Carbon Accounting for Coffee-Based Farming Systems

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Abbreviations

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Agrecalc	Agricultural Resource Efficiency Calculator
ALU	Agriculture Land Use National Greenhouse Gas Inventory Software
BSI	British Standards Institute
CBP	Carbon Benefits Project
CFP	Carbon footprint of a product
CF-PCR	Carbon Footprint Product Category Rule
CFT	Cool Farm Tool
DEFRA	Department for Environment, Food and Rural Affairs
EX-ACT	EX-Ante Carbon-balance Tool
FAO	Food and Agricultural Organization
GHG	Greenhouse gas
IOS	International Organization for Standardization
IPCC	Intergovernmental Panel on Climate Change
PAS	Publicly Available Standards
SHAMBA	Small-Holder Agriculture Monitoring and Baseline Assessment
SOC	Soil organic carbon
SOM	Soil organic matter
UNFCCC	United Nations Framework Convention on Climate Change

The objective of this white paper is to collate and synthesize information on commonly used tools in estimating the carbon footprint (CFP) of coffee-based farming systems, discuss pros and cons of those tools, review recent research on coffee's CFP, and propose improvements to measure CFP more accurately at the farm level.

Key Takeaways

- There are limited studies on the CFP of coffee. The published literature demonstrates that coffee production, even with shade and organic systems, produces net carbon emissions. However, CFP ranges vary widely due to the use of different methodologies and tools.
- Most coffee carbon footprint calculation tools omit key components that are critical to accurately assessing the GHG emission and computing the CFP for coffee, in particular: SOC stock, SOC loss due to erosion, change in biomass (above and below ground), and GHG emission. Because CFP tools used for coffee do not include these factors, we should consider that there are no accurate estimates of coffee's carbon footprint.
- Using a proposed new accounting system that includes missing components will result in more accurate emissions figures than prior existing carbon estimation tools would generate.
- A revised approach to calculating carbon footprints that takes into account missing factors would provide coffee growers and roasters an improved protocol for identifying the best management practices for growing coffee.

Introduction

Rising demand, diverse farming systems, and limited tools to measure coffee's carbon footprint

Earth's climate is in crisis due to CO_2 emissions and other GHGs released by human activities (IPCC 2021). CO_2 is the main driver of climate change, but other GHGs and air pollutants also affect the climate (IPCC 2021). Agriculture, forestry and other land uses (AFOLU) emit 12 GT CO_2-e every year, or about a quarter of all anthropogenic emissions (IPCC 2014). IPCC's Sixth Assessment Report (AR6) warns that human actions still have the potential to determine the future course of climate. Many consumers, shareholders, and corporate boards in Europe (Roser-Renouf et al. 2016) and the United States (Sorkin 2021) have great concern about the climate crisis and GHG emission per unit of product.

Coffee is one of the world's most widely consumed beverages and a highly exported agricultural commodity (Capa et al. 2015; Chen et al. 2011). As such, it contributes meaningfully to global GHG emissions (Killian 2013). We can assume that emissions from coffee are growing as demand rises. Between 1992 and 2016, global coffee production increased by 61%, from 94.6 million bags on average in the first half of the 1990s to 152.2 million bags on average estimated for 2012-2016. This was driven both by a growth in coffee exports, which increased by 57% during the same period, and increased domestic consumption in producing countries, which doubled. This trend continues into the present. World coffee production increased 6.3% in 2020 over the prior year, from 164.35 million 60-kilo bags to 175.95 million bags, and exports increased by 2.5% to 98.55 million bags in the first nine months of the 2020/2021 coffee year (ICO 2021). Brazil, followed by Vietnam and Colombia, are the top three producers, and the European Union, the United States, and Brazil are the top three consumers (ICO 2021).

Coffee is a tropical cash crop with a complex life cycle from seedling to cup. The rise in global demand for coffee has led overall to intensified coffee-based farming systems and higher use of fertilizers and pesticides (Byrareddy et al. 2019). But there remains incredible diversity and complexity in the types of farming systems used by coffee farmers, including shaded and unshaded monoculture, agroforestry, and traditional polyculture with organic and conventional practices (Noponen et al. 2012; Solis et al. 2020; van Rikxoort et al. 2014). Because there is such diversity in coffee cropping systems globally, the industry needs a tool to calculate its carbon balance that allows the integration of individual components of the coffee cropping system (Martins et al. 2015). (Carbon balance is the net result of added carbon [biomass, SOC stock] and carbon loss [GHG emissions, loss due to erosion].)

There are few scientific reviews about carbon emissions in the coffee sector and even fewer that measure carbon at the farm level (Killian et al. 2013; Martins et al. 2018; Noponen et al. 2012). Studies on carbon accounting in coffee production systems focus on fertilizer application and processing of green coffee (milling, roasting, transportation, grinding). However, few studies consider soil organic carbon (SOC) dynamics and carbon sequestered in the above and below ground biomass of the coffee plant and shade trees (Killian et al. 2013; Nab and Maslin 2020; Usva et al. 2020), and the losses of SOC and related gaseous emissions due to accelerated soil erosion.

This article discusses recent research on carbon accounting in coffee farming systems, describes different tools used for computing coffee's carbon footprint (CFP), outlines pros and cons of these tools, and proposes improvements to accurately measure the CFP.

How carbon footprints are calculated today

International standards and available tools for agriculture

Because it would be impossible to measure actual carbon emissions in real time from all human activities, researchers have created tools to estimate carbon footprints. Estimation tools are based on international standards that lay out principles and definitions, including conversion factors. These standards are developed by agencies such as the British Standard Institute (BSI) and the Intergovernmental Panel on Climate Change (IPCC) to provide consistent internationally applicable methods for assessing GHG emissions associated with the life cycle of goods and services and quantifying carbon footprints. The Department of Environment Food and Rural Affairs (DEFRA) and the Carbon Trust, with the British Standard Institute (BSI), developed the Publicly Available Standards (PAS) 2050 as the first public product carbon methodology published (Minx et al. 2008). The French Agency for Environmental and Energy Management developed the GHG emission assessment tool Bilan Carbone (ADEME 2009), and Germany initiated the Project Carbon Footprint of Products, which estimates the climate impact of individual products and processes (Priess 2011). In addition, the GHG Protocol is included in the International Standards of Carbon Accounting to help governments and corporations understand, quantify, and manage GHG emissions. The International Organization for Standardization (IOS) (14067:2018) was developed to outline principles, requirements, and guidelines for CFP quantification and reporting CFP (ISO 2018). The CFP tools developed in Europe and the United States use conversion factors provided by PAS 2050:2011 and proposed in the IPCC guidelines for national GHG inventories to determine the CFP of each emission factor (BSI 2011; DEFRA 2011; Eggleston et al. 2006 [IPCC]).

Around 8% of all global GHG emissions are from agriculture in developing countries, where coffee is primarily grown, often in tandem with other crops and/or livestock. Quantifying the CFP of coffee therefore not only addresses carbon emission from coffee farming, but also to some extent agriculture in developing countries more generally (Motacha et al. 2012). Coffee farming both emits and sequesters carbon. It can sequester carbon in shade trees and in soil, and carbon emissions can be reduced through agronomic interventions (Tchibo 2008).

Common tools for CFP calculations

Our knowledge about the CFP of coffee is based on several recently developed tools (see summary in Table 1), which are also used widely in other crops. Some of these tools are based on IPCC guidelines (Eggleston et al. 2006) Tiers 1 and 2, and others are guided by PAS 2050:2011 (BSI 2011, DEFRA 2011).

Most global CFP calculation are done using simulations based on external data. For example, Century (Parton et al. 2006), DayCent (Parton et al. 2008), and US cropland GHG calculator (McSwiney et al. 2010) compute the crop production footprint per unit area using climate and soil driving variables to model carbon dynamics. Other tools use farm-level data and models based on specific practices to calculate CFP. Tools to calculate CFP under different farming systems include CFT, the Farm Carbon Calculator, Small-Holder Agriculture Monitoring and Baseline Assessment (SHAMBA), Agrecalc, ALU, EX-ACT, and CBP. Some CFP tools focus on livestock production (Farm Carbon Calculator, Agrecalc), and others on agroforestry (SHAMBA), cropland (CFT), and forestland (EX-ACT). Some tools are free (SHAMBA, EX-ACT) and others are either available to farmers (Farm Carbon Calculator, CBP), Cool Farm Alliance members (Cool Farm Tool), or must be purchased.

The Cool Farm Tool (CFT), developed by the Cool Farm Alliance, is the most popular CFP tool used in coffee agriculture systems (Martins et al. 2015; Rahn et al. 2014; van Rikxoort et al. 2014). CFT software combines IPCC Tier 2 methodology and empirical GHG quantification models built from peer-reviewed studies (Hillier et al. 2011). Its parameters include crop yield, cropped area, fertilizer application (type and rate), pesticide application, energy used in farm operations (diesel or electricity), water use, compost production, and shade biomass. However, some coffee CFP studies have made direct use of PAS 2050 (BSI 2008) and IPCC (Eggleston et al. 2006) guidelines in computing CFP (Killian et al. 2013; Nab and Maslin 2020; Noponen et al. 2012; Usva et al. 2020). Ratchawat et al. (2020) used national guidelines for computing CFP (Thailand) and IPCC (Eggleston et al. 2006) to calculate the CFP of coffee. Each tool has advantages and disadvantages based on the study objectives and the land area for computing the CFP calculation (see Table 1).

Table 1. Comparison of Commonly Used CFP in Agriculture Sector with Inputs Used and Pros and Cons

Tool name: Cool Farm Tool Run by: Cool Farm Alliance

Inputs Used	Pros	Cons
Harvest yield Cultivated area Fertilizer application Pesticide application Soil information Soil organic carbon stock from tillage, cover crops, and land use change Energy use (electricity and fuel) Transportation (mode and distance)	Used at farm level (crop or livestock) Good for initial assessment Easy to compare individual field crops and livestock Driven by alliance members' investment Global application on all major crops and livestock (30) Standard Tier 1 inventory methods (Eggleston et al. 2006 [IPCC]) Ecoinvent emission factor inventory (Ecoinvent 2007) Used N_2O emission relating to fertilizer developed by Bouwman et al. (2002)	Difficult to get whole farm assessment Aggregating data requires membership Limited machinery accountability in calculation Limited carbon sequestration accounting[1] SOC stock not considered GHG emission during crop duration not calculated[1]

[1] CFT is piloting a new "perennials module" that addresses unique elements of perennial crops, including changes in above- and below-ground biomass and GHG emissions from residue. It will also calculate emissions over the crop lifecycle.

Reference: *Hillier et al. 2011*

Tool name: Farm Carbon Calculator Run by: Farm Carbon Toolkit

Inputs Used	Pros	Cons
Growing area Yield Fuels, electricity, business travel Materials, machinery, building Livestock Fertilizer and spray Waste and recycling Distribution Carbon sequestration in soils and biomass SOC	Very thorough and interactive Helpful spreadsheet to collect information Includes carbon sequestration approach Calculates carbon balance for farms Accounts renewable energies and capital items User-friendly	All relevant information might not be available Livestock information not recorded Inaccurate carbon sequestration calculation

Reference: *Bochu et al. 2013*

Tool name: Agrecalc Run by: SAC Consulting

Inputs Used	Pros	Cons
Crop area Fertilizer use Yield and output Manure application Livestock numbers Purchased feed Age at slaughter Production level and output Wastewater, transport, renewables, electricity, fuel use	Detailed assessment Able to calculate by farm, enterprise, product Includes key performance indicators for both carbon and productivity Benchmark against other farms Considers livestock productivity and feed components	Time consuming Expert support needed during data entry Livestock diet components information needed Carbon sequestration only for woodland Livestock numbers average across the year

Reference: *Sykes et al. 2017*

Tool name: Agriculture and Land Use National Greenhouse Gas Inventory Software Run by: Colorado State University

Inputs Used	Pros	Cons
Land use and management Livestock and management N fertilizer and liming Sewage sludge amendments Crop residue management Grassland/savanna burning Biomass carbon loss Peatland burning Methane, N_2O, CO_2, soil carbon stocks	Based on United Nations Framework Convention on Climate Change (UNFCCC) Allows integration with spatial data, such as remote sensing, and national data on agriculture and forestry Ensure data integrity	Requires large data input and greater level of expertise Lack of country-specific emissions and stock change factors

Reference: *Ogle 2011*

Tool name: **SHAMBA** Run by: **University of Edinburgh**

Inputs Used	Pros	Cons
• Creates baseline and intervention scenarios with climate-smart agriculture • Plot location, plot area, tree stocking density, growth rate tree mortality	• Identifies changes in carbon stocks in soil and woody biomass at hectare level • Calculates GHG emissions that result from changes in agricultural practices and tree planting • Can be calculated for any time • Databases contain emission factors, tree allometry, soil, and climate information • Follows IPCC model to calculate non-CO_2 GHG • Available in platforms including Excel, R, and Python	• Focuses only on the tropical region • Multiple baseline data required • Mainly used in agroforestry scenario • Requires Python to be installed before running

Reference: *Berry et al. 2012*

Tool name: **EX-ACT** Run by: **FAO**

Inputs Used	Pros	Cons
• Estimates carbon stock changes and GHG emissions per unit of land • Based on land use and management practices • IPCC default values (Tier 1) and region-specific coefficients (Tier 2) • Agricultural inputs, energy, infrastructure, management of mineral and organic soils, coastal wetlands, fisheries, and aquaculture • Includes all the agriculture, forestry, and other land use sectors	• Compares the situation project and without project • Can be adapted to scale (project, landscape, regions) • Free, open-source, Excel-based model	• Follows only in FAO invested projects • Based on the value chain guidelines

Reference: *FAO 2010*

Tool name: CBP: modeling, measurement, and monitoring
Run by: Colorado State University

Inputs Used	Pros	Cons
Two options (simple and detailed assessment) Based on the UNFCCC GHG source categories Land use cover, soil class, land management information Soil carbon stock was calculated up to 30 cm depth	Has a spatial component Ideal for landscape scale projects Considers land management strategies in terms of economic and social constraints Online and free	Initial or baseline scenario required for comparison and only changes in the carbon can be measured

Reference: *CBP 2013*

What we know about coffee's carbon footprint on the farm

Significant variance in emissions for farm-level emissions

Compared to the relative importance of coffee agriculture globally, little carbon accounting research has been done in coffee farming systems. Most research in the CFP of coffee is focused on processing and exportation (Arce et al. 2009), and less on CFP at the farming level. Published CFP estimates for coffee show a large variation: 0.4 kg to 10.8 kg CO_2e kg-^{1}. The large range is because authors followed their own methodologies and tools to calculate CFP for their studies' ecological settings and inputs. Some studies calculate the CFP of green coffee, while others focus on parchment or coffee cherry. The CFP also varies depending on the type of coffee growing system (polyculture compared to monoculture, sustainable compared to conventional, shade- compared to sun-grown). Most studies in the CFP of coffee focus on the processing (wet or dry) and transportation. Only a few aspects of coffee farming are included in those studies. Table 2 summarizes a selection of the CFP literature for coffee, tools used to calculate CFP, and key priorities for further research. But clearly, methodologies and tools need to be streamlined to allow for more robust comparison of CFP differences and to develop plans to address issues of carbon accounting in coffee-based farming systems.

Table 2: Literature of CFP of Coffee Production System, Tools Used, and Significance of Study at Coffee Growing Countries

Methodology/tool	Coffee type	Country/level/ time frame	Area of research	Reference
Calculation based on the emission factor guided by PAS 2050:2011 (DEFRA and BSI 2011; Eggleston et al. 2006 [IPCC])	Arabica	Costa Rica; large/small scale; 2009/10 coffee production period	Calculate GHG emissions in the coffee supply chain (farm, central mill, and exportation process)	Killian et al. 2013
CFT	Arabica and robusta	Espirito Santo, Brazil; 46,184 km$_2$; 2001–12	Carbon balance (carbon stock, footprint) for monoculture in four regions of state in tropical area	Martins et al. 2015
CFT	Arabica and robusta	Brazil; 8,515,767 km$_2$; 2005–15	92% of CFP can be mitigated by carbon sequestration on the biomass of coffee trees	Martins et al. 2018
Calculation based on emission factor guided by PAS 2050:2011 (DEFRA and BSI 2011; Eggleston et al. 2006 [IPCC])	Arabica and robusta	Brazil and Vietnam	Complete life cycle assessment of carbon equivalent footprint of coffee produced in Brazil and Vietnam and exported to the UK	Nab and Maslin 2020
Calculation based on emission factor guided by PAS 2050 (BSI 2008; Eggleston et al. 2006 [IPCC])	Arabica	Costa Rica and Nicaragua; two 3-ha field sites; 2000–12	Identify emission hotspots within different management systems, levels of inputs, and shade types	Noponen et al. 2012
CFT	Arabica	North-central Nicaragua; 2012	Identify relevant lower CFP management practice for organic coffee smallholders	Rahn et al. 2014
National guidelines: carbon footprint of product (TGO 2015)	Robusta	Thailand; 180 coffee farms in Chumphon Province; 2015	Crop management and size of coffee area were significant factors affecting the CFP of robusta coffee	Ratchawat et al. 2018
Calculation based on the emission factor guided by PAS 2050:2011 (DEFRA and BSI 2011; Eggleston et al. 2006 [IPCC])	Arabica and robusta	Brazil, Nicaragua, Colombia, and Honduras (cultivation); Finland (processing)	Fertilizer was the most important process contributing to the CFP, larger share of climate impacts in the cultivation stage	Usva et al. 2020
CFT	Arabica	Mexico, Guatemala, Nicaragua, El Salvador, and Colombia; 116 farms; 2007–11	Traditional compared to commercial polyculture and shaded compared to unshaded monoculture	van Rikxoort et al. 2014
IPCC methods	Arabica	Colombia; 30 coffee farms; 2014–15	SOM, organic matter incorporation, and coffee leaf litter decomposition were 84.3% of total emissions; remaining 15.7% resulted from nitrogen fertilization emissions	Otalvaro et al. 2017

Noponen et al. (2012) used the PAS 2050 (BSI 2008) model for CFP calculations to compare coffee production systems (organic compared to conventional) in Costa Rica and Nicaragua. This study reports that CFP for 1 kg of fresh cherries is between 0.26 kg and 0.67 kg CO_2e for conventional and 0.12 kg and 0.52 kg CO_2e for organic management systems. Decomposition of pruning residue from shade trees and coffee plants emits N_2O, which contributes between 7% to 42% of CFP.

In Thailand, Ratchawat et al. (2020) report the CFP of *Coffea canephora* (robusta) at 0.40 kg ± 0.12 kg CO_2e kg-^{1} of coffee cherry and observe that almost 70% of GHG emissions are from chemical fertilizers followed by those from liquefied petroleum gas in roasting and electricity used in the grinding processes. The authors conclude that crop management practices and size of coffee farms have significant impacts on the CFP of cherry coffee. Their research considered national guidelines for CFP of products for evaluation of CFP (TGO 2015) with a functional unit as 1 kg of fresh, roasted, and ground robusta beans. Ratchawat et al. (2020) used national guidelines (TGO 2015), GHG emission factors from the national life cycle inventory (TGO 2014), and the IPCC database (Eggleston et al. 2006) to calculate GHG emissions.

In a study of five coffee growing countries using the Cool Farm Tool, van Rikxoort et al. (2014) observe that a coffee polyculture has a lower CFP (6.2 kg to 7.3 kg CO_2e kg-^{1} parchment coffee) than a coffee monoculture (9.0 kg to 10.8 kg) (these estimates include emissions from fermentation and waste production). Martins et al. (2015) used an average coefficient of 7.6 Mg CO_2-e kg-^{1} to measure the CFP of parchment coffee in their study of spatial distribution of carbon balance (as suggested by van Rikxoort et al. [2014]). For *Coffea arabica*, Nab and Maslin (2020) report a CFP range of 1.01 to 1.04 kg of CO_2e kg-^{1} of green coffee for conventional production systems in Brazil and Vietnam, and a range of 0.05 to 0.08 kg of CO_2e kg-^{1} for sustainable production systems. The authors used combined guidelines from PAS 2050:2011 (BSI 2011; DEFRA 2011) and the IPCC (Eggleston et al. 2006) to calculate the CFP.

All of the above studies show that coffee production has a negative carbon balance, meaning more carbon is used to produce a unit of green coffee than is sequestered. But coffee farms have a less negative carbon balance with the adoption of agroforestry and organic farming system, and higher negative carbon balance with the adoption of full-sun farming and high use of inorganic fertilizer at the farm level.

Limitations of current tools

Critical components missing, including soil and biomass

Most tools omit key components that are critical to accurately assessing the GHG emission and computing the CFP for coffee. These omissions can lead to the over- or underestimation of coffee's CFP. Most tools that calculate farm-level CFP focus on four inputs: fertilizer application, fossil fuel use, electricity, and pesticide use. They may also include tillage methods and herbicide application (Killian et al. 2013; Martins et al. 2015; Nab and Maslin 2020; Noponen et al. 2012). Although all tools are based on IPCC Tiers 1 and 2 and some with PAS 2050:2011 (BSI 2011), none consider changes in carbon stocks in soil, above and below ground biomass (such as carbon sequestered in shade trees and coffee plants), or emission of GHGs from soil under different management practices, and erosion-induced loss of SOC and its fate during the transport and redistribution over the landscape. Some of these components are being addressed in tool updates, such as a "perennials module" in the Cool Farm Tool, which is currently under development but is not yet available for use. Because CFP tools available for use today for coffee do not include these factors, we should consider that there are no accurate estimates of coffee's carbon footprint.

Biomass

Above ground and below ground biomass such as from litter decomposition and pruning play key roles in the magnitude of CFP of the coffee production system. Coffee is a perennial crop and starts producing fruits after three years. Coffee plants and shade trees require regular pruning to get high-quality green coffee yield.

Soil organic carbon (SOC)

The importance of SOC dynamics to CFP is indicated by research in Peru (Solis et al. 2020), which documents that polyculture shaded coffee production system may contribute as much as 189 Mg C ha^{-1} of carbon stock, followed by Inga-shaded (146 Mg C ha^{-1}) and unshaded (113 Mg C ha^{-1}) system. SOC dynamics contribute to carbon storage, even in unshaded systems, but they are not considered in the literature on coffee carbon footprints, nor are they built into most of the tools that estimate footprints.

Soil erosion

Another factor omitted by most of the carbon accounting systems is the loss of SOC by soil erosion. Coffee is grown in tropical climates, often on sloping lands, and a good harvest requires more than 1,400 mm of rainfall. This topography is prone to soil erosion, and thus, erosion-induced loss of SOC and the attendant emission of GHGs must be considered.

Ataroff and Monasterio (1997), Noponen et al. (2013b), Ramos-Scharron and Thomaz (2016), and Sepulveda and Carrillo (2015) stress the importance of change in carbon stock of biomass, SOC, GHG emission, and soil erosion for computing the CFP of coffee.

Unique Needs for Coffee Carbon Accounting

Coffee-based cropping systems are unique. Thus, protocols to compute accurate CFPs must consider coffee's unique characteristics such as crop duration, farming practices and farm-management-induced changes in soil properties and processes.

Perennial crop

Several tools to estimate CFPs have been developed for major grain crops such as corn, soybean, wheat, and rice. Grain crops are annual, but coffee is a perennial crop that does not bear fruit until three years after planting. For annual crops, fields are prepared at the start of season, followed by planting, intercultural operations (fertilizer and herbicide application, weeding), and harvesting at the end of season. These activities change the physical, chemical and biological properties of the soil, thereby affecting how much carbon is emitted. Coffee is planted once, and for the subsequent 10-30 years is tended annually using various intercultural operations (pruning, weeding, fertilizer application). The carbon emission process is therefore different for perennial crops such as coffee. Taking into account coffee as a perennial crop is important for producing accurate measurements CFP.

Diverse Cropping Systems

As we have seen, coffee is grown in a very wide range of cropping systems globally, which can have a significant impact on the CFP of coffee. Coffee is grown as monoculture (sun grown without trees) or polyculture (shade grown) (van Rikzoort et al., 2014). In a polyculture, coffee is often grown in association with fruit trees which may be leguminous or non-leguminous. These trees provide greater diversity in the sources of GHG emission that must be accounted for in evaluation of CFP. For example, Table 3 shows that sustainable coffee farming systems have a low CFP compared to conventional systems in both Brazil and Vietnam. Table 4 shows that the CFP for soil and fertilizer production and application, crop residue, and energy used varies among traditional compared to commercial polyculture and shaded compared to unshaded monoculture systems. Different cropping systems can produce substantially different crop residue management, fertilizer usage, soil organic matter, soil erosion, and organic matter from shade trees and coffee leaf litter—all of which are key factors in GHG emission from soil during the growing cycle and which influence coffee's CFP (Otalvaro et al. 2017). Including these key factors in carbon accounting will help to identify the best coffee farming practices that reduce the CFP and provide coffee's maximum, marketable quality yield.

Agricultural Management Systems and Soil Organic Carbon

Data show that SOC stock and GHG emissions change with adoption of different farming systems, and any new tool must include these key variables in computing the CFP. SOC stocks have changed after the adoption of new agricultural management systems in the Cerrado and Amazon regions of Brazil. For example, conversion to no till increased SOC storage by 1.08 relative to SOC stocks under native conditions; and there was loss of SOC stock under conventional tillage (Maia et al. 2010). The coffee farming system affects the population of soil microorganisms, which affects SOC stock. In Indian coffee agroforestry systems, arabica coffee harbors more arbuscular mycorrhizal fungi, bacterial population, nitrogen fixers, phosphorus solubilizer, and cellulose decomposing organisms; in contrast, robusta coffee harbors higher numbers of fungi and actinomycetes (Bagyaraj et al. 2015). Noponen et al. (2013a) observe reduction in the SOC stocks by 12% in Costa Rica and 0.13% in Nicaragua during the first nine years of coffee establishment. The SOC differed consistently among soil layers, such as a 2.14 Mg carbon ha^{-1} increase in Costa Rica in the 0–10 cm layer but a greater reduction at the 20-40 cm layer. Ortiz-Gonzalo et al. (2018) report that the highest annual GHG flux in coffee plots ranged from 1 kg to 1.9 kg N_2O-N ha-^{1}, 6.57.6 Mg CO_2-C ha-^{1}, and -3.4 kg to 2.2 kg CH_4-C ha-^{1}, with 66% to 94% of annual GHG fluxes occurring during rainy season compared to those under Napier grass and maize intercropped with beans.

Table 3. Comparison of CFP of Coffee (kgCO_2e kg-^{1} of Green Coffee) by Country and by Cropping System

Farm-level	**Costa Ricaa**	**Brazil** (conventional)[b]	**Brazil** (sustainable)[b]	**Vietnam** (conventional)[b]	**Vietnam** (sustainable)[b]
Fertilizer	0.96	0.96	0.01	0.96	0.01
Fossil fuel	0.03	0.03	0.03	0.03	0.03
Electricity	0.02	0.01	0.01	0.04	0.04
Pesticide	0.01	0.01	0	0.01	0.01
Total	**1.02**	**1.01**	**0.05**	**1.04**	**0.08**

***kgCO_2e kg-^{1} of green coffee**

[a] *Killian et al. 2013.* [b] *Nab and Maslin 2020.*

Table 4. Carbon Footprint of Coffee by Latin American Country and by Production System

Coffee production system	**Soils and fertilizer production and application**	**Crop residue management**	**Electricity, fuel, gas use, and transport**
Traditional polyculture	3.5	1.3	0.16
Commercial polyculture	2.4	0.6	0.21
Shaded monoculture	3.2	0.5	0.11
Unshaded monoculture	2.7	0.2	0.1

***kg CO_2-e kg-^{1} parchment coffee**

Source: van Rikzoort et al. 2014.

Shade Systems

Noponen et al. (2013a) report a negative carbon balance in an intensively managed full sun coffee system (-0.57 Mg CO_2e ha-^{1} yr-1) compared to that of other shaded systems. The shaded system sequestered above and below ground carbon biomass, which far outweighed the GHG emissions from the shaded coffee crop at all management intensities (conventional and organic). Sepulveda and Carrillo (2015) report that cover and height of coffee strata and mixed shade trees, ground cover, slope gradient, and soil features affect the erosion rates in Nicaraguan coffee farms. These production systems use agroforestry in arabica with mixed shade trees such as *Musa spp* and *Igna spp*. SOC stocks under coffee agroforestry systems with nonfruit species in arabica were higher (57.56 Mg C ha-^{1}) compared to robusta, and the opposite trend was observed with fruit trees such as *Artocarpus heterophyllus* and *Mangifera indica*. SOC stocks under CAS were higher than those under coffee monocrops for both coffee types (Tumwebaze and Byakagaba 2016). This difference in carbon sequestration for different types of coffee agroforestry systems should be addressed in any new CFP tool.

Soil Erosion

Conversion of native forest to coffee plantation leads to degradation of soil and water. A simulation study of coffee farms in Puerto Rico showed higher soil erosion rates under bare cultivated coffee farms compared to those under mulched and forested conditions (Ramos-Scharron and Thomaz 2016). Topsoil loss due to soil erosion decreases SOC stock (Lal 2003). Accelerated soil erosion contributes to carbon mineralization, thereby increasing vertical carbon flux in the atmosphere (de Nijs and Cammeraat 2020; Lal 2003; Stockmann et al. 2013). Ataroff and Monasterio (1997) studied soil erosion under sun- and shade-cultivated arabica in the Venezuelan Andes and observed significant loss of greater than 4 mm of mineral fraction due to soil erosion under sun-cultivated coffee during the initial growing years.

Example of a New Carbon Accounting System

Adding missing components could dramatically change farm-level CFPs for coffee

Review of the literature indicates that it is possible to develop carbon accounting systems for coffee that include components missing from current calculators, which can dramatically change the total carbon footprint estimates for coffee. These market-available CFP tools, or any new tool, must consider inputs listed in Table 5 to capture carbon dynamics in the coffee farming system. Any new carbon accounting system for coffee should include multiple growing years, carbon input in the system (above and below ground carbon, SOC stock), and carbon output from the system (carbon loss due to soil erosion, loss by GHG emission, and farm inputs such as fertilizer, pesticide, and energy used).

In the proposed carbon accounting system, carbon balance should be calculated annually to guide farmers to adopt efficient and carbon-friendly management practices. The difference in the carbon input and output is divided by the green coffee yield of that year to calculate the amount of carbon used to produce a unit of green coffee by farming system. Carbon input is calculated by change in biomass (root and shoot) and SOC stock each year. Carbon output from the system is calculated on the basis of all inputs (fertilizer, pesticide, energy), loss of carbon due to soil erosion, and GHG emission each year. The carbon balance is calculated using equation 1.

Equation 1

$$CB_{yr} = \frac{(\Delta C_{bio} + \Delta SOC) - (E_{soil} + GHG + \text{Farm Inputs})}{\text{GC yield}}$$

CByr is carbon balance, ΔCbio is change in the above and below ground biomass, and ΔSOC is change in SOC stock during the study year. Esoil is carbon loss due to soil erosion, GHG is carbon loss due to GHG emission computed as CO_2 equivalent, and Farm Inputs include use of carbon equivalent in fertilizers, pesticides, and energy production during the study year. GC yield is green coffee yield in the particular year. Negative value of CByr shows the amount of carbon emitted to produce the CFP per unit of green coffee yield, and positive value shows carbon sequestered in the system.

Table 5. Inputs Collected Each Year for Precise Carbon Accounting in Coffee Production System

SN	Inputs proposed
1	Field establishment
1.1	Initial SOC stock measurement (1 m depth)
1.2	Field residue content
1.3	Tillage practice (fuel used diesel) (ha-^{1})
1.4	Fertilizer application per ha
1.4.1	Nitrogen fertilizer (kg ha-^{1})
1.4.2	Phosphorous fertilizer (kg ha-^{1})
1.4.3	Potassium fertilizer (kg ha-^{1})
1.4.4	Farmyard manure/compost/coffee pulp (Mg ha-^{1})
1.4.5	Micronutrient used (kg ha-^{1})
1.4.6	Fuel used diesel (l ha-^{1})
2	Transplantation of coffee plant
2.1	Fuel used diesel (ha-^{1})
3	Shade- or sun-grown coffee: tree species
3.1	Carbon sequestered in the shade trees (initial assessment, year 1, 2...) (Mg C ha-^{1})
3.2	Tree density (number of trees ha-^{1})
4	Irrigation (mm of water)
4.1	Type of irrigation
4.2	Frequency of irrigation
4.3	Fuel used per time (diesel or electricity ha-^{1})
5	Harvesting (after 3 years of planting)
5.1	Fuel used for machinery if mechanical harvesting (L ha-^{1})
5.2	Green coffee harvested (Mg ha-^{1})
6	GHG emission (N_2O, CH^4, CO_2) each year
7	Soil erosion loss (Mg ha-^{1})
8	SOC stock (each year for surface 30 cm, every 3 years to 1 m depth)

Equation 1 was used to calculate the carbon budget that includes soil carbon and biomass in different coffee growing systems. The equation was applied to data from prior studies for shaded compared to unshaded coffee farming systems (see Table 6), and for organic compared to conventional coffee agroforestry systems (Table 7). SOC loss due to soil erosion is calculated by using data from Lal (2003).

Using the new equation, all four systems continue to show a negative carbon balance, meaning more carbon is used to produce a unit of green coffee than is sequestered. While the estimates suggest that coffee production, even with shade and organic systems, still produces net carbon emissions, total emissions are potentially lower than what current tools suggest. Similar to calculations performed with existing tools, the carbon footprint for shaded coffee farming system is less than that for unshaded (full sun) system, 1.64 kg CO_2e kg-^{1} green coffee compared to 2.12 kg CO_2e kg-^{1}, respectively (see Table 6). Similarly, the CFP for the organic farming system (0.82 kg CO_2e kg-^{1}) is lower than that of the conventional coffee (1.32 kg CO_2e kg-^{1}) (see Table 7). This proposed new carbon accounting protocol will guide producers to choose the most carbon-friendly method by scenario.

Table 6. Total Estimated Carbon Balance (Mg CO_2e kg-^{1} of Green Coffee) Using New Protocol under Shaded and Unshaded Coffee Farming System

SN	Inputs proposed	Shaded	Unshaded	Reference
1	Fertilizer production (Mg CO_2e ha-^{1} yr-^{1})	3.92	6.4	van Rikxoort et al. 2014
2	Pesticide production (CO_2e ha-^{1} yr-^{1})	0	0	van Rikxoort et al. 2014
3	Fuel used (Mg CO_2e ha-^{1} yr-^{1})	0.14	0.24	van Rikxoort et al. 2014
4	GHG emission (N_2O, CH_4, CO_2) (Mg CO_2e ha-^{1} yr-^{1})	9.32	9.96	Hergoualc'h et al. 2008
5	SOC loss due to erosion (Mg CO_2e ha-^{1} yr-^{1})	0.009	0.0331	Ataroff and Monasterio 1997; Lal 2003
6	Below and above ground carbon sequestered in shade trees and coffee plants (Mg CO_2e ha-^{1} yr-^{1})	3.62	1.5	Harmand et al. 2007
7	SOC stock (Mg CO_2e ha-^{1} yr-^{1})	1.09	0.25	Noponen et al. 2013b
8	Total green coffee harvested (Mg ha-^{1} yr-^{1})	5.3	7.01	van Rikxoort et al. 2014
9	Carbon balance per unit green coffee harvested (Mg CO_2e Mg-^{1} green coffee)	-1.64	-2.12	n.a.
10	Carbon footprint (kg CO_2e kg$_1$green coffee)	1.64	2.12	n.a.

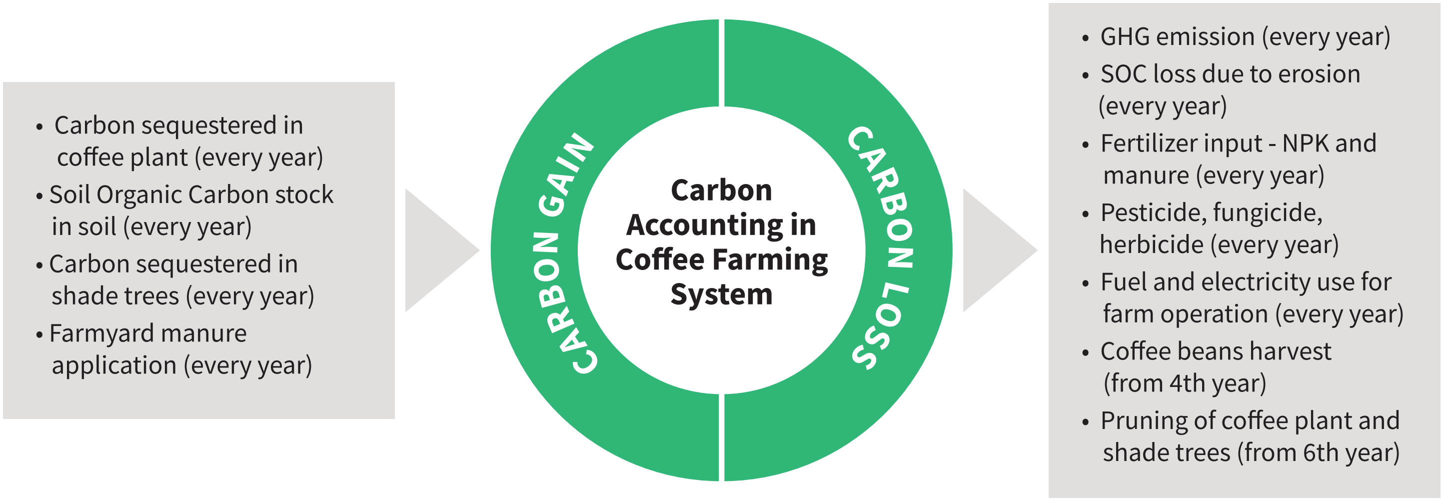
Table 7. Total Estimated Carbon Balance (Mg CO_2e kg-^{1} of Green Coffee) Using New Protocol under Organic and Conventional Coffee Farming System

SN	Inputs proposed	Organic	Conventional	Reference
1	Fertilizer production (Mg CO_2e ha-^{1} yr-^{1})	0.04	2.2	Noponen et al. 2012
2	Pesticide production (CO_2e ha-^{1} yr-^{1})	0.04	0.19	Noponen et al. 2012
3	Fuel used (Mg CO_2e ha-^{1} yr-^{1})	0.135	0.13	Noponen et al. 2012
4	GHG emission (N_2O, CH_4, CO_2) (Mg CO_2e ha-^{1} yr-^{1})	7.36	9.1	Ortiz-Gonzalo et al. 2018
5	SOC loss due to erosion (Mg CO_2e ha-^{1} yr-^{1})	0.01	0.0305	Iijima et al. 2003; Lal 2003
6	Below and above ground carbon sequestered in shade trees and coffee plants (Mg CO_2e ha-^{1} yr-^{1})	2.4	1.3	Noponen et al. 2013a
7	SOC stock (Mg CO_2e ha-^{1} yr-^{1})	1.24	1.12	Noponen et al. 2013b
8	Total green coffee harvested (Mg ha-^{1} yr-^{1})	5.7	8.45	Noponen et al. 2013
9	Carbon balance per unit green coffee harvested (Mg CO_2e Mg-^{1} green coffee)	-0.82	-1.32	n.a.
10	Carbon footprint (kg CO_2e kg green coffee)	0.82	1.32	n.a.

Conclusion

Carbon accounting in the coffee farming systems is a multiyear process involving a range of vital components. This report's data and syntheses indicate that the estimated CFP of coffee has a large range (0.4 kg to 10.8 kg CO_2e kg-^{1}) because of the wide range of methodologies and tools used, as well as varying objectives and motives. Furthermore, none of tools used for coffee CFP calculation address all the components that play a crucial role in carbon accounting, lacking SOC stock, SOC loss due to erosion, change in biomass (above and below ground), and GHG emission. This suggested methodology addresses all major components involved in the CFP of the coffee farming system. Figure 1 provides a synthesis of the critical components required for comprehensive carbon accounting to guide tool developers to expand or create more complete CFP tools for coffee. Documenting the factors contributing to carbon gain and loss in coffee farming systems can help producers, researchers, and others understand variables in carbon accounting, facilitate improvement of available CFP tools, and respond to issues related to the CFP of coffee. In particular, a revised approach to calculating carbon footprints that takes into account missing factors would provide coffee growers and roasters an improved protocol for identifying the best management practices for growing coffee.

Figure 1. Flow chart showing the net gain and loss of carbon in coffee farming system.



- Carbon sequestered in coffee plant (every year)
- Soil Organic Carbon stock in soil (every year)
- Carbon sequestered in shade trees (every year)
- Farmyard manure application (every year)

- GHG emission (every year)
- SOC loss due to erosion (every year)
- Fertilizer input - NPK and manure (every year)
- Pesticide, fungicide, herbicide (every year)
- Fuel and electricity use for farm operation (every year)
- Coffee beans harvest (from 4th year)
- Pruning of coffee plant and shade trees (from 6th year)

Note: NPK = nitrogen, phosphorus, and potassium

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