would remain constant at an average of 641 mm yr^{-1}. CERES-EGC was run for the current land-use (2010).

2.3. Life-cycle assessment

LCA was performed following a cradle to farm gate approach (Goglio et al. 2014; Goglio et al. 2012), considering grains as final products. System boundaries encompassed all agricultural inputs and farm machinery production from raw material extraction to transport to farm (Brentrup et al. 2004b). LCA was carried out using one ha of land and one GJ of grain energy output as functional units, according to previous research (Nemecek et al. 2011a; Nemecek et al. 2011b).

The impact categories evaluated were cumulative energy demand, global warming potential (GWP) with a 100 year horizon, acidification potential, and eutrophication potential, using the CML 2001 method integrated in SimaPro 7.3 (2012) (Guinée et al. 2001; Nemecek et al. 2011a; Nemecek et al. 2011b; SimaPro 7.3 2012). Toxicity impacts were evaluated with the EDIP 2003 method available in SIMAPRO 7.3 (Nemecek et al. 2011a; Nemecek et al. 2011b; SimaPro 7.3 2012), involving the following categories: human ecotoxicity for water, soil and air; chronic ecotoxicity for soil and water; acute ecotoxicity for water. The 5% and 95% percentiles of the modelled field emissions were used to evaluate the effect of spatial and temporal variability of emissions on LCA indicators. This procedure was adopted for all the reactive N species considered in this study (i.e. nitrous oxide, nitric oxide (NO), ammonia (NH_3) volatilisation and nitrate (NO_3^-) leaching) and also for soil CO_2 exchanges.

Within the system boundaries, farm transport from the field to the farm centre was the only post-harvest process considered. During cultivation, transport of farm machinery from the farm centre to the field and its return journey was also accounted for (Brentrup et al. 2004b; Gasol et al. 2012). No drying process, except hay drying was included in the present system according to local conditions, since all the grain is directly sold to the wholesale company at field moisture.

The life cycle elaboration was carried out with the SIMAPRO software with different data sources: *ex ante* evaluation data from the ICC trials, databases integrated in the SIMAPRO software (SimaPro 7.3 2012), data taken from literature (Audsley et al. 1997; Brentrup et al. 2004a; Brentrup et al. 2004b), CERES-EGC model results for soil GHG emissions in agreement with the ISO standards 14040 and 14044 (ISO 2006a; ISO 2006b) (Table 2).

Table 2. Main data sources for different processes included in the analysis of crop management for the cropping systems analysed in the Ile the France region (PHEP, 50%GHG)

Upstream processes for agriculture	**Technical operation during cultivation**	**Fuel and material consumption for each field operation**	**Soil GHG emissions and reactive N species**	**Pesticide fate emission**	**Transport processes**
Elaborated using databases integrated in SIMAPRO together with data taken from literature (Audsley et al. 1997; Brentrup et al. 2004b; SimaPro 7.3 2012)	*Ex ante* evaluation of the ICC trial	Elaborated on the basis of the tractor power (ASABE 2003; Audsley et al. 1997; Brentrup et al. 2004b; Peruzzi and Sartori 1997)	Modelled with CERES-EGC	Elaborated according to Audsley et al. (1997)	databases integrated in SIMAPRO (SimaPro 7.3 2012)

Crop management differences among the cropping systems are described in Table 1. It was assumed that farm transport of fertilisers and pesticides involved a 80.9 kW tractor either with a fertiliser spreader or pesticide

sprayer. All seeds for sowing were transported to the field within the seed drill with a 95.6 kW tractor. The same machinery is subsequently utilised to sow the various crops present in the rotation.
Harrowing in the PHEP system and mulching in the 50%GHG system was assumed to be carried out with a 80.9 kW tractor, together with pesticide treatments; while ploughing in PHEP was done with a 118 kW tractor. Cultivator pass in PHEP and roller pass in both systems were performed with the 95.6 kW tractor. Finally, a 180 kW combined harvester was assumed to be used for grain harvest together with a 10 Mg maximum load trailer and a 80.9 kW tractor.

Regarding fertilizer production, all data needed to account for raw material extraction, fertiliser manufacture and transport from raw material extraction sites to local storehouse were accounted with SimaPro 7.3 (2012). Fate factors for P and K fertilizers into the various environmental compartments were taken from Audsley et al. (1997) (Table 2).

The crop management of the two cropping systems analysed made use of several different pesticides: herbicides, molluscicides, insecticides and fungicides. Due to the high heterogeneity of pesticides and herbicides used, a common procedure was utilised to estimate the emissions to the air, water, and soil compartments, on the basis of the amount and type of active ingredient, which was also used to evaluate upstream impacts (Audsley et al. 1997; Brentrup et al. 2004a) (Table 2); while pesticide transport impact was computed on a total weight basis (Goglio et al. 2012).

3. Results

3.1. Simulation of field emissions

The emissions of reactive N (as N_2O, NH_3, NO and NO_3) simulated by the ecosystem model over Ile de France are given in Table 3, along with the annual change of soil organic C (SOC) for the two cropping systems due to soil mineralization. As expected, the 50%GHG system achieved higher C sequestration rates than the reference system (PHEP), with a 6-fold relative difference due to higher returns of crop residues to the soil. Surprisingly, N_2O emissions were 20.6% higher for the 50%GHG system in comparison with the PHEP system. NO emissions followed a similar pattern, being controlled by the same soil processes as N_2O.

Table 3. Simulated emissions of reactive N and soil C change for the two cropping systems over the Ile de France region. Data correspond to the spatially-weighted average over the 18 (50%GHG system) to 20-year (PHPE) simulation periods, with the 5-95% percentiles given in brackets.

Cropping system	**Emissions of reactive N (kg N ha^{-1} yr^{-1})**				**Soil organic C change (kg C ha^{-1} yr^{-1})**
	N_2O (direct)	NO	NH_3	Nitrate	
PHPE	0.29 (0.05 – 0.94)	0.44 (0.34 – 0.51)	0.43 (-0.11 – 1.40)	14.6 (4.17 – 42.34)	-140 (-540 – 95)
50%GHG	0.35 (0.05 – 0.98)	0.50 (0.15 – 0.62)	0.34 (-0.09 – 1.19)	13.0 (3.15 – 33.5)	1000 (210 – 1460)
Relative difference (50%GHG – PHPE)/PHPE	+20.6%	-13.7%	-20.7%	-11%	+ 610%

Conversely, the 50%GHG system presented 10 to 20% lower ammonia and nitrate losses than PHEP on average, due to the systematic presence of catch crops over the winter, which limited the build-up of nitrate and ammonium near the soil surface. Over the entire region and the 680 spatial simulation units (representing different combinations of soil properties and climate data series), Nr fluxes per hectare had large variability around their spatial means (Table 2), as their percentiles values showed. Except for the C variation rates, the distribution of the 5% percentiles and 95% percentiles largely overlapped between the two systems, implying that their differences were not significant.

3.2. LCA results

The 50%GHG system was successful in reducing some of the impacts analysed compared to the reference PHEP system. It abated GWP by 184%, air human toxicity by more than 2% and water chronic ecotoxicity by more than 3% (Table 4). Its GWP was actually negative, with a regional average of -2 Mg of CO_2 eq ha^{-1} and -22.5 kg of CO_2 eq GJ^{-1} of grain energy thank to soil CO_2 uptake (Tables 3 & 4). The minimum change in GWP among treatments was 6.66% corresponding to the difference between GWP of the 95% percentile of the 50%GHG system and the GWP of the 5% percentile for the PHEP system. However the 50%GHG system had 16% higher water chronic ecotoxicity and 7% larger water human toxicity and water acute ecotoxicity than PHEP system with both functional units (Table 4). For the other impact categories, differences were limited (1-2%) (Table 4).

Table 4. LCA results for the two cropping systems (50%GHG and PHEP) across the Ile de France region. Data correspond to the mean value for each impact category with the impact results estimated from the 5% and 95% percentiles of reactive N species and CO_2 emissions in brackets

		50%GHG	PHEP		50%GHG	PHEP
Impact category	**Category unit**	**(ha^{-1})**	**(ha^{-1})**	**Category unit**	**(GJ^{-1})**	**(GJ^{-1})**
Cumulative energy demand	GJ eq[a]	28.1 (28.1-28.1)	28.5 (28.5-28.5)	MJ eq[b]	317 (317-317)	322 (322-322)
Global warming 100a	Mg CO_2 eq	-1.99 (-3.86-1.27)	2.38 (1.36-4.25)	kg CO_2 eq	-22.5 (-43.5-14.3)	26.9 (15.4-48.1)
Acidification	kg SO_2 eq	16.5 (15.9-16.6)	16.2 (16.0-16.3)	g SO_2 eq	185 (179-188)	183 (181-185)
Eutrophication	kg PO_4^{-3} eq	21.4 (16.8-30.5)	21.6 (17.0-33.9)	kg PO_4^{-3} eq	0.241 (0.190-0.344)	0.245 (0.192-0.384)
Air human toxicity	m^3	2.43E7 (2.42E7-2.44E7)	2.48E7 (2.47E7-2.49E7)	m^3	2.74E5 (2.73E5-2.75E5	2.81E5 (2.80E5-2.82E5)
Water human toxicity	m^3	1.21E5 (1.21E5-1.21E5)	1.12E5 (1.12E5-1.12E5)	m^3	1.37E3 (1.37E3-1.37E3)	1.27E3 (1.27E3-1.27E3)
Soil human toxicity	m^3	258 (258-258)	251 (251-251)	m^3	2.91 (2.91-2.91)	2.84 (2.84-2.84)
Water chronic ecotoxicity	m^3	5.27E6 (5.27E6-5.27E6)	4.42E6 (4.42E6-4.42E6)	m^3	5.94E4 (5.94E4-5.94E4)	5.00E4 (5.00E4-5.00E4)
Water acute ecotoxicity	m^3	2.03E5 (2.03E5-2.03E5)	1.89E5 (1.89E5-1.89E5)	m^3	2.29E3 (2.29E3-2.29E3)	2.14E3 (2.14E3-2.14E3)
Soil chronic ecotoxicity	m^3	1.20E6 (1.20E6-1.20E6)	1.23E6 (1.23E6-1.23E6)	m^3	1.35E4 (1.35E4-1.35E4)	1.39E4 (1.39E4-1.39E4)

[a] 1GJ eq corresponds to 1 GJ of energy from difference sources
[b] 1MJ eq corresponds to 1 MJ of energy from difference sources

In terms of variability only for cumulative energy demand, GWP, and toxicity impacts, the impact distributions could be considered different (Table 3). For the other impact categories impact differences were not significant despite having different means because their impact distribution overlaps. Table 4 shows that some impacts are not affected by variability in reactive N species and CO_2 emissions including cumulative energy demand and all the toxicity impacts except water human toxicity.

4. Discussion

4.1. Field emissions

Regional modelling was mostly aimed at generalizing results obtained at the local scale in the Grignon trial to a larger area; an administrative region featuring about 1 Mha of cropland on which the two cropping systems could be applied. A major limitation in this exercise was that the spatial and inter-annual variability of management practices were ignored since all cropping operations occurred at fixed dates from one experimental site and a few years, regardless of the climatic conditions of the year and the soil types. In practice cropping operations depend strongly on soil conditions, weather and field conditions so that this assumption is quite questionable. Thus, these simulations can only convey a sense of the spatial and temporal variability associated with the diversity of soil and climate combinations occurring within a large region (through the means and percentiles in the emission fluxes), and their impacts on the performance of cropping systems. The implementation of decision rules (e.g. a balance-sheet method for N inputs in spring) would also be an interesting avenue to improve on this point (Bergez et al. 2010).

Modelled yields for the field trial in Grignon were within 5% of the observed values during the 2009-2012 seasons, thanks to the calibration of parameters related to crop phenology and dry matter partitioning. Regional means with the model were slightly lower than the yields obtained in the Grignon trial (e.g. 15% lower for winter wheat), but this could be expected since the soil in Grignon is a deep loam with a relatively high yield potential. In a previous modelling exercise in the same region (Ile de France), Gabrielle et al. (2014) found that simulated yields compared well with yield records for the 2000-2010 time period for winter wheat, but noted a possible over-estimation bias for rapeseed. Some of the crops present in the cropping systems tested here are relatively uncommon (e.g. faba beans), and have seldom been attempted with crop models. Little information was available in the literature to parameterize the CERES-EGC model for these crops, and their simulation therefore carried a high degree of uncertainty.

Simulated emissions of Nr were relatively small compared to estimates based on emission factors such as the Tier 1 methodology from IPCC guidelines for N_2O (De Klein et al. 2006). Given the average N application rates (around 100 kg N ha^{-1} yr^{-1}), the latter would have yielded about 1 kg N_2O-N ha^{-1} yr^{-1}, compared to the 0.05–1.00 kg N_2O-N ha^{-1} yr^{-1} obtained here. Such trend was already noted and discussed by Gabrielle et al. (2014) observing that a top-down study based on atmospheric inversion showed that emission factors were lower in the context of France for N_2O than the Tier 1 default values. Regarding the other gaseous emissions (NH_3 and NO), emissions were also in the lower end of values reported for cropland. Conversely, the rate of C sequestration simulated for the 50%GHG system is in the higher range of literature values. For instance, a recent review on C sequestration rates cited a maximum figure of 1 Mg C ha^{-1} yr^{-1} for set-aside (as a cropland management option) in cool-moist climates such as Ile de France (Smith et al. 2008). On the other hand, the slight C loss rate predicted for the reference system (PHEP) is consistent with values recorded after 10 years in a nearby arable plot under minimum tillage (Loubet et al. 2011).

4.2. Differences in LCA results across systems

Compared to PHEP, the 50%GHG system reduced GWP by 184% across Ile de France, with both functional units (hectare and GJ of harvested biomass). The original 50% target assigned to 50%GHG was then largely achieved. Even considering the worst-case scenario for this system (the 95% percentile) and the best case for the PHEP system (the 5% percentile), the abatement still amounted to 6.66%. This difference in GWP among cropping systems was mostly due to soil C changes. The slight increase in N_2O emissions with the 50%GHG system was largely offset by the decrease in CO_2 emissions (Brady and Weil 2002; Six et al. 2004). Negative GWP values (as obtained with the 50%GHG system) were observed in previous work in relation to tillage, with an effect on SOC dynamics. For instance, Six et al. (2004) evaluated a negative GWP in humid conditions of up to 2.07 Mg of CO_2 eq ha^{-1}, which is in agreement with the findings of this study. However the large range of the 5% and 95% percentile GWP values for both systems confirmed the high variability highlighted by Six et al. (2004). The GWP range for the PHEP cropping system was comparable with figures obtained by Kim et al. (2009) for continuous maize in the US, who estimated reactive N species and carbon storage with the DAYCENT model and integrated its results in a LCA. They reported GWP ranges of 17.3-56.1 kg of CO_2 eq GJ^{-1} and 1.87-5.19 kg of CO_2 eq ha^{-1}, respectively. However, the latter applied to only one crop whereas the systems evaluated here included 4 to 6 different crops, and to a different agro-ecological zone.

Most of the agricultural LCAs found in the literature rely on IPCC emission factors and simple models to evaluate reactive N fluxes, and disregard soil C dynamics (Brentrup et al. 2004b; Charles et al. 2006; Goglio et al. 2012; Nemecek et al. 2011a; Nemecek et al. 2011b; Pelletier et al. 2008). Despite these differences with the methodology proposed here, some of these studies were comparable with the data elaborated here for the PHEP system. For instance, Brentrup et al. (2004b) reported GWP ranges of 8.2-26.5 kg of CO_2 eq GJ^{-1} and 0.29-4.10 Mg CO_2 eq ha^{-1} for wheat using different fertilizer rates. For the same crop in Switzerland, Charles et al. (2006) reported GWP values of 2.42 Mg of CO_2 eq ha^{-1} and 22.4 kg of CO_2 eq GJ^{-1}. The PHEP system had slightly lower GWP values than those reported by Nemecek et al. (2011b), for Swiss intensive and extensive cropping systems involving grain cereals (with a range of 2.89-5.03 Mg of CO_2 eq ha^{-1}). Notwithstanding, the GWP of the

PHEP system was more in line with the integrated and organic management of cropping systems with grain cereals (with a 2.15-5.03 Mg of CO_2 eq ha^{-1} range), estimated by Nemecek et al. (2011a).

There were less pronounced variations across the two cropping systems for the other impact categories, except for chronic and acute water ecotoxicity and human toxicity to water (with more than 7% difference). The two systems had similar energy consumption, both on ha basis and GJ basis. This was due to two compensating factors: the substitution of most mechanical weeding and tillage in the PHEP system with frequent pesticide treatments in the 50%GHG system for crop protection, and a limited difference in fertilizer application rates. The latter are known to largely affect energy consumption of agricultural products (Brentrup et al. 2004b; Charles et al. 2006; Goglio et al. 2012).

The energy demand for both systems was slightly greater than reported by Kim et al. (2009) for maize cultivation with and without tillage in a series of locations in the Corn belt (with ranges of 14.2-27.2 GJ ha^{-1} and 143-224 MJ GJ^{-1}, respectively). Other research evaluated only non-renewable energy demand for intensive and extensive (11-22 GJ ha^{-1}) (Nemecek et al. 2011b) or integrated and organic (10-22 GJ ha^{-1}, Nemecek et al. (2011a)) cropping systems with cereal grains in Swiss conditions and showed at least 21.7% less energy consumption on ha basis than the present assessment.

Acidification potentials presented here were consistent with numbers obtained for maize by Kim et al. (2009) on GJ basis (184-531 g of SO_2 eq GJ^{-1}), but lower than the range the latter reported on a ha basis (22.4-53.0 kg of SO_2 eq ha^{-1}). The same pattern occurred with the estimates of Charles et al. (2006) for wheat in Swiss conditions (with a 17.8 kg of SO_2 eq ha^{-1} value). Conversely, our data were somewhat larger than the range reported by Brentrup et al. (2004b) for wheat cultivation in the UK (3.1-15.9 kg of SO_2 eq ha^{-1}).

The eutrophication potentials calculated here were larger than Kim et al. (2009) (>14.5 kg PO_4^{-3} eq ha^{-1} and >156 g PO_4^{-3} eq GJ^{-1}) for maize cultivation. Using simple models to estimate reactive N species, Charles et al. (2006) reported lower values than eutrophication potentials elaborated here for the two cropping systems (over 3.47 kg PO_4^{-3} eq ha^{-1} and 0.0032 kg PO_4^{-3} eq GJ^{-1}, respectively). However both studies (Charles et al. 2006; Kim et al. 2009), evaluated either maize or wheat while the present cropping systems included also rapeseed, barley, faba beans, triticale and several cover crops. Regarding toxicity impacts, the PHEP system had lower water ecotoxicity (both chronic and acute) and water and soil human toxicity than 50%GHG. These differences might arise from the different types of pesticides used in both systems. Soil chronic ecotoxicity impacts estimated in this research were within range with those estimated with EDIP 97 method in integrated and organic cropping systems (3.7 e4-6.19 e6 m^3 ha^{-1}) (Nemecek et al. 2011a) and for intensive and extensive cropping systems including cereals in Switzerland (0.10-3.23 e6 m^3 ha^{-1}) (Nemecek et al. 2011b). These discrepancies might be due to different climatic conditions, but also to other crops present in the cropping systems evaluated by Nemecek et al. (2011a; 2011b).

5. Conclusion

Compared to the reference system representing current practice (PHEP), the 50%GHG cropping system achieved lower environmental impacts for some impact categories, including GWP (by 184%), on average, whether on a hectare or GJ basis. Using the latter functional unit, which may be deemed more relevant to the primary function of the cropping systems (which is providing biomass for food, feed or energy purposes), the relative differences between the two systems varied between -184% and 16% for the various LCA indicators. This demonstrates the benefits of the 50%GHG system and validates its *ex ante* design, although the large variability around the mean indicators tends to mitigate these benefits at the regional scale.

The present work emphasized the interest of evaluating the performance of agricultural crops at the cropping system level since it is the only relevant scale for most of environmental impacts because of the interactions between crops and the interplay with climate conditions. In terms of time scale, field emissions of Nr and especially of carbon dioxide involve dynamics that are hardly detectable on an annual level. Thus, long field trial evaluation is a key factor to have a better estimation of these dynamics and their interplay with climatic conditions. Indeed, long term trial data allow the evaluation of real crop management in relation to seasonal effects, avoiding a mean crop management independent from climatic seasonality.

The CERES-EGC model proved to be a useful tool to evaluate cropping systems on a time scale relevant to capture the differences gradually occurring between the two crop management options tested here. It gave the possibility of generalizing the results obtained in one location to the surrounding administrative region, taking into account interactions with soil and climate factors. Despite the absence of decision rules to account for management x environment interactions, and the lack of data to test model outputs at this scale, this exercise proved useful to explore routes to the mitigation of environmental impacts of arable crops via a systemic approach.

6. References

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