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Improving carbon footprinting of agricultural systems: Boundaries, tiers, and organic farming

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ABSTRACT

Purpose: The purpose of this commentary is to call for consistent and improved methodology for agricultural carbon footprint (CF) studies.
Methods: The methods of published agricultural CF studies were compared to identify areas of inconsistency. Organic agriculture has been proposed as an approach to reduce net agricultural greenhouse gas (GHG) emissions and sequester carbon. Therefore we used organic agriculture as a focal system to explore the impact on CF estimates of using inconsistent boundaries, soil emission accounting, and emission factor (EF) tiers.
Results and discussion: Studies of agricultural CF use inconsistent boundaries and most use EFs based on national averages or regional models. As a result the local and farm-to-farm variability of EFs are obscured and the comparability of CFs from different studies is dubious. We propose three principles for agricultural CF calculation: use of consistent broad agricultural system CF boundaries, incorporation of soil emissions and sequestration, and development and use of fine-scale EFs for agricultural inputs. The potential use of organic practices in GHG mitigation efforts, along with the annual inspection process for certified organic farms, justify the future use of organic farms as a longitudinal national or international study population using the proposed principles.
Conclusions: Using different boundaries, or generalized vs. site-specific EFs, can give not only different levels of precision but also fundamentally different answers. Policy based on averaged data or incomplete estimates may be misdirected. To support effective policy and individual decision-making that reduce GHG emissions and/or sequester more carbon, accurate and consistent assessments of the GHG emissions of agricultural practices and systems at a finer temporal and spatial scale are needed.

1. Introduction

Agriculture contributes to global greenhouse gas (GHG) emissions. The direct GHG contributions of agriculture are estimated to account for 10 to 15% of total anthropogenic GHG emissions and 48% of global non-CO_2 anthropogenic GHG emissions (Fig. 1) (Vermeulen et al., 2012; Tubiello et al., 2015). However, estimates of current contributions vary, and many alternative practices could reduce agricultural GHGs or increase C sequestration (Lal, 2004a; Hutchinson et al., 2007). To support effective policy and individual decision-making that reduce GHG emissions and/or sequester more C, accurate and consistent assessments of the GHG emission impacts of agricultural practices and systems are needed.

A carbon footprint (CF) estimates the total balance of emissions and sinks of GHGs from a product or system across its life cycle (Rotz et al., 2010). A CF thoroughly accounts for all inputs and processes within a defined system boundary. The system boundary is an imaginary line drawn around the activities and materials that will be used for calculating CF. As such, the system boundary helps to define the relationship between the scope of the LCA study and the final environmental impacts (International Organization for Standardization, 2006). Outcome of CF studies have potential to supply information that supports effective decision-making to mitigate GHG and climate change, but currently there is poor consistency in the methods of CF calculation for agricultural systems. Consistency is particularly lacking in the choice of functional units, definition of system boundaries, and specificity of emission factors (EFs).

To improve and normalize agricultural system CFs, net soil emissions must be consistently included and considered within the system boundaries. Croplands hold an estimated 362 Pg C, 13% of global terrestrial C (Carvalhais et al., 2014) and nearly 50% as much C as resides in Earth's atmosphere (Fig. 1). Cropland is the most actively managed

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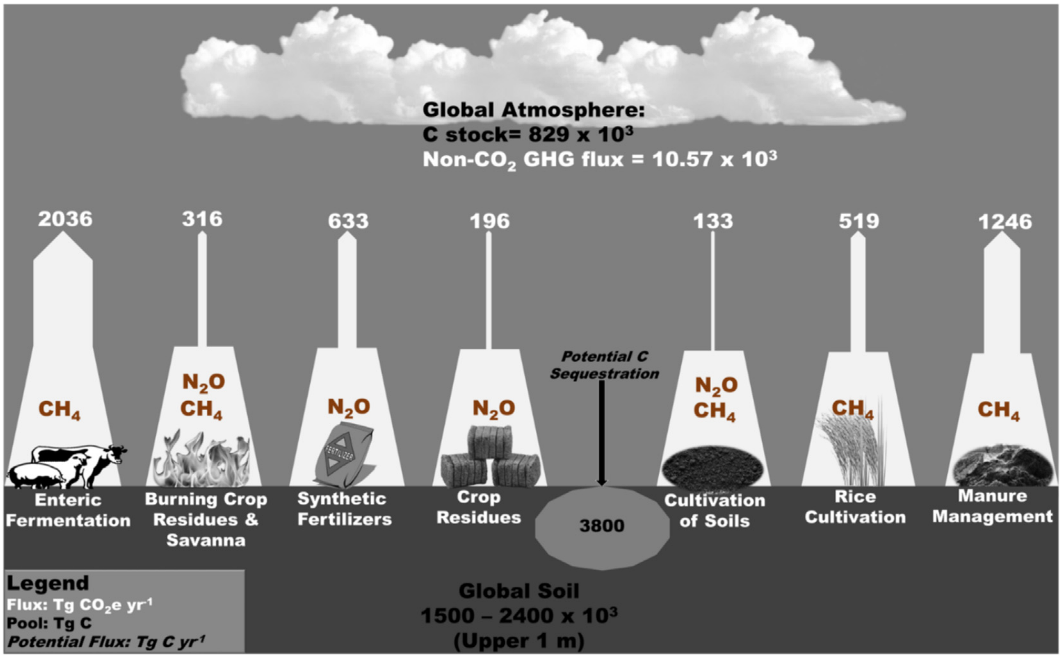

Fig. 1. Agricultural contributions to global non-CO_2 GHG emissions (Tg CO_2e yr^{-1}) estimated for the year 2011 (FAOSTAT, 2011), compared with global soil and atmospheric carbon pools (Ciais et al., 2014) and global potential C sequestration (Lal et al., 2015).

land use, representing an opportunity for active management of its significant C pool. Carbon sequestration in soil may have potential to offset 5 to 15% of the global fossil-fuel emissions per year (Smith et al., 2008; Lugato et al., 2014). One of the goals of Soil Quality Indicators in Life Cycle Assessment Consensus Group (SQILCACG) that met in Dublin in October 2016 is to develop LCA methodology on how to incorporate soil quality into impact pathways and impact assessment models. The SQILCACG group recognizes the importance of incorporating soil dynamics into LCA methodology. However, many studies on CF of agricultural systems still fail to incorporate soil emissions and C sequestration. Including factors affecting C sequestration in GHG emission estimation protocol will not only improve the overall CF accuracy but also further clarify the importance of soil organic carbon (SOC) sequestration as a GHG emission mitigation tool (Smith, 2004; Wiesmeier et al., 2014).

A three tiered approach was provided by the Intergovernmental Panel on Climate Change (IPCC) to estimate GHG emissions (Houghton et al., 1997; Eggleston et al., 2006). Tier 1 uses IPCC national or international default values, tier 2 builds a more specific EF using country-level or more specific data, and tier 3 uses local data from monitoring, experiments, or validated calculation methods (Eggleston et al., 2006). Progress has been made beyond the tier 1 EFs first developed by the IPCC. The country or regional-specific tier 2 EFs for agricultural systems that have been developed over the last several years have increased our understanding of the variability of GHG emission estimates from different sources. Currently, most agricultural CFs use EFs based on national average data or regional models (tier 1 or 2). As a result the ecoregional, local, and farm-to-farm variability of EFs and CFs are obscured. Using generalized vs. site-specific EFs can give not only different levels of precision but also fundamentally different answers (Karimi-Zindashty et al., 2012; Kouazounde et al., 2015; Skiba et al., 2016). Sound policy requires robust scientific reporting of GHG exchange at a finer temporal and spatial scale to identify the most effective management and policies. In this paper, we argue for the development and use of more regional or finer scale tier 3 EFs.

Organic farming systems may be particularly important in agricultural GHG mitigation efforts. Some have proposed government support or justified individual support of organic agriculture as an approach to reduce net agricultural GHG (Niggli et al., 2009; Scialabba and Müller-Lindenlauf, 2010). Yet, inconsistent boundaries, soil emission accounting, and EF tiers make this decision and its basis questionable. Organic agriculture generally uses less energy and stores more C per hectare than conventional agriculture (Tuomisto et al., 2012; Larsen et al., 2014; Reganold and Wachter, 2016). However, energy use and CF on a production unit basis do not always favor organic (Meier et al., 2015; Reganold and Wachter, 2016). Moreover, a wholesale conversion of global food production to organic methods is unlikely. It is necessary to identify the particular factors and practices that lead organic or any system, farm, or product to be more global warming potential (GWP) efficient so that these factors can be adopted as widely as is feasible in all farming systems.

Given the diversity of soils, inputs, transportation, and farming systems across the US and the world, individual EFs and CFs vary from national or regional averages and vary from the findings of individual studies. Policy based on averaged data or large scale estimates may be misdirected. More detailed studies, more accurate input EFs, more complete assessment of food production systems, and more user-friendly tools are needed to accurately identify hotspots, hot moments, and meaningful interventions. Using organic farming as a focal system, here we propose three principles for agricultural CF calculation: use of consistent broad agricultural system CF boundaries, incorporation of soil emissions and sequestration, and development and use of fine temporal and spatial scale EFs.

2. Weaknesses in agricultural carbon footprinting, and their solutions

2.1. Inconsistent boundaries

Life cycle assessment (LCA) is systematic set of procedures used to assess environmental impacts associated with all the stages of a product, system, process or service, through production, usage, and disposal (ISO, 2006). As a technique, LCA is used to account for all major resource uses and emissions in the life cycle of a product or system. The LCA methodologies are designed to give a complete picture of inputs and outputs with respect to generation of air pollutants, energy

Table 1
Recent CF studies of agricultural production highlighting different categories of contributing factors considered by the studies.

Study	FR[a]	Fuel	SE	EL	PCI	PMI	AM	ENT	CS	SA	IF	LUC
Hillier et al., 2009	T_2[b]	NR[c]	NR	NR	T_2	NR	NR	NA	NR	T_2	NR	NR
Cavigelli et al., 2009	T_2	T_2	T_3	T_2	NR	NR	NR	NA	NR	NR	NR	NR
Rotz et al., 2010	T_2	T_2	NR	T_2	T_2	NR	NR	T_3	NR	NR	T_2	NR
Page et al., 2011	T_1	T_1	T_1	T_1	T_2	T_1	NR	NA	T_2	T_1	NR	NR
Flysjö et al., 2011	T_2	T_2	T_2	T_2	NR	NR	NR	T_2	NR	NR	NR	NR
Gan et al., 2014	T_2	NR	T_3	NR	T_2	NR	NR	NA	NR	NR	NR	NR
Roer et al., 2012	T_3	T_2	T_3	NR	T_2	T_2	T_2	NA	T_3	T_2	T_2	NR
Bosco et al., 2013	T_1	T_2	T_3	T_2	T_2	T_2	NR	NA	T_3	NR	T_2	NR
Vergé et al., 2013	NR	T_2	NR	T_2	T_1	T_2	NR	NA	NR	NR	NR	NR
Roer et al., 2013	T_3	T_2	T_3	T_2	T_2	T_2	T_2	T_3	T_3	T_2	T_2	T_2
Xu et al., 2013	T_2	T_2	T_2	T_2	T_2	T_2	NR	T_2	T_2	NR	NR	NR
Yan et al., 2013	T_2	T_2	T_2	T_2	NR	NR	NR	T_3	NR	NR	NR	NR
Van Middelaar et al., 2013	T_2	T_2	T_3	T_2	T_2	NR	T_2	T_2	T_3	T_2	NR	T_2
Knudsen et al., 2014	T_1	T_2	T_2	T_2	T_2	NR	NR	NA	T_1	NR	NR	T_1
Jensen and Arlbjørn, 2014	T_2	T_2	T_1	T_2	T_2	T_2	NR	NA	NR	NR	NR	NR
Gan et al., 2014	T_2	T_2	T_2	T_2	T_2	T_2	NR	T_2	T_2	NR	NR	NR
Proietti et al., 2014	T_2	T_2	T_2	T_2	T_2	T_2	NR	T_2	T_2	NR	NR	NR
Cheng et al., 2015	T_2	T_2	T_2	T_2	T_2	T_2	NR	NA	NR	T_2	NR	NR
Bartzas et al., 2015	T_2	T_2	NR	T_2	T_2	T_2	T_2	NA	NR	T_2	T_2	NR
Jianyi et al., 2015	T_2	T_2	T_2	T_2	T_2	T_2	NR	T_2	NR	T_2	T_2	NR
Ruviaro et al., 2015	T_2	T_2	T_2	T_3	NR	T_2	NR	T_2	NR	NR	NR	NR
Adewale et al., 2016	T_2	T_2	T_3	T_3	T_2	T_3	T_3	NA	T_3	T_3	T_3	T_2
Cerri et al., 2016	T_2	T_2	T_2	T_3	T_2	T_2	NR	T_2	NR	NR	NR	NR
Cordes et al., 2016	T_2	T_2	T_1	T_2	T_2	T_2	NR	NA	NR	T_2	NR	T_1
Pishgar-Komleh et al., 2017	T_2	T_2	T_2	T_2	T_2	T_2	NR	NA	NR	T_2	T_2	NR
Ali et al., 2017	T_1	T_2	T_1	NR	T_1	T_2	NR	NA	NR	NR	NR	NR
Ntinas et al., 2017	T_2	T_2	NR	T_2	T_2	T_2	NR	NA	NR	NR	NR	NR
de Figueiredo et al., 2017	T_2	T_2	T_2	NR	T_2	T_2	NR	T_2	T_2	NR	NR	NR

[a] FR = Fertilizers, SE = Soil emission, EL = Electricity, PCI = Pesticide and chemical inputs, PMI = Plastic and material inputs, AM = Agricultural machinery, ENT = Enteric fermentation, CS = Carbon sequestration, SA = Soil amendments, IF = Infrastructure, LUC = Land use change.
[b] T_1 = Tier 1 emission factor, T_2 = Tier 2, T_3 = tier 3.
[c] NR = Not Reported, NA = Not Applicable.

consumption, water use and wastewater generation, GHGs emitted, or any other environmental impact category of interest. For the purpose of carbon footprinting, LCA estimates the GHGs emitted and embodied at each identified step of the product's lifecycle. Identifying the system boundary is one of the most important steps in LCA protocols for CF modelling (Matthews et al., 2008). In practice, system boundaries should clearly define the following: (i) The boundaries between nature and the system under study; (ii) the boundaries between included and excluded unit processes in the system under study; and (iii) the boundaries between the system under study and any related external systems that might share any flow of energy or mass (Tillman et al., 1994; ISO, 2006).

Past CF studies of agricultural production have considered four to eleven categories of contributing factors (Table 1 and Fig. 2). Inconsistency in the factors considered in CF estimation preclude equitable CF reporting for agricultural products. The importance of the choice of system boundary was illustrated by Roer et al. (2012), who found that CF of barley production was reduced by 9%, 6%, and 30% when machinery manufacturing, building infrastructure, and humus mineralization (soil emission) were excluded from the boundary, respectively. These are factors that are not commonly included in agricultural CF studies (Table 1). This shows that CF estimates can greatly underestimate real system or product CFs and miss opportunities for CF reduction unless comprehensive and consistent system boundaries are adopted in CF protocols for agricultural systems.

The boundaries of agricultural CFs and the detail for processes within the boundaries have gradually broadened over the past 8 years (Table 1). In 2009–2011, many agricultural CFs considered only a few inputs such as fertilizers, fuel use, and electricity, or used lower-tier EFs. By 2012–14, more studies were including plastics and farm operations. In 2015–2016, agricultural CFs commonly included seven or more major factors at tier 2 to 3 specificity. New CFs should be expected to meet consistent and broad boundary definitions. We propose that future agricultural CFs should include, where applicable, the following: land-use change, farm infrastructure, electricity use, machinery, farm operations, fuel use, pesticide and other chemical inputs, plastics and other material inputs, fertilizer, SOC sequestration, soil GHG emission, and livestock enteric fermentation.

2.2. Soil emissions and carbon sequestration

Many studies have raised the need to include soil C dynamics in agricultural CFs (Bosco et al., 2012; Adewale et al., 2016), particularly because soil C sequestration is often identified as a viable GHG mitigation strategy (Wiesmeier et al., 2014; Lal et al., 2015). The soil C pool capacity is about 3 times the size of the atmospheric C pool, 4 times the size of the biotic C pool (Ciais et al., 2014), and may have the potential to sequester 3.8 PgC per year (Fig. 1) (Lal et al., 2015). The potential soil C sink capacity of managed ecosystems approximately equals the cumulative historic SOC loss of 55 to 78 Pg (Lal, 2004a). Inherent place-based factors including soil texture and climate affect soil C content and sequestration potential (Batjes, 1998; Lal, 2004a; Baker et al., 2007). However, managed systems may have more capacity for C sequestration than non-managed systems for the following reasons: (i) past management has reduced the current SOC to below its capacity; and (ii) cultivated systems experience less N, P, water, and other limitations to plant biomass production than native or non-managed systems do, increasing their capacity beyond native levels (Zan et al., 2001; Reich et al., 2006). Agricultural practices that minimize soil disturbance, conserve soil and water, add large amounts of biomass to the soil, enhance activity and diversity of soil fauna, improve soil structure, and strengthen nutrient cycling tend to increase SOC sequestration (Lal, 2004b). Consequently, a successful agricultural GHG mitigation strategy must consider the C sequestration implications of different agricultural activities in a site-specific context.

Yet, few CF studies have accounted for soil C emission and

Fig. 2. Three different levels of system boundaries commonly used in agricultural carbon footprint studies.

sequestration (Table 1). For instance, Rotz et al. (2010) did not account for soil C sequestration or depletion in dairy production systems. Gan et al. (2011) determined the CF of durum wheat produced in various cropping systems using the total GHG emission from the decomposition of crop residues, tier 2 direct soil N_2O emissions from the synthetic N fertilizer and crop residue N, and additional N_2O emissions from fertilizer-based water pollution and volatilization of NH_3, NO, and NO_2; however, soil C accounting was not considered. Similarly, Hillier et al. (2009) determined the CF of multiple crops, including potatoes, winter cereals, winter oilseed, spring cereals, and legumes, and field operations like fertilizing, tillage and pest management in Scotland using published EFs; however, the impact on soil C balance was not mentioned. Many other studies have reported the CF of farms and farm products without considering soil C sequestration potentials (Gan et al., 2012; Yan et al., 2013; Ortiz-Rodríguez et al., 2016).

When included, soil C can significantly affect an agricultural CF. Bosco et al. (2013) and Xu et al. (2013) considered changes in soil organic matter (SOM) and C sequestration in the CF estimates of vineyard and rice production, respectively. Bosco et al. (2013) found that, by incorporating SOM accounting into the wine chain's CF analysis, the vineyard phase (agricultural production) changed from a source of GHG to a modest net GHG sink and reduced the overall CF of one bottle of wine (0.75 L) from 0.663 to 0.531 kg CO_2e. Adewale et al. (2016) considered both soil C loss and gain, and found net soil emission to contribute 12% of the CF of a small-scale vegetable farm. Consequently, a comprehensive view of net GHG emissions attributable to a particular farm, farm product, or field activity needs to reflect soil C emission or sequestration of each farming activity (Brandão et al., 2011). This is an important consideration for identifying agricultural practices that could result in a successful GHG mitigation campaign.

Estimating soil GHG emissions attributable to different farming activities does pose many challenges. For instance, there are substantial discrepancies in estimates of soil C both at global and field scales (Todd-Brown et al., 2013; Scharlemann et al., 2014). Likewise, the dynamics of labile and recalcitrant soil C pools is still a subject of ongoing debate (Hassan et al., 2015; Lehmann and Kleber, 2015; Halvorson et al., 2018). Methods to directly measure agricultural N_2O emissions or to accurately estimate N_2O emissions have been the subject of multi-decadal debate (Hutchinson and Mosier, 1981; Smith et al., 1995; Freibauer, 2003; Huang and Gerber, 2015), in part due to high temporal and spatial heterogeneity of N_2O emissions. These difficulties and debates can be addressed by standardizing methodology for estimating soil emissions and SOC change (Olson et al., 2014). The potential importance and the current difficulty in measuring soil GHG fluxes argues for a concerted development of consistent methods and models that utilize site-specific information.

2.3. Emission factor tiers

The dearth of tier 2 and 3 agricultural EFs further exacerbates uncertainty in CF modelling. Currently, studies primarily use IPCC tier 1 and tier 2 EFs (Eggleston et al., 2006), which carry an uncertainty ranging from −50 to +100% (Philibert et al., 2012; Röös, 2013). For instance, none of the studies identified in Table 1 used tier 3 EFs for fertilizer. Many studies have shown a high uncertainty in emissions of N_2O from agricultural soils due to synthetic and organic nitrogen (N) fertilization (Flynn et al., 2005; Philibert et al., 2012). Tier 1 EF for N fertilizer cannot adjust for crop type or climatic conditions, which greatly affect N_2O emissions. Philibert et al. (2012) found that the IPCC tier 1 EF of N fertilizer was an overestimate compared to both measured emissions and 13 different models. In addition, GHG emissions from soil are often nonlinearly related to the quantity of input. The emission of N_2O in response to synthetic N inputs has been found to be exponential in for most crops (Shcherbak et al., 2014). These findings contradict the fundamental linear relationship of input and emission assumed by tier 1 EFs.

Other factors, such as soil C, soil pH, and N-fixing capability of the crop (Shcherbak et al., 2014), farming system, and specific N source (Skiba et al., 2016), also influence fertilizer-derived N_2O emissions. Skiba et al. (2016) found that 1.3% of N fertilizer applied to grassland, but only 0.5–0.8% of that applied to arable crops, was released as N_2O. The study also found the EFs for cattle dung and urine to be 0.2% and 0.7% respectively, as compared to 2% IPCC-tier 1 EF (Skiba et al., 2016).

Unlike tier 1 EFs, tier 3 methodologies are developed using more complex process-based model simulations or in situ measurements. Several studies have argued higher tier methodology to be more accurate and/or have lower uncertainties compared to IPCC-tier 1 methodology (Lokupitiya and Paustian, 2006; Buckingham et al., 2014). For instance, Kouazounde et al. (2015) estimated tier 2 EF for cattle from Benin to be 27.4% higher than the default IPCC-tier 1 EF for African cattle. Karimi-Zindashty et al. (2012) also identified the use of IPCC tier 1 EF as the greatest source of uncertainty in estimating methane emissions from livestock in Canada. Charles et al. (2017) also demonstrated that the IPCC tier 1 EF value (1%) for N_2O emissions was too high when considering the N_2O contribution from agricultural soils amended with organic fertilizers. The study conducted a meta-analysis on spatio-temporal variability of N_2O emissions from agricultural soils and specifically examined the effect of organic amendments on cumulative fluxes of N_2O and EF using a general matrix of results from 38 selected studies. In addition to finding the global EFs to range from −0.99 to 12.80% of N applied, the study also reported the average EF for soils amended with organic fertilizers, organic combined with synthetic fertilizers, and synthetic fertilizers alone to be 0.82%, 1.50%, and 1.34% respectively (Charles et al., 2017). Peter et al. (2016) concluded that the development of tier 3 EFs for agricultural inputs that influence land-based emissions is critical for improving the accuracy of CF estimation of agricultural products. Tier 3 EFs are needed for a diverse range of inputs and soil amendments. This is an important step toward correcting underlying assumptions of tier 1 EFs, capturing differences in farming systems, increasing accuracy of EFs, and reducing uncertainties of agricultural system CF estimation and comparison.

3. The carbon footprint of organic agriculture

3.1. Comparing organic and conventional agriculture

Organic agriculture presents a useful subset of agriculture for CF studies due to its mandate to maintain or improve natural resources, and its annual certification process. Hundreds of studies have assessed the effects of organic agriculture on environmental impacts, often finding benefits over conventional systems. In their meta-analysis comparing the environmental impacts of organic and conventional farming in Europe, Tuomisto et al. (2012) found organic farming practices had several positive impacts per unit area including greater SOM content, less nutrient loss, and less energy use.

But there is no single answer as to whether organic agriculture produces more or less GHG than conventional agriculture, as the findings differ based on the product and particular farms studied. The same study (Tuomisto et al., 2012) reported organic farming systems had greater ammonia emissions, nitrogen leaching, and N_2O emissions per unit product. Olsen et al. (2015) reported that organic milk and organic pork production often had greater GHG emissions per unit product than in conventional systems, but organic beef production had lower GHG emissions per kg beef than conventional production. Meier et al. (2015) compiled data from 34 studies comparing LCAs of organic and conventional agriculture. Eight of these studies assessed GWP in fruit and vegetable production, finding the GWP of organic products ranged from −81 to +130% of the conventional products per unit product (Meier et al., 2015). With such great variability, no clear-cut conclusion can be made in comparing the CF of systems overall.

Similarly, different units of comparison (per unit area or per unit product) often lead to different conclusions. A comprehensive LCA of 18 grassland farms in Germany (Haas et al., 2001) found organic and extensified farming systems to have lower GWP per unit area (6.3 t $CO_2e\ ha^{-1}\ yr^{-1}$) compared with conventional intensive systems (9.4 t $CO_2e\ ha^{-1}\ yr^{-1}$); however, GWP per unit of milk were similar. A global meta-analysis by Skinner et al. (2014) reported the N_2O emissions from organically managed soils to be lower than emissions from conventionally managed soils per unit area by 492 ± 160 kg $CO_2e\ ha^{-1}\ yr^{-1}$, but slightly greater per unit crop yield by 41 ± 34 kg $CO_2e\ t^{-1}$ dry matter.

Clearly, depending on the product and specific inputs and operations of the farm studied, both organic and conventional production systems can offer CF advantages. The CF of agriculture overall may be reduced by identifying inputs and practices that work and can be replicated elsewhere, regardless of system certification or label. A fair and useful comparison between systems must therefore account for as many factors as possible, using broad and consistent boundaries, in order to encompass potential differences and identify potential replicable improvements. For instance, common management practices in organic systems significantly alter the average SOC content and pesticide use (Reganold and Wachter, 2016) as compared to conventional systems. Therefore, only CF studies that include soil emissions and materials such as pesticides within the boundary will accurately capture the differences in CF caused by soil management and pesticide use. Moreover, the use of different boundaries, different tiers of EFs, and lack of consideration for specific characteristics of different farming systems may make direct comparison of past studies inappropriate (Chen and Corson, 2014; Notarnicola et al., 2017). Also, extending the comparison of organic and conventional agriculture beyond climate performance is crucial to have a comprehensive and balanced view of the systems.

3.2. Organic farming demands complex carbon accounting

The role of organic farming in C sequestration has been a much debated subject over the last 3 decades. Many studies have attempted to answer the question of whether organic farms sequester more C than conventional farms. Multiple meta-analyses comparing organic and conventional farming have concluded that soils in organic farming systems have a higher content of organic matter (Mondelaers et al., 2009; Gattinger et al., 2012; Tuomisto et al., 2012). Organic systems are more likely to sequester C because organic amendments, cover crops, and livestock integration are commonly used (Brock et al., 2011; Liang et al., 2012), although these practices are not unique to certified organic systems. The potential importance of C sequestration in agricultural GHG mitigation justifies consistently acknowledging organic inputs and C sequestration within the boundary of agricultural CFs.

Organic farms tend to use more complex crop rotations than conventional farms (Stockdale et al., 2001; Bengtsson et al., 2005), making them more difficult to assess with LCA and C models (Brankatschk and Finkbeiner, 2015). For instance, the use of cover crops as nutrient catch crops and green manures is more prevalent in organic farming systems. Cover crops become nutrient inputs for the following crops, which presents a unique temporal challenge for LCA protocols. Extensive crop rotations and cover crops necessitate multi-year analysis of the crop-soil C cycle and total CF. Multi-year effects add complexity to the accounting of individual cash crops (Bessou et al., 2013), in contrast to the more common annual basis of fertilization and CF analysis of most conventional farms and farm products.

3.3. Need for tier 3 emission factors of organic agricultural inputs

The prohibition of synthetic N sources in certified organic agriculture begets a reliance on organic materials to supply crop nutrients (Gattinger et al., 2012; Leithold et al., 2015). Tier 3 EFs are needed for organic inputs because of their direct influence on soil N_2O emission, their effect on SOC, and their unique system boundaries.

N fertilizers are significant determinants of N_2O emissions from agricultural soils (Petersen et al., 2006; Skinner et al., 2014). Organic farming systems are often found to have lower N_2O emission due to the use of organic amendments to meet crop nutrient needs (Watson et al., 2002). Organic amendments have lower CF because their production does not require intensive energy as inorganic N-fertilizers (McLaughlin et al., 2000). These organic inputs themselves are also a C input, with differing half-lives in soil (Karhu et al., 2012; Maillard and Angers, 2014). Organic C content of the soil in turn influences fertilizer-derived N_2O emissions (Shcherbak et al., 2014). Thus, developing tier 3 EFs for organic inputs will aid our understanding of the impact of organic farming inputs on N_2O emissions, C sequestration, and total CF.

The process of creating an EF for an agricultural input is itself an exercise in carbon footprinting. An input has its own inputs, processing, and transportation within a defined boundary, which are quantified to calculate the EF (Crosson et al., 2011). Organic materials used as fertilizers have different system boundaries than synthetic or mined fertilizers, and therefore require development of different EFs. For example, many organic farms use compost or organic fertilizers produced from waste emanating from conventional livestock production or food processing (Watson et al., 2002). Most studies assign zero CF for the direct use of materials that are byproducts of other processes, but only account for the GHG impact for the transport, processing, and handling of the material. However, an argument could be made for the opportunity cost of the GHG that could have occurred had the material not been used for organic fertilizer and instead had been managed as waste. Capturing the opportunity cost of waste management benefits of organic inputs made from biological wastes is important for full accounting of organic farming system CF.

The need to consider the unique temporal and spatial boundaries of most organic inputs necessitates development of tier 3 EFs for CF modelling of organic farming systems. Specific tier 3 EFs for organic inputs must use expanded boundaries, which will help avoid underestimation of GHG that is often associated with narrowly defined boundaries (Matthews et al., 2008; Adewale et al., 2016). Expanding the available tier 3 EFs for agricultural materials overall and organic inputs in particular will increase the comprehensiveness and accuracy of CF of whole organic and integrated agricultural systems.

3.4. Organic farming certification to validate C sequestration and GHG mitigation

Organic agricultural systems may be an important model for low-CF or high C-sequestering agriculture. Moreover, the organic certification process presents an opportunity to validate predicted soil C changes. Many consumers are interested in organic products not only because they are perceived to be safer for human health, but also because they are considered to be less detrimental to the environment (Brandt and Mølgaard, 2001). This perception, especially in the US, is rooted in the National Organic Program (NOP) final rule ~ 7 CFR 205.203(c): *"The producer must manage plant and animal materials to maintain or improve soil organic matter content in a manner that does not contribute to contamination of crops, soil, or water by plant nutrients, pathogenic organisms, heavy metals, or residues of prohibited substances."* (National Organic Program, 2015). Soil C stewardship is therefore a key principle in organic farming. Additional guidance on meeting this natural resource management requirement for USDA organic certified farms was issued in 2015 (National Organic Program, 2015). However, there is no consistent method to estimate or monitor the actual maintenance or improvement of SOM or other environmental services in certified organic agroecosystems.

Organic farming already has a potential monitoring mechanism through the annual process of certification. Each farm unit selling products with the USDA organic label undergoes an annual inspection and re-certification (National Organic Program, 2015). Globally, similar requirements and certification are implemented through the International Federation of Organic Agricultural Movements, Quality Assurance International, and other certifiers. Integrating CF and SOC monitoring into the organic farming certification process would improve compliance with the final rule and dramatically increase the information available about C sequestration and CF of organic agricultural systems and practices. The development of tier 2 and 3 EFs for organic inputs and practices will increase the usefulness of the information provided through the annual organic farm certification. Ideally, the farm inventory and activities would link to a CF calculator populated by tier 3 EFs. Such an effort could dramatically increase our understanding of farming activities and effects of inputs on C sequestration and GHG emissions.

4. Conclusion

Several studies have called for more tier 3 EFs in order to increase the accuracy and usability of GHG estimation methodology for agriculture. In this paper, we have further expanded and consolidated the argument for broad and consistent boundaries for agricultural CFs, inclusion of soil emissions and C sequestration, and development of more agricultural tier 3 EFs. Boundaries of an agricultural system CF should be expected to include not only the commonly considered fertilizer, fuel, and electricity, but also farm infrastructure and machinery, pesticides and other chemical inputs, plastics and other materials, land-use change, soil emissions and C sequestration, and livestock enteric fermentation. Any of these factors can prove essential in differentiating systems or identifying best practices for CF reduction. Further, tracking farm operations is necessary to parse machinery and fuel use and soil carbon changes sufficiently to support decision-making by growers.

Organic agriculture commonly carries a lower CF than conventional agriculture on an area basis, and sometimes on a product unit basis. The potential advantages of practices commonly used in organic agriculture, along with the annual inspection and certification process, justify the future use of certified organic farms as a longitudinal national or international study population. Owing to the potential importance of organic fertilizers and methods in GHG mitigation efforts, there is a critical need for tier 3 EFs particularly for organic inputs.

Declarations of interest

None.

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