Improving the accounting of land-based emissions in Carbon Footprint of agricultural products: comparison between IPCC Tier 1, Tier 2 and Tier 3 approaches

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ABSTRACT

In this paper, we discuss different methods to calculate greenhouse gas field emissions from fertilization and soil carbon changes to be integrated into Carbon Footprint (CFP) of food and biomass products. At regional level, the simple Tier 1 approach proposed in the IPCC (2006a) AFOLU guidelines is often insufficient to account for emission variability which depends on soil type, climate or crop management. However, the extensive data collection required by Tier 2 and 3 approaches is usually considered too complex and time consuming to be practicable in Life Cycle Assessment. We present four case studies to compare Tier 1 with medium-effort Tier 2 and 3 methodologies. Relevant differences were found: for annual crops, a higher Tier approach seems more appropriate to calculate fertilizer-induced field emissions, while for perennial crops the impact on CFP was negligible. To calculate emissions related to soil carbon change higher Tiers are always more appropriate.

Keywords: agricultural production, GHG accounting, regional variability, field emissions, soil carbon change

1. Introduction

During the last decade, the interest of companies and policy makers in Carbon Footprint (CFP) as a supporting tool to assess the global warming impact of food and biomass productive processes and to design impact reduction plans has grown. All greenhouse gas (GHG) emissions occurring within the established boundaries of such a study have to be taken into account, as instructed in the ISO 14067 (2013), the most recent international reference standard for the development of CFP studies.

Land-based CO_2 and N_2O emissions from fertilization and crop residues management can account for a considerable amount in the GHG balance of food and bioenergy products, together with CO_2 fluxes due to soil carbon change (Brentrup et al. 2000; Petersen et al. 2013), but they are often disregarded in CFP studies. IPCC guidelines for National GHG Inventories (IPCC 2006a) provide, within the fourth volume dedicated to Agriculture, Forestry and Land Use sector (AFOLU), three calculation pathways (Tiers) for the accounting of these land-based emissions characterized by different degrees of complexity: Tier 1 level includes the less accurate methodologies, which can be applied by using the provided global emission factors; the Tier 2 level methodologies require using emission factors specific for the region which is subject of the study, while Tier 3 level methodologies are based on measurements or simulations performed by models. The mentioned IPCC guidelines suggests always using a more accurate methodology if possible, and provides decision trees to support the identification of the suitable Tier.

At regional and sub-regional level, Tier 1 level methods are not always sufficiently accurate to account for geographical variation of emissions dependent on different soil, climate or management practices. Conversely, field measurements and extensive data collection required by higher Tiers (Tier 2 and Tier 3) are usually considered too complex and time consuming to be practicable in the development of Life Cycle Assessment (LCA) studies.

The first aim of this paper is to test assessment methods at Tier 2 and Tier 3 level to calculate land-based GHG emissions from crop cultivation with medium efforts for stakeholders. The selected Tier 2 method consists of calculating N_2O emissions from fertilization in consideration of pedoclimatic and crop management conditions based on Bouwman et al. (2002) and the Tier 3 method of simulating CO_2 fluxes occurring as consequence of soil carbon stock change based on Petersen et al. (2013). The second aim is to assess and compare the influence of the variability of regional inventory data on CFP results, depending on the adoption of Tier 1 or Tier 2 and Tier 3 accounting methods. We performed analysis in four case studies: two wheat croplands in Germany and one peach orchard in Italy managed with two different regimes. The choice of case studies was based on different soil characteristics, climate conditions and crop types (annual and perennial), to test how different methodologies may represent this variability.

2. Materials and Methods

2.1. Methodologies for the assessment of fertilization induced emissions on field

The simple IPCC Tier 1 method (IPCC 2006a) for calculating the emission of nitrous oxide (indirect and direct N_2O) from managed soils only takes into account 1% of the anthropogenic N inputs on the field. This approach disregards differences of crop type, fertilizer type, management system and local climate conditions. In contrast, considering all these agricultural relationships to calculate N_2O, NO and NH_3 emissions, the heterogeneity of environmental and management conditions occurring in agriculture would be reflected more accurately.

We have chosen the model approach from Bouwman et al. (2002) for direct and indirect N_2O emissions and the approach from FAO and IFA (2001) for NH_3 volatilization. These methods are more performant on the local scale and under different agricultural management systems to reduce the uncertainty range within the global emission Tier 1 factors (IPCC 2006a). Implementing this Tier 2 approach more detailed data are required. The multivariate empirical model of Bouwman et al. (2002) divides the parameters which have an influence on the N_2O and NO emissions into specific categories (fertilizer type and application rate, crop type, soil texture, soil organic carbon (SOC), soil drainage, soil pH and climate type), for each factor. NO and NH_3 emissions were converted to N_2O based on IPCC (2006a) by the factor 0.01. For the NH_3 emissions induced from organic fertilizer (mature and liquid manure, digestate, poultry manure) we made an exception and used the model approach based on KTBL (2009). CO_2 emissions from the application of urea and liming on soil were calculated based on Tier 1 IPCC (2006a) factors.

2.2. Methodologies for the assessment of emissions from soil carbon stock change

To include the soil carbon change into the CFP accounting the Tier 1 and the Tier 3 methodology have been tested and compared.

The simple Tier 1 is explained in Chapter 5 of Volume 4 (cropland remaining cropland) of IPCC guidelines (IPCC 2006a). The soil organic carbon reference (SOCref) under native vegetation, has to be selected depending on six soil types and nine climate regions, together with three relative stock change factors: F_{LU} related to land use, F_{MG} related to tillage regime and F_I related to carbon input level. These factors are characterized by different error ranges (between ±5% and ±50%) and have to be selected, based on the climate region, for both conditions before and after the management or land use change occur.

The Tier 3 methodology consists in a simulation of the turnover of carbon in soil with the model Roth C 26.3 (Coleman and Jenkinson 1999), integrated with the Bern Cycle Model as suggested by Petersen et al. (2013); the Bern Cycle Model (IPCC 2007) simulates the decay of CO_2 in the atmosphere in order to represent the release of CO_2 into the atmosphere over several years. The outputs of the Roth C simulation are the CO_2 emissions and removals related to soil organic carbon change. The Roth C simulations were run for both scenarios (baseline and changed) for a number of years sufficient to reach the equilibrium (n), and the resulted emissions and removals were divided by the same number of years in order to obtain the yearly figures. The following equation was used to calculate the Tier 3 results:

$$\Delta CO_{2\,(n)}\ [t\ CO_2\ year^{-1}] = [(CO_2\ E_{CS} - CO_2\ E_{BS}) + (CO_2\ R_{CS} - CO_2\ R_{BS})]/n \qquad \text{Eq.1}$$

where $\Delta CO_{2\,(n)}$ represents the net balance of CO_2 in the atmosphere after *n* years, related to crop management change; E_{CS} and E_{BS} are the emissions resulting from soil organic matter decomposition after *n* years, respectively in changed scenario and in baseline scenario; R_{CS} and R_{BS} are the removals resulting from carbon stored in soil after *n* years in the changed scenario and in the baseline scenario.

2.3. Field experiments

Four field trials were selected based on crop type (annual crops and perennial crops), soil and climate conditions. Characteristics of experimental sites are presented in Table 1. The two winter wheat experiments were cultivated as sole-food-crop at two different sites in Germany (Site 1 and 2). They were sown at the end of September after ploughing and harvested in the following summer (end of June), leaving the straw at field. The rate of nitrogen fertilizer was determined site-specifically and split into 50% mineral and 50% organic N-fertilizer (digestate).

The perennial crop field trials were conducted on a peach orchard located in Southern Italy (Site 3). The orchard was divided in two plots, one cultivated with local management practices and one converted to improved management practices. The local management regime consisted of: no tillage, micro-jet sprinkler irrigation, pruning residues mulched and left on field, chemical weed control with glyphosate and mineral fertilization based on experience. The improved management regime introduced some innovative: drip irrigation based on daily water balance, spontaneous grass cover mowed twice per year, precision fertilization based on periodic monitoring of soil nutrient availability and organic fertilization with 10 tons of compost per hectare and year.

We assumed that no land use change occurred in our four case studies, but the cultivation management changed. In the winter wheat case studies the straw management was changed. Before the change all straw was harvested to be used for energy production or animal feeding. However, after the change it was left at field and incorporated later. In peach orchard experimental site managed with local regime the change occurred after the orchard establishment, when pruning residues started to be incorporated in the field instead of being burned (as in the past orchard). In the plot converted to improved management one more change occurred: compost and grass cover were added to the soil to increase the quantity of the carbon input comparing to the local management regime.

Table 1: Characteristics of experimental sites

Site number	**1**	**2**	**3 (Local and Improved)**
Crop	winter wheat (*Triticum aestivum L.*)	winter wheat (*Triticum aestivum L.*)	Peach (*Prunus Paersica*) Variety Big Bang/ GF/677 Trained to delayed vase Layout: 5,50 x 4
Name	Ascha	Dornburg	Scanzano Jonico
Period of data collection	2011-2013	2011-2013	2006-2013
Country	Germany (south)	Germany (central)	Italy (south)
Geographical location	48°59´N 12°39´E	51°00´N 11°39´E	40°14´N 16°42´E
Height above sea level (m)	431	247	16
Soil type	Stagnic Cambisol	Luvisol	Eutric Vertisols
Soil texture	Loamy sand	Silty clayey loam	Sandy clay loam
pH-value	5,1	7,4	7,4
Bulk density (g/cm³)	1,7	1,5	1,5
SOC (%)	0,5	0,5	1,3
Total annual precipitation (mm) (long term mean)	957	582	550
Mean temperature (°C)	8,3	9,6	16,8

2.4. Goal and scope, Life Cycle Inventory and Impact Assessment

Greenhouse gas emissions of the four crop cultivations were investigated according to the standards ISO 14040 (2006), ISO 14044 (2006) and ISO 14067 (2013).

The focus in the case studies was on the agricultural activities during the food production, which is why the selected functional unit was the unit of cropland (1 hectare). System boundaries were fixed from cradle to farm gate, starting with production of all inputs (seeds, fertilizers, pesticides, agricultural machinery and fuels) and ending with harvesting the crop, encompassing all direct and indirect emissions

For peach case studies, the whole life cycle of the orchard has been included within the time boundaries, from the first year of orchard establishment till the last year before removal, coherently with the most common practice of LCA sectorial studies about fruit production from perennial tree crops (Cerutti et al. 2010; Milá i

Canals and Polo 2003). The considered impact category was the Global Warming Potential (GWP) – 100 years with the characterization factors from the "CML, 2001" method (Ecoinvent 2013).

The calculation of CFP have been divided in three main parts: land based emissions from fertilization, CO_2 fluxes from soil carbon change, and all other impacts from agricultural operations.

Consequences of methodological choices have been analyzed by comparing the CFP results based on IPCC Tier 2 and Tier 3 approach with the reference CFP results based on IPCC Tier 1.

3. Results and discussion

Applying the approach from Petersen et al. (2013) it is possible to evaluate if the change in crop management practices results or not in a net saving in terms of CO_2 released to the atmosphere. For the wheat case studies (Site 1 and 2), the CO_2 removed from atmosphere caused by soil carbon stock change is much lower using Tier 3 than using Tier 1. This means that for changes in management practices of annual crops (straw added to soil) the Tier 1 overestimates the benefits in terms of carbon stored in soil (Figure 1 B). This result is determined by the stock change factor related to carbon input level F_I. Performing the calculation with Tier 3, the real quantity of straw added to soil is considered, which results in a lower saving of CO_2 linked to soil carbon stock change. In both case studies of winter wheat (site 1 and 2) the Tier 3 estimates are outside the error range indicated in Tier 1.

For the peach orchard case study the situation is opposite. The amount of CO_2 stored in soil is much higher using Tier 3 than using Tier 1(Figure 1 D). The stock change factors from Tier 1 are not sufficient to represent the real entity of soil carbon change in a perennial crop. Even if the Roth C model does not consider the effect of tillage on CO_2 emission from soil organic matter decomposition, the Tier 3 methodology gives higher results in terms of soil carbon change than Tier 1 in the case of perennial crops. In the peach case studies the results of Tier 3 methodology are inside the error range forecasted for Tier 1.

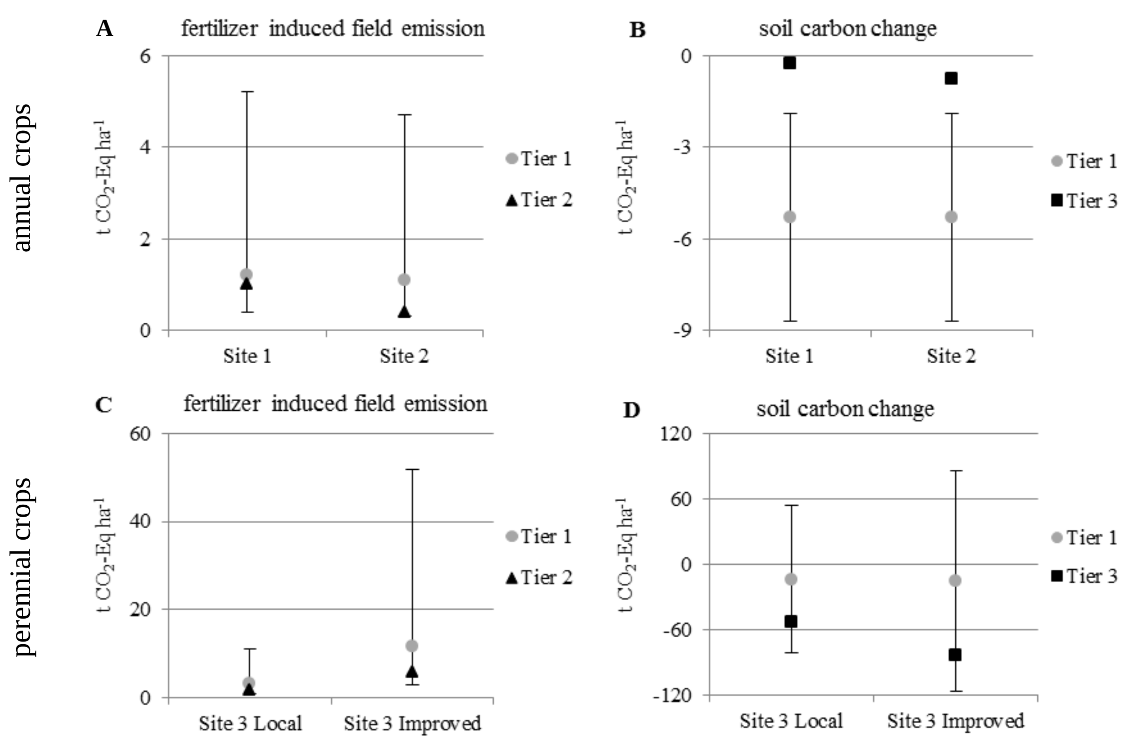

Figure 1. Comparison of the emissions from fertilizer applied on field and soil carbon change calculated with Tier 1 and Tier 2/3 approaches for the four case studies (Site 1 and 2: mean values from two cultivation years at each site, Site 3: values are summed up over 13 years)

For annual crops (wheat cropland), field emission from fertilizer application is an important factor, accounting for almost 50% of the whole CFP-emissions calculated with Tier 1 at Site 1 and 2. In contrast, for perennial crops (peach orchard) the amount of emissions from fertilizer application is less than 25%. Using a higher Tier (Bouwman et al. 2002) to calculate GHG emissions from fertilizer application on field, the CFP is reduced by −8% for wheat production in Site 1, −28% for wheat production in Site 2, −6% for peach production in Site 3 with local management and −12% with improved management. Looking at the Tier 2 fertilizer induced field emissions (Figure 1 A, C), the estimated values are in any case study lower than the Tier 1 approach, and are within the uncertainty range of ~ -70% to +350% reported for the default global emission factor from Tier 1.

As reported in the IPCC (2006a) guidelines, in many cases the global default values (Tier 1) are adequate to determine the field emissions like in one of our wheat case study (Site 1). But in most cases these factors have to be more specified based on environmental conditions (climate and soil characteristics) like in our wheat case (Site 2) as well as on crop management conditions like in our peach cases (Site 3 local and improved management). Considering these fertilizers induced field emissions a higher Tier approach will allow to detect more specific mitigation potentials.

4. Conclusion

We identified appropriate assessment methods on Tier 2 and Tier 3 approach level with medium efforts for stakeholders and explored the consequences of these methodological choices on CFPs of annual and perennial crops for land-based GHG emissions from crop cultivation. The results for fertilizer induced field emission calculation were consistent among studies, using the higher Tier (Tier 2) led to a reduction of the GHG emissions. We have observed that using the Tier 1 approach overestimates the field emissions from fertilization.

To include field emissions related to soil carbon stock change into CFP of agricultural products is challenging. A wide difference was found between results calculated with Tier 1 and Tier 3 methodologies.

A more shared consensus within the LCA practitioners community is needed about how to perform the calculation using higher Tiers, in order to improve the assessment of agriculture´s mitigation potential and support the development of GHG reduction plans in the primary sector. Using the Tier 1 approach can lead to wrong estimations, due to the qualitative nature of the relative stock change factor. This is why we suggest using the Tier 3 approach for perennial crops where CO_2 emission savings related to soil carbon change are more relevant and for annual crops to avoid an overestimation caused by the use of Tier 1.

Variability in methods can considerably affect the CFP from agricultural productions. A harmonization and more transparency in methods are necessary to distinguish between actual differences of case studies and differences caused by methods. For annual crops the higher Tier approach is very important to perform the fertilizer induced field emissions, for perennial crops on the other side the fertilizer induced field emissions have just a minor impact on the CFP. The soil carbon change is negligible because of the short cultivation period of annual crops. However, for perennial crops the soil carbon change should be considered in the CFP. Only a few more site-specific data are needed to perform these higher Tier approaches, which can be used in both methodological improvements.

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