# Carbon Footprint Estimation in the Agriculture Sector

**Divya Pandey and Madhoolika Agrawal**

**Abstract** The term "carbon footprint" has evolved as an important expression of greenhouse gas (GHG) intensity for diverse activities and products. Widespread public acceptance and the ease of conveying information about GHG intensity with this term has also attracted scientists and policy makers to review and refine its calculations. Standard methods for carbon footprinting have been prepared, and sector-specific standards are under development. These standards direct the procedures to carry out carbon footprinting through life cycle assessment in conjunction with GHG accounting, classifes activities into three tiers based on the order of emissions. Agriculture is the largest contributor to anthropogenic emissions of greenhouse gases, so the quantification of different agricultural practices is essential for identification of more sustainable practices. Carbon footprinting has potential as a tool for assessing and comparing GHG performances of different agricultural products along with identification of points to improve environmental efficiencies. Case studies on the application of carbon footprinting to cultivation practices are increasing in the scientific literature, but the majority of studies do not comply with the standard three-tier methodology. This leads to nonuniformity among different studies and their comparisons. Hence, a standard guideline addressing carbon footprinting specifically for agriculture is essential for the effective application of this tool in the quantification of GHG intensity, mitigation of global warming, and adaptation against future climate change scenarios.

**Keywords** Cultivation practices · Mitigation · Agricultural management · Three-tier methodology

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# 1 Introduction

Climate change has emerged as the biggest environmental and developmental challenge of the present time; it also influences the focal possibilities for sustainable development. The effects of climate change have already been felt all over the world, in diverse forms ranging from shifting weather patterns, receding ice caps, crop losses, altered distribution of precipitation, increased frequency and intensities of floods and droughts, and serious ecological imbalances. All of these effects also have resulted in significant economic losses (Stern 2006). To prevent projected and unforeseen disasters, global temperatures must not exceed 2 °C more than 1990 levels. For this, the atmospheric stock of greenhouse gases (GHGs) should be controlled to remain below 550 ppm in terms of $CO_2$ equivalents ($CO_2$-e). Among different GHGs, carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), sulfur hexafluoride ($SF_6$), perfluorocarbons (PFCs), and hydrofluorocarbons (HFCs) are the six important anthropogenic GHGs. GHG inventories can identify, quantify, and manage all sources and sinks of GHGs. Among different quantitative indicators, the carbon footprint has gained popularity and widespread application. Moreover, because of its ease of conveying information about the GHG intensity of variety of products and activities among the general public, carbon footprint also offers a simple mode of communication about climate responsibility of different entities between people, scientists, and policy makers. Scientific analyses of carbon footprinting are being conducted, mainly for consumer products and industrial processes; its application to agricultural systems is less, despite the fact that agriculture alone is responsible for GHG emissions to the largest degree. Here, we review the available scientific literature on the concept and calculations of carbon footprint, and its application to the agriculture sector. We begin with an overview of agriculture's role in regulating GHG fluxes, followed by the concept and general principle of carbon footprinting. Applications and challenges in using carbon footprinting in agriculture are also discussed.

# 2 Agriculture as a Source of Greenhouse Gases

Covering about 35 % of the land area, agriculture accounts for nearly 13.5 % of the total global anthropogenic GHG emissions, contributing about 25, 50, and 70 % of $CO_2$, $CH_4$, and $N_2O$, respectively (Montzka et al. 2011). As it is recognized that cereal production must increase at a rate not less than 1.3 % annually (Cassman et al. 2003), related emissions are also expected to increase. GHG emissions from agriculture originate mainly in the form of $CH_4$ from rice cultivating systems and cattle rearing and $N_2O$ from fertilizer management practices.

Rice fields alone emit 32 to 44 Tg $CH_4$ $yr^{-1}$ (Le Mer and Roger 2001). Del Grosso et al. (2008) estimated that agricultural activities add into the atmosphere about 4.2 to 7 Tg N annually in the form of $N_2O$. Due to their high global warming potential of 298, emissions of $N_2O$, even in a small quantity, cause significant radiative forcing. Increased soil temperatures coupled with high moisture conditions during cooler months will increase $N_2O$ production in soil. Elevation in $CO_2$ concentrations is also projected to increase $N_2O$ emissions from upland agricultural soils (Van Groeningen et al. 2011). Regarding $CO_2$, soil respiration is an important source, but the majority of the farm operations and inputs, such as fertilizers, pesticides, and energy, also have embodied $CO_2$ content.

The majority of GHG estimates cover only soilborne emissions, generally of $CH_4$ and $N_2O$ only, whereas numerous studies have been carried out targeting only $CH_4$ measurements (Le Mer and Roger 2001) and its mitigation from rice fields, mainly through water (Pathak et al. 2003), fertilizer, and manure managements (Linquist et al. 2012). Among different management techniques, mulching and organic manure applications are found to increase the emissions of $CH_4$ (Ma et al. 2007), whereas midseason drainage can cut $CH_4$ emissions significantly (Zou et al. 2005). Aerobic soils, on the contrary, may act as $CH_4$ sinks (Le Mer and Roger 2001; Smith et al. 2008) or sources (Ma et al. 2013), but they too are poorly quantified (Robertson 2000).

As a widely recognized effect, application of mineral nitrogen increased the emissions of $N_2O$. However, the effects of different management practices on emissions of all the GHGs are highly inconsistent, depending on the cultivation system and environmental conditions. Some inhibitors to methanogenesis and nitrification have also been tested in agricultural soils (Liu et al. 2010). It is found that frequency and timing of tillage also influence fluxes of soilborne GHGs. In the long term, the elimination of tillage reduced the emissions of $CH_4$ and $N_2O$, but increased $CO_2$ from rice cultivation (Pandey et al. 2012) as compared to conventional practice of regular tillage.

## 3 Agricultural Management as a Carbon Offsetting Option

Although, agriculture is an emissions source, there are opportunities for reducing the emissions and even using cultivated soils as a GHG offsetting tool if better management practices are identified and adopted (Hutchinson et al. 2007). Soils are the largest terrestrial carbon store; they hold carbon in the form of organic and inorganic molecules. Due to erosion and oxidation, a significant part of soil organic carbon has been lost. Scientific evidence suggests that 50–66 % of the cumulative historic carbon loss from soil can be recovered if managed intelligently (Lal 2004b). Increasing the organic carbon content in soil may lock the carbon out of the atmosphere for centuries a  phenomenon is termed as carbon sequestration. The two fundamental keys to support carbon sequestration in soils is minimization of soil disturbance and increasing inputs of organic matter. Therefore, cover crops, mulching, no tillage, organic manure, and decreasing the fallow period are among the recommended management practices (Lal 2004a). Improvement in nutrient status, particularly of nitrogen and phosphorous, also strengthens carbon sequestration; hence, intercropping with legumes and certain permutations of crop rotations are found to be greatly effective (Nishimura et al. 2008). It is estimated that under recommended management, soils of the European Union and UK, respectively, can offset 0.09–0.12 and 0.010 Pg C annually (Smith et al. 2005); at the global level, soils offer an annual sequestration potential of 0.6–2.0 Pg C (Lal 2000). Long-term studies have shown that organic manure application increases the carbon sequestration capacity of soil in the range of 70–551 kg C $ha^{-1}$ as compared to mineral fertilizer use (Mandal et al. 2007, 2008).

## 4 Understanding Product Carbon Footprints: Concept, Scope, and Calculation

Carbon footprints originated as a subset of the "ecological footprint" proposed by Wackernagel and Rees (1996). *Ecological footprint* referred to the biologically productive land and sea area required to sustain a given human population, expressed as global hectares. According to this concept, carbon footprint was the land area that will assimilate the $CO_2$ produced during the lifetime of a person or total global population. The calculation of carbon footprint as a part of the ecological footprint was very tedious and complex. But as the issue of global warming gradually gained prominence on the global environmental forefront, carbon footprinting emerged independently, in a modified form (East 2008). The present form of carbon footprints can be regarded as a hybrid that derives its name from "ecological footprint" but conceptually is a global warming potential indicator. However, few studies still report carbon footprints in terms of global hectares with regard to its origin (Browne et al. 2009).

In spite of its widespread popularity among the public as an indicator of contribution of an entity to the global warming, until few years back, there was confusion over what carbon footprints exactly meant (Wiedmann and Minx 2007; Pandey et al. 2011). This was particularly due to the lack of a standard methodology for carbon footprint calculation and its scientific analyses. Most studies have been carried out by private organizations and companies for business purposes rather than environmental responsibility (Kleiner 2007; East 2008). However, recognizing the public response to carbon footprinting studies and increasing financial transactions in the carbon market, standards are now under construction by the International Organization for Standardization (ISO); British Standards Institution (BSI) is also developing and upgrading their guidelines. Scientific literature is also growing, with more and more case studies of carbon footprinting, thus adding to the development of standard methods.

Based on a survey, Wiedmann and Minx (2007) recognized that definitions of carbon footprints were also different among different studies. They suggested that the term carbon footprint should reflect measure of the exclusive total amount of $CO_2$ emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product. A similar indicator, "climate footprint," was proposed to be used, if all the GHGs were included in the calculation instead of only $CO_2$. But keeping in mind the motive of carbon footprinting, (i.e., assessing the impact of the activity on global climate), new studies and guidelines suggested inclusion of all the GHGs that are covered under the Kyoto Protocol (Kelly et al. 2009; Eshel and Martin 2006). However, still there are terms that are used interchangeably with carbon footprints, such as embodied carbon, carbon content, embedded carbon, carbon flows, virtual carbon, GHG footprint, and climate footprint (Courchene and Allan 2008; Peters 2010). Selection of direct and embodied emissions is also inconsistent among different studies. Direct emissions take place onsite. For example, in an industrial unit, $CO_2$ released during the combustion of gasoline fired in boiler is a direct emission. On the other hand, if the boiler was electrically powered, no direct emissions will be observed on the site. But during production of that electricity in a thermal power plant, a certain amount of $CO_2$ should have been released. Such an emission is referred as the embodied or indirect emission. In most cases, it becomes too complicated to include all possible indirect emissions; hence, many carbon footprinting case studies report only direct or first-order indirect emissions (Carbon Trust 2007; Wiedmann and Minx 2007; Matthews et al. 2008). But indirect emissions may constitute the major share of carbon footprints for many activities (Matthews et al. 2008). In spite of prevailing differences among the calculations, the $CO_2$ equivalent ($CO_2$-e) mass based on 100 years global warming potential of GHGs is used as the reporting unit of carbon footprints (WRI/WBCSD 2004; Carbon Trust 2007; BSI 2008), although there had been certain critical comments over it. Hammond (2007) and Global Footprint Network (2007) hold the opinion that "footprints are spatial indicators"; therefore, the carbon footprint should precisely be called a "carbon weight" or "carbon mass" (Jarvis 2007). However, convenient calculations and widespread acceptance makes $CO_2$-e mass the practical unit of carbon footprints.

The definition of carbon footprints is therefore proposed as follows: "The quantity of GHGs expressed in terms of $CO_2$-e, emitted into the atmosphere by an individual, organization, process, product or event from within a specified boundary" (Pandey et al. 2011).

## *4.1 Scope of Product Carbon Footprinting*

The main drivers of carbon footprint calculations are legislative requirements, carbon trading, corporate social responsibility, and scientific analyses for devising effective policies to combat global warming (Carbon Trust 2007). The scope of carbon footprinting is wide and includes virtually all kinds of products, services, activities, and processes. Carbon footprinting of products and services has proven useful in not only managing the emissions more effectively across the supply chain, but also as a business tool (Kleiner 2007). It is proven by the continually increasing number of companies participating in the Carbon Disclosure Project (CDP 2009). This rush gained momentum from changing marketing strategies as more consumers began to prefer products with low carbon footprints (LEK Consulting 2007). Therefore, regulated carbon labeling of products has also been introduced. Suh (2006) calculated carbon footprints for different products in the USA and concluded that lime was the most GHG intensive product (22.1 kg $CO_2$-e $\$^{-1}$), followed by chemicals, fertilizers, and meat production. Services such as health care, water supply, computing and data processing, and amusement left smaller carbon footprints, ranging from 42.1 to 46.1 Tg $CO_2$-e for an average household. Hoefnagels et al. (2010) used product carbon footprinting for comparing the overall performances of different energy options. Under optimum conditions, biofuels production emitted between 17 and 140 g $CO_2$-e $MJ^{-1}$. Carbon footprints of different fuels are calculated to decide about the import of nonconventional vehicular fuels in California (Courchene and Allan 2008). Gemechu et al. (2012) also advocated the application of carbon tax based on product carbon footprinting for kraft pulp production, in which energy usage was the most polluting sector with nearly 0.32 kg $CO_2$-e $kg^{-1}$ of pulp produced.

Among services, aviation has been identified among the highest GHG emitters; hence, the carbon footprinting of airlines is ongoing, covering different aspects such as aircraft types, load factors, and seat configurations (Miyoshi and Mason 2009). The European Union has taken the lead in formulating legal bindings for reduction in emissions embodied in aviation. Schools and universities are also participating in such calculations. GAP et al. (2006) in the UK Schools Carbon Footprint Scoping Study estimated that, in 2001, all schools in the United Kingdom left a carbon footprint of $9.2 \times 10^9$ kg $CO_2$-e. Elsewhere, the University of British Columbia and University of Pennsylvania left carbon footprints of $8.2750 \times 10^7$ and $3.0 \times 10^8$ kg $CO_2$-e, respectively (Ferris et al. 2007; TC Chan Centre for Building simulation and Energy Studies/Penn Praxis 2007). Carbon footprints have also been included in the management of cities and organizations to improve environmental policies (Courchene and Allan 2008; Good Company 2008). The UNDP (2007) and Edgar and Peters (2009) used per capita CF of different countries to compare the contributions of countries, cities, and sectors to global warming. These reports clearly indicated that high-income countries leave the biggest footprint, while it was substantially lower for developing countries. Carbon footprint is now used as an indicator in event management as well (London-2012 Sustainability Plan 2007).

In addition to the above, voluntary carbon footprinting by organizations as well as individuals is growing at a fast rate. Consultancies and online calculators have further promoted individual carbon footprinting, particularly in developed countries (Padgett et al. 2008; Kenny and Gray 2008). Such calculators also offer carbon offsetting options, mainly through supporting forestation and renewable energy resources (Murray and Day 2009). A dramatic growth in the voluntary carbon market has been reported since 1989 (Hamilton et al. 2007). Carbon footprinting is also extended to the natural and semi-natural systems, which may help compare natural versus anthropogenic impacts on the environment (Chambers et al. 2007). Hence, we see that there is hardly any entity that cannot be a candidate for carbon footprinting.

## 4.2 Calculation of Product Carbon Footprints

Being a quantitative expression of GHG emissions, carbon footprinting helps in emission management and evaluation of mitigation measures (Carbon Trust 2007). Through carbon footprint analyses, important sources of emissions can be identified and areas of emission reductions can be prioritized. For carbon footprint calculation, estimates of GHGs emitted/embodied at each identified step of the product's/activity's/individual's life cycle are conducted, which is technically known as GHG accounting. Standards and guidance are available for GHG accounting. Common resources are:

(a) GHG protocol of World Resource Institute (WRI)/World Business Council on Sustainable Development (WBCSD): Nearly all GHG accounting guidelines, including ISO 14064 and PAS 2050 of BSI (2008), are based on this protocol. The GHG protocol provides separate guidelines for GHG accounting and reporting during the life cycles of products and corporate organizations. ISO 14064 (parts 1 and 2): International Organization for Standardization has developed this standard for determination of boundaries, quantification of GHG emissions, and removal (ISO 2006a, b). Part 1 deals with carbon footprinting of organizations, addressing guidance for the quantification, monitoring, and reporting of GHG emissions. Part 2 deals specifically with well-defined activities and projects.
(b) Publicly Available Specifications-2050 (PAS 2050) of British Standard Institution (BSI): It specifies the requirements for assessing the life cycle GHG emissions of goods and services (BSI 2008). PAS 2050 is preparing a standard method to calculate carbon footprints of agricultural systems as well.
(c) Intergovernmental Panel on ClimateChange (IPCC) guidelines for National Greenhouse Gas inventories: IPCC categorizes all anthropogenic sources of GHG emissions into four sectors—energy, industrial process and product use, agriculture, forestry, and other land use and waste.

All of these guidelines and standards proceed through life cycle assessment (LCA) or 'cradle-to-grave analyses' for the activity for which the carbon footprint is to be calculated. ISO formulated standard methods for conducting LCA as a part of the ISO 14000 series. ISO 14040 provides the principles and framework for carrying out LCA (ISO 2006c), whereas ISO 14044 provides guidelines on detained methodology (ISO 2006d). It also directed the Life Cycle Impact Assessment (LCIA) as the last and compulsory stage of LCA. For effective application of ISO 14044, two technical revisions have been made: ISO 14047

(ISO 2012a) and 14049 (ISO 2012b). They focus on the key points of LCIA that are important for carbon footprinting, with specific examples and sample practices.

To provide guidelines and principles of product carbon footprinting, ISO 14067 is under development (ISO 2013). This technical specification is based on the ISO's standards of LCA and environmental labeling of products. Although there are provisions of different modes of communicating product carbon footprints and performance tracking, it is under critical review and evaluation so that an international standard can be developed.

According to the available standards, following structured framework is suggested for carbon footprinting (WRI/WBCSD 2004; Carbon Trust 2007; BSI 2008):

a. Selection of GHGs
b. Setting boundaries
c. Collection of GHG emission data
d. Footprint calculation

### 4.2.1 Selection of GHGs

Selection of the set of GHGs covered in the calculation depends on the guideline followed, the need for carbon footprinting, and the type of activity. For example, in a thermal power plant, where $CO_2$ is a predominant emission and other gases are almost negligibly emitted, only $CO_2$ emission measurement will be feasible, whereas for a cattle farm, $CH_4$, $CO_2$, and $N_2O$ emissions may be significant. Although some studies include only $CO_2$ emissions in carbon footprinting (Patel 2006; Wiedmann and Minx 2007; Craeynest and Streatfeild 2008), the guidelines recommend all six Kyoto gases (Bokowski et al. 2007; Garg and Dornfeld 2008; Good company 2008; Matthews et al. 2008). All guidance and standards also direct to include all Kyoto gases.

### 4.2.2 Setting Boundaries

A boundary refers to an imaginary line drawn around the activities that will be used for calculating carbon footprints. It depends on the objective of footprinting and characteristics of the entity for which footprinting will be done. Defining the boundary is crucial as it determines the activities, which will be included in the study. To facilitate convenient accounting, the following tiers have been suggested (WRI/WBCSD 2004; Carbon Trust 2007; BSI 2008):

Tier$_1$: direct, i.e., onsite emissions

Tier$_2$: emissions embodied in purchased energy

Tier$_3$: all indirect emissions not covered under tier$_2$, such as those associated with the transport of purchased and sold goods, business travels, waste disposal, etc. Carbon footprint has also been divided into two parts: basic/primary and full carbon footprint. Primary carbon footprint is calculated from tier$_1$ and tier$_2$ only, whereas full carbon footprint covers emissions up to tier$_3$ (Carbon Trust 2007; Lynas 2007).

Most carbon footprinting studies limit up to tier$_2$ because going beyond tier$_2$ increases the complexity and uncertainty in estimates (Matthews et al., 2008). Even during trading of carbon offsets, only tier$_1$ and tier$_2$ emissions are important. It is also advocated that embodied emissions are beyond the control of the organization of process for which carbon footprints are to be calculated and hence tier$_3$ should be left out during carbon footprinting (Lenzen 2001). For this reason, PAS-2050, GHG protocol, and other registries and consultancies based on these have kept tier$_3$ optional. Critical analyses of carbon footprinting case studies, however, reveal that indirect emissions compose a significant part of total carbon footprint (Matthews et al. 2008). Hence, attempts must be taken to count tier$_3$ emissions. To make the definition of tier$_3$ more clear, Mathews et al. (2008) proposed that emissions exclusively related to delivery, use, and disposal of products also should be kept out of tier$_3$ An additional tier$_4$ can be used for the same.

Advancement in the tracking and management of emissions in the supply chain is expected to promote tier$_3$ accounting (Matthews et al. 2008; CDP 2009). In the Carbon Disclosure Project (CDP), 72 % of respondents among 500 companies reported their basic carbon footprints, but the number of companies reporting up to tier$_3$ is increasing (CDP 2009). As more and more organizations carry out their complete LCA, a database can be developed through which average sector-specific emission factors can be calculated (Matthews et al. 2008; Weidema et al. 2008). International trade of raw materials and finished products poses further challenges in tier$_3$ estimation (Courchene and Allan 2008). Appropriate assumptions over sharing of responsibilities of countries and organization related with emissions associated with international trade of goods and services need to be developed (Peters 2010).

Regarding natural systems and land uses, almost all the carbon footprinting studies focus on emissions; the amount of GHG removal and sequestration appears to be neglected (Peters 2010).

### 4.2.3 Collection of GHG Data

Estimation of GHG emissions and removals associated with all the activities identified within the boundary can be carried out by direct measurements or estimated using emission factors or models. Direct measurements yield near accurate estimates and are clearly prescribed in globally accepted protocols, but their cost and application may be prohibitive in certain cases (WRI/WBCSD 2004). Under such conditions, indirect estimations through models and emission factors are applicable. If developed or modified specifically for a particular region or sector, they yield fairly accurate results. Usually, customized tools relying on combinations of direct measurements, emission factors, and models are popular and practicable (USCCTP 2009). For large-scale GHG estimation, observation networks such as FLUXNET have been initiated (Sundareshwar et al. 2007), but due to high costs and nonuniform global distribution of sites, they are still far away from global representativeness. To overcome the patchy coverage of ground-based monitoring networks, satellites have been launched to monitor sources and sinks of $CO_2$ and other GHGs (Haag 2007). A Japanese satellite, (the "greenhouse gas observing satellite") and Vulcan, a joint project of NASA and the US Department of Energy, are two such examples (Gurney et al. 2009; Kelly et al. 2009). Remote sensing and geographic information systems are also used extensively for large and relatively less accessible areas. Such an example is the case of carbon footprinting of Hurricane Katrina on the US coast, carried out by Chambers et al. (2007) using LANDSAT imageries.

### 4.2.4 Footprint Calculation

The collected GHG data is translated into $CO_2$-e using global warming potentials of different GHGs as provided by IPCC (2007). The final unit of the carbon footprint depends on the nature of the entity. For individuals and dynamic processes, carbon footprints need to be calculated periodically, but events such as conferences, sports events, etc. have one-time emissions. Some entities have a combination of both; for example, for building, a one-time emission take place during construction phase, while periodic calculations are needed during the operation phase. For such activities, there is a provision of sharing one-time emissions over the operation phase. Natural processes are highly complex; hence, they have a temporally as well as spatially dynamic carbon footprint.

## 5 Carbon Footprinting as a Tool to Estimate Agriculture's Contribution to Atmospheric Stock of Greenhouse Gases

As discussed, the emissions as well as sink capacity of the agriculture sector are still highly uncertain, and available estimates must be refined through an extensive monitoring network covering different geographical regions, environmental conditions, and management practices (Seip 2011). In addition to soilborne GHGs and carbon sequestration, keeping in mind the increasing energy and chemical inputs in farming, the boundaries of agriculture must be expanded to include all relevant emissions and/or removals of GHGs. Carbon footprinting therefore can be utilized for cultivation systems by producing a detailed map of different sources and sinks of GHGs. This will identify the points where environmental efficiencies can be improved. This also facilitates a comparison of different management options and their environmental cost-benefit analyses. Although scientific literature is still sparse in carbon footprinting studies targeting cultivation practices, such estimates are essential for upgrading national GHG budgets and to improve environmental efficiency of the agriculture sector.

## 6 Calculating Carbon Footprints for Agricultural Products

The GHG protocol acts as a common resource for carbon footprinting, but it is important to keep in mind the role of the agriculture sector in anthropogenic GHG emissions and sensitivity of this sector to a number of environmental and social factors. Therefore, the development of an agriculture-specific carbon footprinting method is proposed. BSI is developing PAS 2050 specifically for agriculture.

### *6.1 Selection of Boundary and Tiers*

For carbon footprinting of agricultural practices, all activities associated with farming must be identified. A generalized illustration of different activities involved in cultivation practices that are relevant to carbon footprinting is presented in Fig. 1. Because there is no agriculture-specific standard for carbon footprint calculation, the generalized standard three-tier approach of the GHG protocol must be followed in order to maintain uniformity among different studies. The selection of the boundary will depend on the level up to which carbon footprints are to be calculated, as presented in Table 1. For carbon footprinting in the production of cereals, vegetables, fruits, etc., the activities related to cultivation of the concerned crop up to the final harvest and readiness for use as raw material will be covered. To cover the activities up to the shelf of the store, activities related to processing, packaging, and transportation of farm produce must also be included. To calculate carbon footprints of food, the boundary is set to cover home preparations also. Among the three proposed boundaries, carbon footprints of cultivation (i.e., up to the farm gate) is more helpful for comparing different agricultural practices and efficacies of different management systems on GHG performances. Extending the boundary beyond this introduces activities such as the transportation of products to the market, their distribution, and food preparation techniques and preferences, which are more sensitive to local and personal conditions.

Direct emissions to be covered under $tier_1$ for agricultural systems include $CH_4$, $N_2O$, and $CO_2$ emissions from soil and onsite $CO_2$ emissions from fossil fuel-powered farm machines such as tractors, harvesters, threshers, grain cleaning

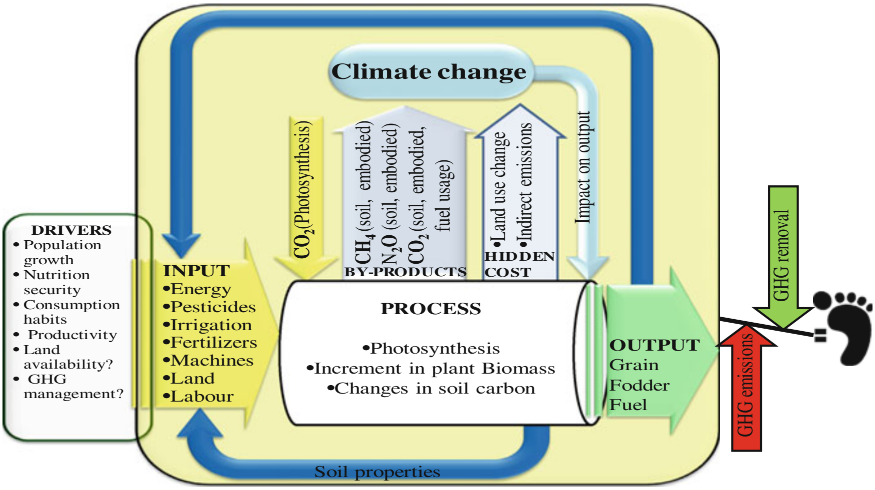


**Fig. 1** A generalized illustration of activities and inputs associated with cultivation of a crop to be considered in the boundary (sowing to farm gate) for carbon footprinting

**Table 1** Choice of boundaries for carbon footprinting of agricultural products

| Objective | Boundary |
|---|---|
| Carbon footprinting of cultivation | Up to the farm gate |
| Carbon footprinting of finished farm products | Up to the shelf |
| Carbon footprinting of food | Up to the table |

systems, etc. Electricity use in activities such as irrigation constitutes $tier_2$. Table 2 lists common farm activities and their classification into different tiers. Most of these activities are also performed manually, but human labor is not considered under carbon footprint calculations (WRI/WBCSD 2004). Because agricultural soils can sequester atmospheric $CO_2$ (Lal 2004b), it is proposed to be a part of $tier_1$.

In addition to these, agricultural inputs such as fertilizers, pesticides, herbicides, and soil conditioners carry embodied emissions, and hence they constitute $tier_3$.

## 6.2 *Estimation of GHG Emissions/Removals*

Because agricultural practices depend significantly on region, traditional practices, economic conditions of farmers, and the crop under cultivation, emission factors and models developed to express emissions of GHGs need to be validated and refined before their application in a particular agricultural system. Particularly for soilborne GHG emissions, which are also sensitive to environmental conditions, direct measurements are the most reliable (Pandey et al. 2012). For this purpose,

**Table 2** Farm activities and their classification into tiers

| Activity | Cultivation practices | Energy source | Tier |
|---|---|---|---|
| Land preparation | Plow | Diesel | $Tier_1$ |
| | Harrow | Diesel | $Tier_1$ |
| | Spader | Diesel | $Tier_1$ |
| | Subsoiler | Diesel | $Tier_1$ |
| | Spreader | Diesel | $Tier_1$ |
| Sowing | Seed drill | Diesel | $Tier_1$ |
| | Broadcast | Diesel | $Tier_1$ |
| | Seeders/spreaders | Diesel | $Tier_1$ |
| | Transplanter | Diesel | $Tier_1$ |
| Irrigation | Channel | Electricity | $Tier_2$ |
| | Sprinkler drip | Electricity | $Tier_2$ |
| | | Electricity | $Tier_2$ |
| Fertilizer application | Spreader | Diesel | $Tier_1$ |
| | Self-propelled sprayers | Diesel | $Tier_1$ |
| | Agricultural aircrafts | Petroleum spirit | $Tier_1$ |
| Pesticide application | Self-propelled sprayers | Diesel | $Tier_1$ |
| | Agricultural aircrafts | Diesel | |
| Irrigation | Channel | Diesel/electricity | $Tier_1$/$Tier_2$ |
| | Drip | Electricity | $Tier_2$ |
| | Sprinkler/central pivot | Electricity | $Tier_2$ |
| Harvesting | Harvester (reaper, thresher) | Diesel/electricity | $Tier_2$ |
| Threshing | Thresher | Diesel/electricity | $Tier_2$ |
| Seed processing | Seed processing systems | Diesel/electricity | $Tier_2$ |

closed chamber systems are a simple, low-cost, and most applied technique (Parkin et al. 2012). There have been different shapes, sizes, and sampling procedures for estimating GHG fluxes using chamber systems depending upon the crop, rates of GHG fluxes, and analyses procedures. The periodically sampled gases are usually analyzed through gas chromatography and infrared gas analyzers; however, with advancements in chamber technique, GHG flux rates can now be measured in situ (Arnold et al. 2001). Automated chambers are capable of carrying out continuous monitoring of GHGs covering diurnal and daily variations under different environmental conditions. However, their cost, maintenance, and electricity requirement prohibits their application in the farmer's field and remote rural areas. The sensitivity of chambers also poses a challenge; in many cases, emission rates are very low and remain below the detection limits of chambers (Parkin et al. 2012). This is particularly important when soil acts as a net sink of GHGs. Also, due to poor chamber sensitivities, low or negative fluxes are often discarded as experimental errors (Chapuis-Lardy et al. 2007). Such low positive or negative fluxes become significant for large cultivated areas. With more refined chamber designs and flux calculation methods, sensitivity has been improved significantly. Flux towers are meant for large farming areas under similar cultivation practices and cropping systems because they provide the cumulative flux of the entire coverage area (Sundareshwar et al. 2007).

Regarding changes in soil carbon, which also constitutes $tier_1$, actual measurement of stock difference in soil over a long period of time is needed. This is because the changes in soil carbon are too slow to be measured reliably over time scales of years (Post et al. 2001). It is observed that changes in soil carbon are a function of management practices, environmental conditions, crop cultivation, and depth of measurement. Another issue related to carbon sequestration measurement is the question of permanence, i.e., for how long the carbon accrued in the soil will stay out of the atmosphere. Therefore, this part is usually left out during GHG accounting, but some studies have shown that carbon sequestration in soils can offset a part of carbon footprint of cultivation systems significantly.

For emissions taking place from farm machines and electricity consumption, emission factors are available for most countries. According to the GHG protocol, an activity data sheet should be maintained, keeping records of different farm activities, fuel consumption, hours of operations, etc. From this activity data sheet, emissions associated with different activities can be calculated using emission factors or models. As a requirement of carrying out GHG emission inventories for countries signatory to the United Nations Framework Convention on Climate Change (UNFCCC), emissions associated with combustion of fossil fuels and electricity generation have to be calculated under their national communications to UNFCCC. These emission factors have been modified according to the types of engines and machines used on the field. However, for $tier_3$ emissions, production technique and country-specific emission factors are not available in most of the countries. In such cases, IPCC (2006) National GHG inventory guidelines provide average and default emission factors for production of fertilizers, GHG emissions from soil under different irrigation, and manure applications etc. Based on these factors, GHG emissions embodied in Urea production have been calculated (Tirado et al. 2010; Lal 2004a) as the most commonly used resource, in which emission factors for $CO_2$ emissions associated with different activities on farm and inputs of fertilizers and pesticides were derived on the basis of extensive literature survey. Such estimates nevertheless need to be refined and updated. Nelson et al. (2009) also calculated the onsite and offsite $CO_2$ emissions from different farm activities in USA during 1990–2004. Results indicated that onsite and total $CO_2$ emissions ranged from 23 to 176 kg C $ha^{-1}$ $yr^{-1}$ and from 91 to 365 kg C $ha^{-1}$ $yr^{-1}$, respectively. Such region-specific emission factors are necessary for reducing uncertainties in the calculations.

## *6.3 Footprint Calculation*

Global warming potential (GWP) of all the tiers is calculated individually using the conversion factors of IPCC (2007) corresponding to a 100-year time horizon. The formula for the calculation of GWP of $tier_i$ ($i = 1, 2$ or 3) is given by:

$$\text{GWP}\,(\text{tier}_i) = \text{emission/removal of CH}_4 \times 25 + \text{emission/removal of N}_2\text{O} \times 298 + \text{emission/removal of CO}_2$$

where GWP is in kg $CO_2$-e $ha^{-1}$.

Emissions are taken as positive while removal as negative. Values are given in kg $ha^{-1}$.

Carbon footprint is calculated by adding the GWP of all tiers. The final representation of the carbon footprint of agricultural systems can be made as spatial or yield scaled carbon footprints according to the formulae given below:

$$CF_s = \sum_{i=1}^{3} [\text{GWP}(\text{tier}_i)]$$

$$CF_y = \frac{CF_s}{\text{Grain yield}}$$

where $CF_s$ is the spatial carbon footprint. Units are (kg $CO_2$-e $ha^{-1}$); $CF_y$ is yield scaled carbon footprint. Units are (kg $CO_2$-e $Kg^{-1}$ yield).

These that two units differ by the factor of yield, which is the prime motive of cultivation. Spatial carbon footprints are helpful in comparing agricultural practices that are already under high yielding conditions. Under such cases, the better practices emit less per unit area under cultivation without declining the yield. Yield scaled carbon footprints are considered a better indicator for intercomparison of different cropping systems (Linquist et al. 2011, 2012).

## 7 Case Studies

In the last few years, there has been an increase in number of case studies of carbon footprinting of cultivation systems and food. Some of them considered all three tiers, but none of the studies defined them. Similarly, there was no mention of boundary selection. Table 3 presents different carbon footprinting studies for crop cultivation. Even though it is remarked that GHG emissions from soil are highly sensitive to environmental conditions and management practices, none of the carbon footprinting studies was based on actual measurements. Furthermore, $CH_4$ emissions were considered only for rice cultivation; for the rest, only $N_2O$ emissions were covered (Gan et al. 2011a, b, c, 2012). In light of many studies demonstrating that crops other than rice act as significant $CH_4$ sinks or sources, it becomes essential to monitor $CH_4$ fluxes under such systems. In an attempt to calculate the yield scaled carbon footprint of barley, Gan et al. (2012), calculated that nearly 26 % of the GHG emissions were contributed by farm operations. Gan et al. (2012) however, did not measure $CH_4$ emissions. In most of the studies, $tier_3$ emissions, particularly of fertilizer application alone, contributed from 45 to 85 % of the total yield scaled carbon footprints (Gan et al. 2011a, b, 2012), whereas

**Table 3** Carbon footprints of some agricultural systems and cultivation practices

| | Agricultural system (crop) | Region | Activity and tiers | Estimation protocol | Carbon footprint (kg $CO_2$-e $kg^{-1}$)[a] | Reference |
|---|---|---|---|---|---|---|
| 1 | Canola-mustard (sowing to farm gate) | Canada | $Tier_1$ and $Tier_2$: soilborne $N_2O$, land preparation, pesticide and fertilizer spray, harvester<br>$Tier_3$: fertilizers and pesticides (factory to farm) | Rochette et al. (2008); Lal (2004a) | 0.548–0.966 | Gan et al. (2011a) |
| 2 | Durum wheat (sowing to farm gate) | Canada | $Tier_1$ and $Tier_2$: soil borne $N_2O$, land preparation, pesticide and fertilizer spray, harvester<br>$Tier_3$: fertilizers and pesticides (factory to farm) | Rochette et al. (2008); Lal (2004a) | 0.383–0. 533 | Gan et al. (2011c) |
| 3 | Barley (sowing to farm gate) | Canada | $Tier_1$ and $Tier_2$: soilborne $N_2O$, land preparation, pesticide and fertilizer spray, harvester<br>$Tier_3$: fertilizers and pesticides (factory to farm) | Rochette et al. (2008); Lal (2004) | 0.252–0.456 | Gan et al. (2011b) |
| 4 | Spring wheat (sowing to farm gate) | Canada | $Tier_1$ and $Tier_2$: soilborne $N_2O$, land preparation, pesticide and fertilizer spray, harvester, changes in soil C<br>$Tier_3$: fertilizers and pesticides (factory to farm) | Gregorich et al. (2005); Rochette et al. (2008); EF from previous studies | 0.357–0.140 | Gan et al. (2012) |
| 5 | Potato (farm to table) | Sweden | $Tier_1$ and $Tier_2$: soilborne $N_2O$, soil borne $CO_2$, changes in soil C Electricity | SEPA (2009); IPCC (2006); EC (2007); Swedenergy, (2009); Andrén et al. (2004) | 0.12 | Roos et al. (2010) |

(continued)

**Table 3** (continued)

| | Agricultural system (crop) | Region | Activity and tiers | Estimation protocol | Carbon footprint (kg $CO_2$-e $kg^{-1}$)[a] | Reference |
|---|---|---|---|---|---|---|
| 6 | Rice (sowing to farm gate) | Italy | Soilborne $CH_4$ and $N_2O$ | EF from previous studies | 2.90 | Blengini and Busto (2009) |
| | | | Fertilizer, farm machines (land preparation, harvester, grain processing), irrigation, pesticide and fertilizer spray, harvester | | | |
| 7 | Biofuels (ethanol, methyl ester, FT diesel) (Cultivation to power generation) | Europe, Canada, S.E. Asia, Brazil, USA | $Tier_1$ and $Tier_2$: no demarcation between tiers | IPCC (2007); Croezen et al. (2008) | In kg $CO_2$-e 70-140 $MJ^{-1}$ | Hoefnagels et al. (2010) |
| | | | Soil borne $CH_4$, $N_2O$, $CO_2$<br>Change in soil carbon<br>Power generation<br>$Tier_3$: fertilizers and pesticides (factory to farm) | | | |
| 8 | 57 farms with different organic, conventional and integrated farming (sowing to farm gate) | Scotland | $Tier_1$ and $Tier_2$: soilborne $N_2O$; Land preparation; Harvesting; Fertilizer, pesticide spray | Lal (2004a) | In $\times 10^2$ kg $CO_2$-e $ha^{-1}$; Organic farming: 7.49; Conventional farming: 16.06; Integrated farming: 12.38; Leguminous crops: 4.50; Potato: 19.44; Cereals: 11.16–15.69 | Hillier et al. (2012) |

*EF* Emission factor
[a] Units of carbon footprints are kg $CO_2$-e $kg^{-1}$ unless stated otherwise

changes in soil carbon could turn the carbon footprints of wheat cultivation negative, which was otherwise 0.34 kg $CO_2$-e $kg^{-1}$ (Gan et al. 2012). On basis of this result, PAS 2050 is recommended to include changes in soil carbon in their upcoming guidelines for carbon footprint calculation for agricultural systems.

Practicing different permutations of conventional tillage and no tillage in rice–wheat systems showed that although no tillage led to significant reductions in cumulative GWP of rice cultivation under continuously no-tilled systems, it also reduced the yield; hence the yield scaled GWP was increased, resulting in a higher carbon footprint compared to the conventional practice. On the contrary, during wheat cultivation, the conventional practice acted as a net sink of $CH_4$, thereby leaving a negative carbon footprint of −8.11 to 125.2 kg $CO_2$-e $kg^{-1}$. Under no-tillage practice, emission of GHGs increased along with yield; hence, the carbon footprint became positive (Pandey et al. 2013).

Food as a commodity has independently become an important candidate of carbon footprinting. Kim and Neff (2009) showed that carbon footprint calculators for food items had different scopes and calculations were based on different emission factors. Hence, they could not address effectively the diet-related preferences. Pathak et al. (2010) calculated the carbon footprints of Indian food items, taking into account cultivation of crops, processing, transportation, and kitchen preparations. The average emission factors they used did not address $CH_4$ emissions from non-rice crops, different management conditions, and changes in soil carbon. They calculated the average daily carbon footprint of 723.7 g $CO_2$-e for an Indian adult male.

## 8 Sources of Uncertainty

According to the GHG protocol, sources of uncertainties should be mentioned when reporting carbon footprints. For agricultural practices, nonavailability of activity-specific emission factors is an important source of error. In addition, the associated land use changes and alternative scenarios under different agricultural practices are not easy to predict confidently. For example, in the case of no-tillage cultivation, the stubble left over the soil could have been used as cattle fodder. Loss of fodder under no-tillage practice might put pressure on the cattle rearing; hence, there may be requirements to arrange extra land to compensate for the fodder demand. Land use change to compensate for fodder demand and shifts in yield should be considered. Because agriculture is largely affected by the climate, long-term monitoring and calculation are required to generate better footprint estimates, and how it modulates with changes in different components. Although, soil carbon sequestration is regarded as a ‘win–win strategy,’ there are certain controversies over quantification and assessment of sink capacity reliability (Lehmann 2009). It is argued that sequestration must be able to keep the carbon out of the atmosphere for a relevant time period, conventionally assumed to be at least 100 years. Determination of the degree of permanence of sequestered carbon has not yet been established convincingly; however, scientists have adopted fractionation of the carbon pool physically and chemically (Post et al. 2001; Rovira and Vellejo 2007).

## 9 Conclusions

Carbon footprinting has appeared as a strong and popular indicator of the GHG intensity of any activity or organization. Due to its important role in raising awareness regarding responsibility toward global warming, scientists and policy makers are trying to use it as a management tool. However, its application over the agricultural sector is still limited. A standard methodology is required to address the emissions associated with soil, carbon sequestration in soil, emissions associated with farm equipments, and other relevant activities. Due to widespread differences in agricultural activities over the world, it is essential to have guidelines on the selection of boundaries. In addition, there is also an immediate need for uniformities in GHG estimation techniques. The lack of sector-and region-specific emission factors for important agricultural inputs add to the uncertainty. The standard method must address how to deal with alternative scenarios and land use changes. The number of carbon footprinting studies of agricultural systems is increasing, but due to widespread differences, their comparison remains difficult. Nevertheless, such studies represent the contribution of cultivation practices in a better way than merely focusing on soilborne GHG emissions, carbon sequestration, or energy intensity individually.

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