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A comparison of methods to quantify greenhouse gas emissions of cropping systems in LCA

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Abstract

Carbon dioxide and nitrous oxide are two important greenhouse gases (GHG) released from cropping systems. Their emissions can vary substantially with climate, soil, and crop management. While different methods are available to account for GHG emissions in life cycle assessments (LCA) of crop production, there are no standard procedures. In this study, the objectives were: (i) to compare several methods of estimating CO_2 and N_2O emissions for a LCA of cropping systems and (ii) to estimate the relative contribution of soil GHG emissions to the overall global warming potential (GWP) using results from a field experiment located in Manitoba, Canada. The methods were: (A) measurements; (B) Tier I and (C) Tier II IPCC (Intergovernmental panel on Climate Change) methodology, (D) a simple carbon model combined with Intergovernmental Panel for Climate Change (IPCC) Tier II methodology for soil N_2O emissions, and (E) the DNDC (DeNitrification DeComposition) agroecosystem model. The estimated GWPs (-7.2 to 17 Mg CO_2eq ha^{-1} y^{-1}; -80 to 600 kg CO_2eq GJ^{-1} y^{-1}) were similar to previous results in North America and no statistical difference was found between GWP based on methods D and E and GWP based on observations. The five methods gave estimates of soil CO_2 emissions that were not statistically different from each other, whereas for N_2O emissions only DNDC estimates were similar to observations. Across crop types, all methods gave comparable CO_2 and N_2O emission estimates for perennial and legume crops, but only DNDC gave similar results with respect to observations for both annual and cereal crops. Whilst the results should be confirmed for other locations, the agroecosystem model and method D can be used, at certainly one selected site, in place of observations for estimating GHGs in agricultural LCA.

Keywords: LCA, cropping systems, GHG, methods, model, measurements

1. Introduction

There is an increasing awareness that society needs to reduce greenhouse gas (GHG) emissions (Philp, 2015). The global atmospheric concentrations of CO_2, and other greenhouse gases such as N_2O and CH_4, are increasing and contributing to climate change (Hartmann et al., 2013; Petersen et al., 2013). In contrast to industrial systems, GHG emissions from agriculture are from non-point sources and have a high degree of variability due to climatic conditions, soil type, and agricultural practices (Miller et al., 2006).

There is potential for the agricultural sector to reduce GHG emissions, through soil carbon sequestration (Lal, 2004; Paustian et al., 2016). Instead, soil CO_2 emissions arise from decomposing plant residues, the mineralization of soil organic matter, and urea hydrolysis and this is affected by soil temperature and water content, and the type of residue and tillage (Brady and Weil, 2002; Paustian et al., 2016). Soil CO_2 emissions can be measured using micrometeorological and chamber methods or estimated by measuring soil carbon change (Chirinda et al., 2010; Dendooven et al., 2012; Fortin et al., 1996; Fuentes et al., 2012; Pattey et al., 1993). Several agroecosystem models and simple C models have been developed to account for soil C dynamics affecting soil CO_2 emissions, together with emission factor methods such as the IPCC (Intergovernmental Panel on Climate Change) Tier I and II methodologies (Aalde et al., 2006, 2006; Goglio et al., 2015; Paustian et al., 2006).

Soil N_2O emissions are primarily derived from denitrification and nitrification processes which vary with nitrogen fertiliser and animal manure application, soil tillage and crop residue management, and weather conditions (Saggar, 2010) and by secondary emissions related to nitrate leaching and ammonia volatilisation (De Klein et al., 2006). Soil N_2O emissions, like soil CO_2 emissions, show large spatial and temporal variability (Goglio et al., 2013; Kariyapperuma et al., 2011; Uzoma et al., 2015). Methods used to measure N_2O emissions include micrometeorological techniques, closed and open-chamber techniques (Laville et al., 1999; Rochette and Eriksen-Hamel, 2008). IPCC Tier I and Tier II methodologies (De Klein et al., 2006), and agroecosystem models such as DNDC (DeNitrification and DeComposition), DayCent (the daily-time-step version of CENTURY), CERES-EGC (Crop Environment REsource Synthesis- Environnement et grandes cultures), CropSyst (Cropping Systems Simulation Model) and the DAISY model (soil-plant-atmosphere system model focusing on agro-ecosystems) (Del Grosso et al., 2005; Gabrielle et al., 1998; Hansen et al., 2012; Jones and Kiniry, 1986; Li et al., 1992, 1994; Parton et al., 1988; Zaher et al., 2013) can also be used to estimate these emissions.

Holistic approaches such as life cycle assessment (LCA) are frequently undertaken in an attempt to account for all GHGs emitted and to assess the wide range of environmental impacts of crop production systems. A LCA seeks to identify the environmental impacts of all stages in the production cycle and enables the evaluation of environmental impacts for comparative and improvement purposes (Biswas et al., 2008). A full LCA of different agricultural land management practices should consider changes in soil organic carbon (SOC), net CO_2 emissions, and N_2O emissions. Currently, there are no standard procedures to account for GHG emissions in agricultural LCAs with some using IPCC methodologies and others using agroecosystem models (Goglio et al., 2012, 2015; Kimming et al., 2011a; Smeets et al., 2009). However, some research studies have demonstrated that IPCC methodologies poorly consider crop management effects, climate and soil variability (Gabrielle and Gagnaire, 2008; Goglio et al., 2014).

Several LCA studies have highlighted the compromise between accuracy and feasibility when selecting methods to account for soil C and the need to consider local conditions to estimate GHG emissions (Camargo et al., 2013; Garrigues et al., 2012; Goglio et al., 2015; MacWilliam et al., 2014; Miller et al., 2006; Nemecek et al., 2014). In this study, the objectives were: (i) to compare several methods of estimating CO_2 and N_2O emissions for a LCA of cropping systems and (ii) to estimate the relative contribution of soil GHG emissions to the overall global warming potential (GWP) using results from a field experiment located in Manitoba, Canada. The methods to account for soil GHG emissions in agricultural LCA, compared in this study were: (A) measurements; (B) Tier I and (C) Tier II IPCC methodologies, (D) a simple carbon model combined with IPCC Tier II methodology for soil N_2O emissions, and (E) an agroecosystem model (DNDC).

2. Materials and methods

2.1. Field experiment

A field experiment, described by Glenn et al. (2010, 2011, 2012) and Maas et al. (2013), at Glenlea (49.64°N, 97.16°W), Manitoba, Canada employed micrometeorological techniques to measure soil CO_2 and N_2O emissions over seven years. The soil particle size distribution was 60% clay, 35% silt and 5% sand and the mean soil organic carbon content was 3.2%. Two cropping systems were established in two 200 m by 200 m plots (4 plots in total) between 2006 and 2012. An annual cropping system, referred to as cropping system “A”, and comprising intensive cultivation, high levels of fertiliser use and a seven year rotation of annual crops was established in two plots numbered 2 and 3 (Table 1). The rotation was: maize (*Zea mays* L.), faba bean (*Vicia faba* var. *minor* L.), spring wheat (*Triticum aestivum* L.), canola (*Brassica napus* L.), spring barley (*Hordeum vulgare* L.), spring wheat and then maize. A perennial cropping system, referred to as cropping system “P”, and comprising a rotation of maize, faba bean, four years of perennial cropping with alfalfa (*Medicago sativa* L.) and then maize was established in two plots numbered 1 and 4. The second treatment received only low mineral fertiliser rates and the cultivation comprised reduced tillage except in 2012 (Table 1).

2.2. GHG flux measurements

Method A used soil CO_2 and N_2O emissions measured with a micrometeorological technique described by Glenn et al. (2010, 2011, 2012) and Maas et al. (2013). A micrometeorological flux-gradient system was used for near continuous determination of N_2O emissions, net ecosystem exchange and ecosystem respiration. Together with a sonic anemometer mounted in plot 1 and 3, a tunable-diode-laser trace gas analyser was set inside a trailer located at the junction of four plots, measuring mean CO_2 and N_2O concentration every 30 minutes with two intakes mounted at the centre of each plot at different heights. Data gaps were normally shorter than two consecutive days. The flux-gradient system revisited each plot every two hours and it was assumed that the 30-min flux sample represents the full two hour period.

Respiration was estimated using CO_2 flux measurements and a modified version of the standard Fluxnet-Canada protocol (Glenn et al., 2010, 2011; Maas et al., 2013). The ecosystem exchange was calculated in two steps. First, measurements of net ecosystem exchange during periods when photosynthesis is known to be zero were used to calculate respiration. Next, respiration during daytime or when there were gaps in the carbon dioxide flux were calculated through the Fluxnet Canada Research Network algorithm (Barr et al., 2004). This method was used previously for respiration and net ecosystem carbon dioxide exchange measurements at this site (Glenn et al. 2010). In the case of soil N_2O emissions, missing data were gap filled through linear interpolation of the N_2O fluxes. Missing data usually occurred when fluxes were negligible thus they had little effect on the cumulative flux. Missing data were either caused by instrument malfunction or calibration, quality-control issues, or when wind conditions were too low for flux determination (Glenn et al., 2010). For the full study period, more than 50% of the data were retained. The soil CO_2 emissions were then calculated by deducting the carbon associated with yield from net ecosystem exchange, considering 42% of C content in the harvested biomass (Brady and Weil, 2002). For both N_2O and CO_2 emissions, daily data was summed over 1 year to estimate cumulative yearly values.

2.3. IPCC Tier I and Tier II methodologies

Method B employs simple IPCC Tier I equations, incorporating default N_2O emission estimates and soil carbon change factors. Globally available emission factors for agricultural systems are coarsely differentiated between climate, soil characteristics, and crop management (Aalde et al., 2006; Lasco et al., 2006; Paustian et al., 2006). Emission factors were selected on the basis of the crop management and soil conditions for the field experiment. Tier II uses the same approach as Tier I but applies emission estimates and stock change factors that are based on country- or region-specific data for the most important land-use and livestock categories. Higher temporal and spatial resolution and more disaggregated activity data are typically used in Tier II to correspond with country-specific coefficients for different regions (Lasco et al., 2006; McConkey et al., 2007; Paustian et al., 2006; Rochette and Eriksen-Hamel, 2008). The emissions factors for the Tier II methodology were selected on the basis of the region and the land management adopted. Tier II emission factors were employed to account for N_2O and CO_2 emissions in method C and for soil N_2O emissions in method D (McConkey et al., 2007; Rochette and Eriksen-Hamel, 2008; VandenBygaart et al., 2008). For Tier III, higher order methods are used including models and inventory measurement systems tailored to address national circumstances, repeated over time, and driven by high-resolution activity data and disaggregated at sub-national level (Paustian et al., 2006). The inputs for Tier I and II methodology for the cropping systems assessed included measured yield, soil carbon, urea application, and crop management data.

2.4. Simple carbon model and agroecosystem model

Method D used a simple carbon model, ICBM (Introductory Carbon Balance Model), which was developed in Northern Europe by Andrén and Kätterer (1997) and has been used in several agricultural LCAs (Kimming et al., 2011a, 2011b). The model is a two-compartment first-order kinetic model developed to quantify temporal soil C dynamics using annual time steps (Congreves et al., 2015). For Canadian conditions, country-based parameters have been developed for soil carbon dynamics (Bolinder et al., 2006, 2007). Similar data employed for the IPCC Tier I and Tier II methodologies were used to run the ICBM model for the assessed crop systems. Soil CO_2 emission estimates from ICBM were then combined with estimates of soil N_2O emissions using the IPCC Tier II methodology for method D.

Method E used an agroecosystem model (DNDC). DNDC was selected because it can reasonably simulate soil temperature, soil water content, soil N and N_2O emissions for annual crops (Uzoma et al., 2015). DNDC was originally developed to estimate N_2O emissions (Li et al., 1992) and was later expanded to simulate soil C & N dynamics and CO_2 emissions (Li et al., 1994). The model has been widely tested and developed for many soil types, climate conditions and crop systems. Several regional versions are available on the Global Research Alliance Modelling Platform (http://gramp.org.uk/models/family/2). In this study, the Canadian version of the model was used (DNDCv.CAN) to represent crop production, soil C and N_2O emissions for the cool Canadian climate (Grant et al., 2016; Kröbel et al., 2011; Smith et al., 2013). This model version is based on DNDC version 9.5 and includes new empirical growth curves which regulate water and N demand, the effects of temperature stress on growth, improvements in the estimation of evapotranspiration, and a revised ammonia volatilization sub-model. DNDC was first run for 10 years to stabilize C&N pools and then simulations were continued for a further 7 years from 2006 until 2012 to estimate soil GHG emissions for each experimental cropping system. The climate, crop and soil inputs for the simulations were obtained from Uzoma et al. (2015).

2.5. LCA description and data treatment

The LCA of the cropping systems at the Glenlea site was carried out with the objectives of assessing the GHG emissions of cropping systems per 1 ha of land and per 1 GJ of gross energy output. The LCA was performed using the Crop.LCA tool (https://bitbucket.org/croplcateam/crop.lca). For this study, the impact category considered was the 100 year time horizon global warming potential (GWP) based on the IPCC 5th Assessment report impact factors (Myhre et al., 2013).

The system boundary included the agricultural phase and all the upstream processes (e.g. machinery production, transport, maintenance and repairs; fertiliser manufacture and transport; pesticide and seed production and transport; fuel production, distribution and consumption) of the agricultural phase in agreement with Goglio et al. (2012, 2014). The only downstream process considered was farm transport up to the farm centre (i.e. location of the main farm facilities).

Data for crop management for the field experiment was integrated with statistical data and expert opinion interviews. Fuel consumption for field cultivation and farm transport was calculated on the basis of power and weight of tractors, self-propelled and operating machinery (Dyer and Desjardins, 2003, 2005). Data for upstream processes were taken from different database sources (Ecoinvent, 2015; (S&T)2, 2014) and from a survey of machinery manufacture, agricultural products suppliers and statistical data in agreement with Audsley et al. (1997), Brentrup et al. (2004), Goglio et al. (2014), ISO (2006a, 2006b, 2013), carrying out a site-specific assessment considering local data (Potting and Hauschild, 2006). Soil GHG emissions obtained as outputs from the different methods were fed as input in the Crop.LCA tool to carry out the agricultural LCA.

Using the Crop.LCA results, a contribution analysis was carried out in order to assess the contribution of soil CO_2 emissions and N_2O emissions on the overall GWP per ha of the agricultural phase in agreement with Goglio et al. (2014), ISO, (2006a, 2006b).

2.6. Statistical analysis

A statistical analysis was carried out, using the R software (R Development Core Team, 2005), with three aims: (i) to assess whether there were significant differences among the estimated GWP derived from the methods to account for soil CO_2 and N_2O emissions, however only comparisons with observations (method A) were reported (ii) to test the correlation between measurements and model/emission factor results, and iii) to assess the performance of the different methods for different types of crops (e.g. cereals such as maize, barley, spring wheat; legumes such as faba bean and alfalfa; annual crops such as cereals, canola and faba beans; and perennial crops such as alfalfa).

After testing each dataset for normality, we used a Friedman test followed by pair-wise non-parametric comparisons, considering each year-plot combination separately (Siegel and Castellan, 1988). The correlation among different methods results for GWP was tested using the Kendall correlation test (Rosner, 2011) due to the large number of ties.

3. Results

3.1. Whole cropping system

There was substantial inter-annual variation in the estimated GWP of the cropping systems on a per hectare (Figure 1a) and on a per GJ output basis (Figure 1b). GWP obtained with measurements (method A) ranged from -7.2 to 17 Mg of CO_2eq ha^{-1} y^{-1} and -80 to 600 kg of CO_2eq GJ^{-1} y^{-1}. The GWP values obtained with other estimation methods (B, C, D, E) varied from -5.9 to 9.3 Mg of CO_2eq $ha^{-1}y^{-1}$ and from -67 to 440 kg of CO_2eq GJ^{-1} y^{-1}. For GWP per hectare, there were significant ($p<0.05$) differences (Table 2) considering the whole cropping system between the observations (method A) and the results using emission factor methods (B, C). By contrast the results from Method D and the DNDC model (method E) were similar to field observations (method A) (Table 2). A pattern similar to GWP per ha was observed for GWP per GJ for the whole cropping system (Table 2); however the overall results were affected by the variability of both soil GHG emissions and yields (Fig. 1b). None of the methods based on either emission factors (method B, C) or models (method D, E) tested showed significant correlation with observations (with $p<0.05$) with both functional units. The relative contribution of soil CO_2 and N_2O emissions to the overall GWP was larger than 21% for both gases.

The soil CO_2 emissions estimated using the five different methods were not significantly different (Fig. 2a, Table 2), and there was no statistical ($p<0.05$) correlation between the results from observation and the other four methods. The soil N_2O emissions estimated using Method B, C and D (Table 2) were significantly different from the measured values (Method A)(Fig. 2b). By contrast the results from the DNDC model were similar to those observed. There was a significant ($p<0.05$) positive correlation between observations and IPCC Tier I, and between the observations and DNDC results.

3.2. Crop effects

When the results were considered for individual crop types, the estimated GWP per hectare indicated that Method C, D, and E gave similar results to the observations (Table 2). The IPCC

Tier 1 method also gave similar GWP per hectare results as the field observations for the perennial and legume crops. However method B resulted in different estimates of GWP per hectare, compared to the field observations, for annual and cereal crops (Table 2).

There were no significant ($p<0.05$) differences in GWP per GJ of energy output between emission factor/model methods (method B, C, D, E) and field observations for the perennial crop (Table 2). There was also no difference ($p<0.05$) in the GWP per GJ estimated with observations and model based methods (D, E) for annual crops. However for the same crops, the GWP per GJ estimates using emission factor method (B, C) varied from the observed estimates (Table 2); while for cereals only GWP estimates using method B resulted in different ($p<0.05$) from GWP with observations. Method B and D also resulted in different ($p<0.05$) estimates of GWP per GJ, compared to those obtained from field observations, for legume crops (Table 2).

In contrast to GWP, the soil CO_2 emissions for the methods tested did not indicate any significant ($p<0.05$) differences even when considering different crop types (Table 2). The emission factor (method B, C) and model methods (method D, E) for estimating soil N_2O emissions for the perennial crop and legumes gave similar results to those derived from field observations. However for annual crops and cereals, only DNDC gave similar results to observations; while there were significant differences between the field observations and the N_2O emissions estimated from Method B, C and D.

4. Discussion

4.1. Assessment of methods, soil CO_2 and N_2O emissions

This assessment of methods highlights both the difficulty of estimating GHG emissions from agroecosystems and of choosing the appropriate estimation method. Most often the choice of method is determined by the data availability and the familiarity of the user with a given tool or method, and the availability of experimental measurements (Goglio et al., 2015). The two most complex methods used here were Method D (comprising the ICBM model in combination with IPCC Tier II methodology for N_2O) and Method E using the DNDC agroecosystem model. Methods D-E produced similar results to observations for the cropping systems assessed. Hence these results support their use in place of observations, as practised in existing studies (Gabrielle and Gagnaire, 2008; Goglio et al., 2014; Kim et al., 2009a, 2009b; Zaher et al., 2013). However these more complex methods require model calibration using local datasets, which are often unavailable, and considerable expertise and time (Del Grosso et al., 2008; Goglio et al., 2015; Wallach et al., 2006). Between method D and E, as previously discussed for soil C in agricultural LCA by Goglio et al., (2015), the use of the agroecosystem model (method E) is more challenging than the simple carbon model (method D) due to a larger data and expertise requirements. Instead, for simpler methods such as IPCC Tier I (method B) method, GWP of cereals and annual crops was statistically different from GWP estimated using observations (method A) with both functional units. This can be attributed to the inability of global emission factors to capture local conditions, as previously highlighted by Gabrielle and Gagnaire (2008) for soil N_2O emissions. However, the large interannual variability of GWP with regards to legumes and perennials highly affected the outcomes of the statistical test on ha basis and made the comparison among methods particularly challenging.

In our study GWP results were accompanied by large variability due to crop management and climate conditions in agreement with Kim et al. (2009), who assessed maize cultivation in different locations in the corn belt and Camargo et al. (2013), who estimated the environmental impact of 13 crops which could be grown in US conditions, including wheat, maize, alfalfa and rapeseed. For both functional units and considering similar crops, GWP estimates (-7.2 to 17 Mg CO_2eq ha^{-1} y^{-1}; -80 to 600 kg CO_2eq GJ^{-1} y^{-1}) occurred over a larger range in comparison to several studies carried out in North America (-6.3 to 5.2 Mg CO_2eq ha^{-1} y^{-1}; 16 to 70.2 kg CO_2eq GJ^{-1} y^{-1}) (Dendooven et al., 2012; Dyer et al., 2010; Goglio et al., 2014; Kim et al., 2009b; MacWilliam et al., 2014; Shrestha et al., 2013; Zaher et al., 2013).

Variability in GWP was primarily a result of the large variability in soil CO_2 measurements from the flux gradient study, which was previously highlighted for this site (Glenn et al., 2010). In fact it is known that techniques for measuring CO_2 flux and soil carbon can produce highly variable results and there can be inaccuracies in quantifying net CO_2 emissions on a site specific basis (Goglio et al., 2015; Smith et al., 2012). In particular for 2007, soil CO_2 emissions resulted particularly high, this was previously discussed in Glenn et al., (2010) and was associated to poor establishment of the faba bean. The results show that there was no statistically significant difference between the four emission factor/model methods of estimating soil CO_2 emissions and the site measurements. This is particularly important, considering that the soil CO_2 emissions contribution were very large, as it has been highlighted in other research (Goglio et al., 2014), and these emissions offset soil N_2O emissions.

For the N_2O emissions, the outputs from the DNDC agroecosystem model were closer to the observed emissions than the estimates from other methods. This indicates that DNDC (and potentially other agroecosystem models) could be used to estimate soil N_2O emissions for LCA, as previously carried out in other agricultural LCAs (Gabrielle and Gagnaire, 2008; Goglio et al., 2014; Kim et al., 2009a, 2009b; Zaher et al., 2013). The results also show high soil N_2O emissions in 2012 which were associated to microtopography and poor drainage as reported by Uzoma et al., (2015). For these site-specific conditions, using regional estimation methods, such as IPCC Tier I and Tier II, can be challenging when estimating N_2O emissions (Aalde et al., 2006; De Klein et al., 2006; Lasco et al., 2006; McConkey et al., 2007; Paustian et al., 2006; Rochette et al., 2008; VandenBygaart et al., 2008).

N_2O emissions also contributed significantly to the GWP. The average contribution of N_2O was 33% higher than the N_2O contribution reported by Zaher et al. (2013) for cropping systems in Eastern Washington state with winter wheat, spring wheat and spring barley. However, in our study, more complex cropping systems in continental climate with a longer period of snow cover were assessed and these differences in climate and crops may have affected soil GHG emissions (Goglio et al., 2014; Paustian et al., 2016; Saggar, 2010; Wagner-Riddle et al., 2007) and the relative contribution of N_2O towards GWP.

4.2. Performance of methods for estimating soil GHG emissions by crop type

The emission factor/model methods were also tested against observations to investigate their performance by crop type. Model based methods (D, E) produced GWP estimates similar to observations for cereals, perennial and annual crops. For the estimation of GWP per ha in LCA, all the methods were found to produce insignificant differences for legumes and perennial crops (Table 2). Thus, it would be reasonably appropriate to employ the most applicable method for these crops, as suggested by previous research (Garrigues et al., 2012; Goglio et al., 2015) for soil C accounting in agricultural LCA. The similar statistical performance may be due to the large variability in observations which can make it difficult to distinguish a real pattern for both soil CO_2 and N_2O emissions (Wallach et al., 2006). The high variability of observations could be related to the chosen measurement techniques (Glenn et al., 2010; Pattey et al., 1993, 2007) and the potential deficiencies associated with the chosen methods. Future studies should be conducted towards assessing the uncertainty of the monitoring techniques (Paustian et al., 2016), alongside model validation studies to investigate accounting procedures which better distinguish measurement variability from lack of accuracy. Assessing the uncertainty of the monitoring was outside the scope of the present study.

As indicated in Table 2, the methods tested here were equivalent to each other in predicting soil CO_2 emissions despite differences in complexity and applicability, as highlighted by Goglio et al. (2015). In contrast, the agroecosystem model performed better than did the other methods for estimating soil N_2O emissions for cereals and annuals; while all the methods tested here were equivalent to each other for legumes and perennials.

4.3. Future perspectives

Whilst the above conclusions may be appropriate for systems with similar soil-climate conditions to the present study, there is still a need to test the accuracy of the methods considered here for areas with differing climate and soil conditions. In some cases, the use of a model may be supported by previous LCA studies and literature in similar field conditions. As discussed by Goglio et al., (2015); certain methods or models whilst potentially being accurate, are not applicable in certain geographical areas due to lack of data or user expertise.

This research highlights the need to test GHG accounting methods for different soil-climate conditions in order to gain an improved understanding of the present findings because soil borne GHG emissions are highly dependent on local soil-crop-climate conditions (Hillier et al., 2012; Paustian et al., 2016; Saggar, 2010). As suggested by Goglio et al. (2015), a higher availability of datasets for different cropping systems contributes in developing the LCA methodology and allows a better benchmarking among cropping systems and crop managements. Indeed, a larger number of datasets improves the life cycle inventory of crops and cropping systems available in LCA databases and national GHG accounting systems. Further work is also necessary to understand the appropriate compromise between the feasibility and accuracy of methods to account for soil GHG emissions in agricultural LCA.

5. Conclusions

This research compared and discussed methods to account for GHG emissions in the assessment of the sustainability of cropping systems within the LCA framework. It demonstrated that estimates from a properly calibrated agroecosystem model or a simple C model combined with IPCC Tier II methodology can be substituted for observations to account for GWP in LCA of cropping systems and should be preferred to other methods. It also showed that estimates of CO_2 and N_2O emissions using the DNDC model were similar to field observations. For leguminous and perennial crops, each of the four GHG accounting methods tested, based on emission factors and models, gave similar GWP results to field observations which suggest that simple methods could be used in place of more complex methods. By contrast for annual crops, there was a benefit from model based methods.

It is anticipated that the present LCA results are generally applicable for similar geographical soil-climate conditions and crops, but further investigations are needed to validate these findings in other geographical areas.

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Figure captions

Figure 1 GWP per ha (a) and (b) per GJ of energy output for the annual (A, plot 2 and 3) and perennial (P, plot 1 and 4) cropping systems

Figure 2 Soil CO_2 (a) and N_2O (b) emissions per ha per year estimated with the 5 different methods tested output for the annual (A, plot 2 and 3) and perennial (P, plot 1 and 4) cropping systems

Figure 1

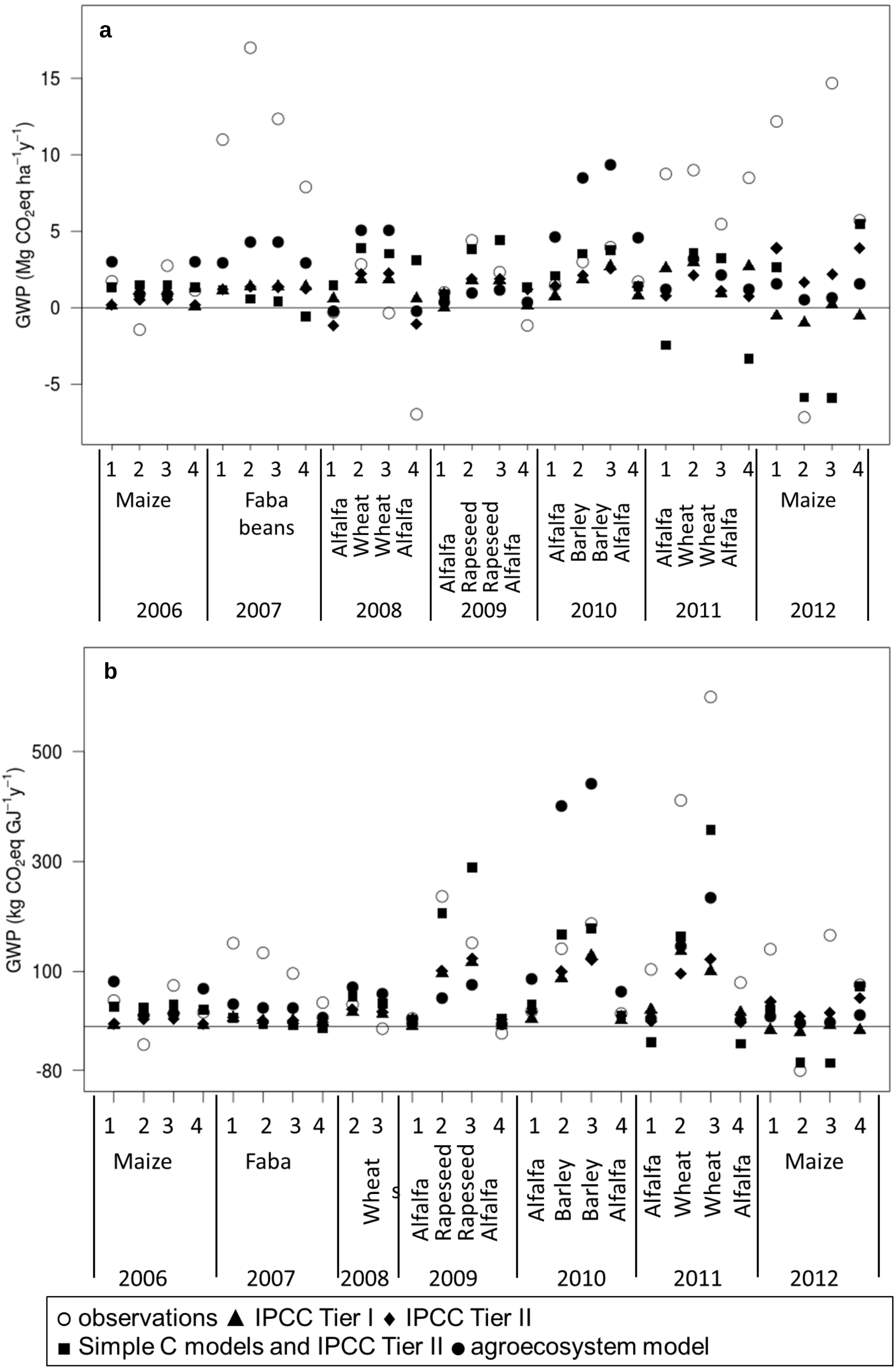
a
GWP (Mg CO_2eq $ha^{-1}y^{-1}$)
15
10
5
0
-5
1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
Maize
Faba beans
Alfalfa Wheat Wheat Alfalfa
Alfalfa Rapeseed Rapeseed Alfalfa
Alfalfa Barley Barley Alfalfa
Alfalfa Wheat Wheat Alfalfa
Maize
2006 2007 2008 2009 2010 2011 2012
b
GWP (kg CO_2eq $GJ^{-1}y^{-1}$)
500
300
100
-80
1 2 3 4 1 2 3 4 2 3 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
Maize
Faba
Wheat
Alfalfa Rapeseed Rapeseed Alfalfa
Alfalfa Barley Barley Alfalfa
Alfalfa Wheat Wheat Alfalfa
Maize
2006 2007 2008 2009 2010 2011 2012
○ observations ▲ IPCC Tier I ◆ IPCC Tier II
■ Simple C models and IPCC Tier II ● agroecosystem model

Figure 2

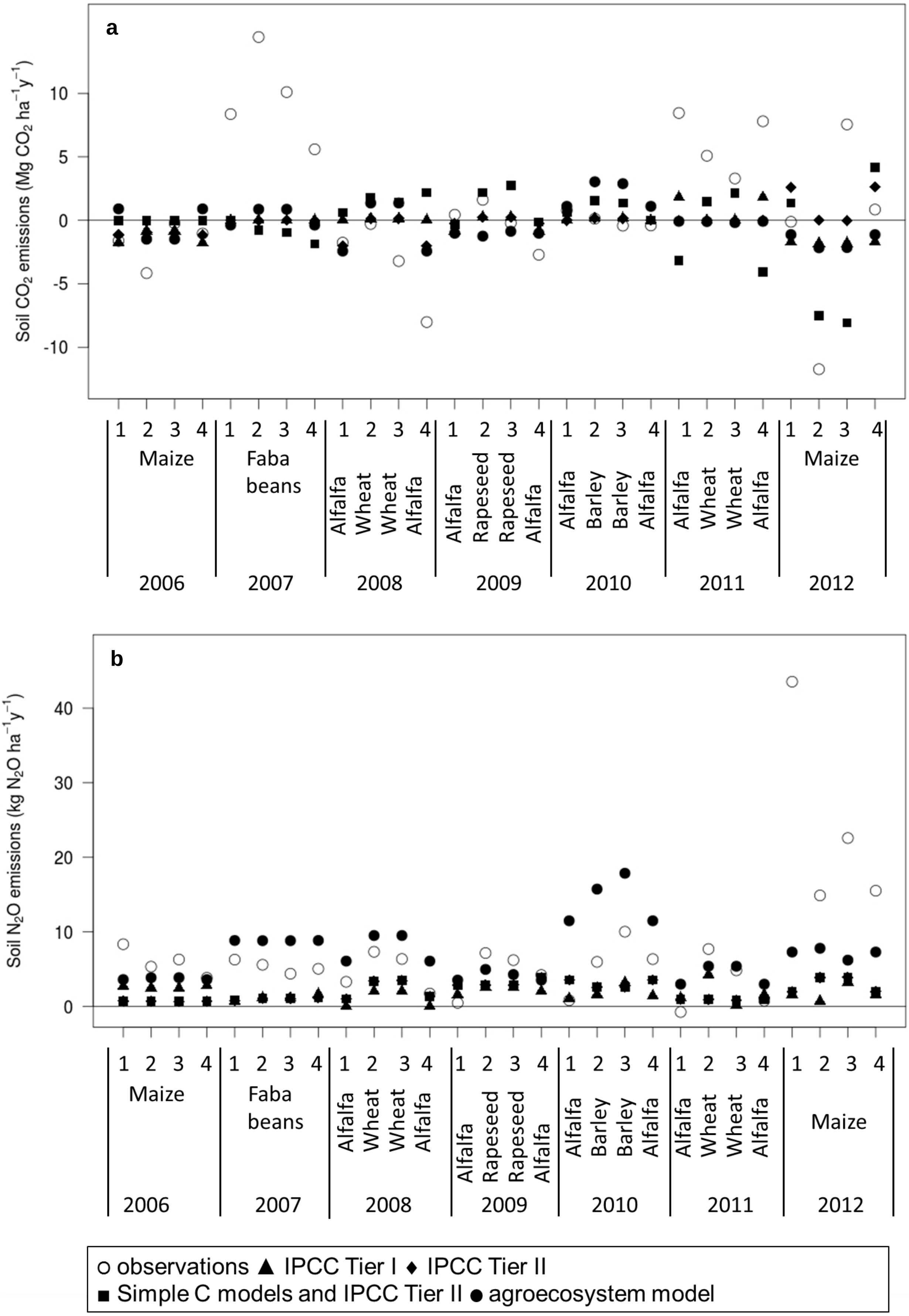
a
Soil CO_2 emissions (Mg CO_2 ha^{-1} y^{-1})
10
5
0
-5
-10
1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
Maize
Faba beans
Alfalfa Wheat Wheat Alfalfa
Alfalfa Rapeseed Rapeseed Alfalfa
Alfalfa Barley Barley Alfalfa
Alfalfa Wheat Wheat Alfalfa
Maize
2006 2007 2008 2009 2010 2011 2012
b
Soil N_2O emissions (kg N_2O ha^{-1} y^{-1})
40
30
20
10
0
1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
Maize
Faba beans
Alfalfa Wheat Wheat Alfalfa
Alfalfa Rapeseed Rapeseed Alfalfa
Alfalfa Barley Barley Alfalfa
Alfalfa Wheat Wheat Alfalfa
Maize
2006 2007 2008 2009 2010 2011 2012
○ observations ▲ IPCC Tier I ♦ IPCC Tier II
■ Simple C models and IPCC Tier II ● agroecosystem model

Table 1

Table 1 Summary of the characteristics of the cropping systems assessed (Note: The fertilizer cells contain the amount of fertiliser spread and nutrient concentration)

Year	Cropping system	Crops[a]	Tillage			Fertilizer (kg ha^{-1})	Total N applied as mineral fertiliser (kg ha^{-1})
			Number of disk harrowing per year	Number of spring tine harrowing	Number of heavy harrow passes		
2006	A	maize	2	1	3	180 NPKS 32-25-10-10; 112 Urea 46-0-0-0	109
	P	maize	1	2	1	180 NPKS 32-25-10-10; 112 Urea 46-0-0-0	109
2007	A	faba bean	0	1	1		
	P	faba bean	0	1	0		
2008	A	spring wheat	1	1	3	213 NP 43-10-0-0	92
	P	alfalfa	0	0	0		
2009	A	canola		1	1	317 Urea 46-0-0-0	146
2009	P	alfalfa	0	0	0		
2010	A	spring barley		0	2	212 Urea 46; 121 Anhydrous ammonia 82-0-0-0 (just plot 3)	98 + 100 (just plot 3)
	P	alfalfa	0	0	0		
2011	A	spring wheat		1	1	121+194 Anhydrous ammonia 82-0-0-0[b]	100 + 160[b]
	P	alfalfa	1	1	1		
2012	A	maize		0	1	64 ammonium polyphosphate 10-34-0-0; 194 Anhydrous ammonia 82-0-0-0 (just plot 3)	6+160 (just plot 3)
	P	maize	0	0	1	64 ammonium polyphosphate 10-34-0-0; 123 Urea 46-0-0-0	63

[a] maize (*Zea mays* L.); spring wheat (*Triticum aestivum* L.); canola (*Brassica napus* L.); spring barley (*Hordeum vulgare* L.); faba bean (*Vicia Faba* var. *minor* L.)

[b] two separate applications on plot 2

Table 2

Table 2 Significance table for the post-hoc non parametric paired comparisons indicating if results from emission factor/model methods (methods B, C, D, E) and observations (obs, method A) are significantly different for the whole cropping system and by crop type for GWP per ha, GWP per GJ, soil CO_2 emissions and soil N_2O emissions (ns, not significant; *: significant at 0.05 level; ** significant at 0.01 level, * significant at 0.001 level. Perennial refers to alfalfa; annuals refers to maize, spring wheat, barley, canola and faba beans; cereals refers to maize, barley, and spring wheat; legumes refers to faba beans and alfalfa)**

Parameter	Crop groups	Obs (A) vs IPCC Tier I (B)[a]	Obs (A) vs IPCC Tier II (C)[a]	Obs (A) vs ICBM-IPCC Tier II (D)[a]	Obs (A) vs DNDC (E)[a]
GWP per ha	Perennial[b]	ns	ns	ns	ns
	Annuals	0.007**	ns	ns	ns
	Cereals	0.023*	ns	ns	ns
	Legumes[b]	ns	ns	ns	ns
	Whole cropping system	0.001**	0.015*	ns	ns
GWP per GJ	Perennial[b]	ns	ns	ns	ns
	Annuals	<0.001***	0.023*	ns	ns
	Cereals	0.024*	ns	ns	ns
	Legumes	0.038*	ns	0.025*	ns
	Whole cropping system	<0.001***	0.01*	ns	ns
Soil CO_2 emissions per ha	Perennial[b]	ns	ns	ns	ns
	Annuals[b]	ns	ns	ns	ns
	Cereals[b]	ns	ns	ns	ns
	Legumes[b]	ns	ns	ns	ns
	Whole cropping system	ns	ns	ns	ns
Soil N_2O emissions per ha	Perennial[c]	ns	ns	ns	ns
	Annuals	<0.001***	<0.001***	<0.001***	ns
	Cereals	<0.001***	<0.001***	<0.001***	ns
	Legumes	ns	ns	ns	ns
	Whole cropping system	<0.001***	<0.001***	<0.001***	ns

[a]The letters in brackets indicate the method as described in the objectives of the paper

[b]The Friedman test resulted not significant, therefore no significant difference were found among methods

[c]The Friedman test resulted significant, but specific comparisons against observations were not significant, while other comparison were significant (for instance: IPCC Tier I vs DNDC)