# FARM CARBON FOOTPRINT – ASSESSMENT METHODS

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**Abstract**

*Minimizing the negative environmental effects of agricultural practices has become a shared objective through initiatives like the 2030 Agenda for Sustainable Development and the European Green Deal. In this regard, this research aimed at complementing the literature with a comparative view on a selection of farm carbon footprint assessment methods. This research is positioned within the broader context of the global efforts aimed at achieving agri- environmental sustainability. Through the exploration of diverse farm carbon footprint assessment frameworks, this paper sheds novel insights onto the quantification techniques of agricultural greenhouse gas emissions. Findings can support policy recommendations based on the identified methodologies that can successfully capture the most influential variables on the agri-food sector's transition towards practices that uphold the principles of sustainability at societal, economic, and environmental dimensions. Research results argue for the potential of life cycle assessment techniques to capture key agricultural elements in the quantification of greenhouse gas emissions. Hence, implementing these techniques in farm carbon footprint assessment frameworks ensures their efficiency.*

**Keywords:** *agriculture; carbon footprint; greenhouse gas emissions; measurement*
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## Introduction

Carbon footprint is a concept that revolves around the measurement of total greenhouse gases (GHGs), or greenhouse gas emissions–as identified in the literature (Bryan et al., 2015; Constantin et al., 2021; Hu et al., 2024; Kokotovic et al., 2015; Rebolledo-Leiva et al., 2017). GHGs can be generated directly or indirectly by individuals and their actions, organizations, farms, farmers, and agricultural activities, products, and services. While some agents are fully aware of their GHGs emissions, some do not understand the societal, economic and environmental impacts of GHG generation (Dósa & Russ, 2020; Ignat & Constantin, 2021). As a complex environmental metric, GHGs are measured in carbon dioxide equivalents units, encompassing a wider range of greenhouse gases, among which methane ($CH_4$), nitrous oxide ($N_2O$), carbon dioxide ($CO_2$), and fluorinated gases can be identified. Thus, this standardized measurement technique efficiently aids in understanding the impact of different activities on climate change and ecosystem dynamics (Munang et al., 2013), especially by pointing out and explaining the correlation between the negative effects of GHGs on global warming (Koneswaran & Nierenberg, 2008). The calculation or assessment technique of a carbon footprint involves taking into consideration all the GHG emission sources during specific timeframes, and such a measurement technique is the life cycle assessment (LCA) of a product or service (Beauchemin et al., 2011; Jeswani et al., 2018; Venkat, 2012).

An ardent research topic that has gathered a lot of attention, especially in the light of the Paris Agreement, the European Green Deal and the 2030 Agenda for Sustainable Development (European Commission, 2019; United Nations, 2015), is that of understanding and of measurement of footprints with the purpose of formulating, developing and implementing strategies to reduce greenhouse gas emissions and mitigating the negative impacts of climate change (Boix-Fayos & de Vente, 2023; Cuadros-Casanova et al., 2023; Istudor et al., 2019). To add more, the reduction of GHGs generated from agricultural activities weighs heavily on addressing the ongoing climate change crisis globally (Gabric, 2023), since agriculture is a significant generator of methane, nitrous oxide and carbon dioxide (Liu et al., 2022; B. Zhang & Chen, 2014). As explained by Lerner et al. (1988), methane is predominantly generated by enteric fermentation in ruminant animal growing, especially in the case of cows, sheep, and goats, because of their digestive process, which involves releasing methane into the atmosphere. Additionally, methane emissions result from manure management practices in livestock operations and rice paddies, on the ground of favorable production conditions of methane, referring to the anaerobic potential (Marañón et al., 2011). Moreover, the intensive use of synthetic fertilizers in agriculture, manure application, as well as the cultivation of nitrogen-fixing crops are some of the causes of nitrogen content increase in the soil, with the potential to boost $N_2O$ emissions, based on the nitrification and denitrification processes (Chen et al., 2019), leading to a gas emission that significantly accounts to the agriculture's carbon footprint due to its high potency and longer atmospheric lifetime (Mohanty et al., 2020; Skiba et al., 2009). Lastly, carbon dioxide emissions caused by agricultural activities are highly linked to factors such as deforestation and land-use change (Arneth et al., 2017; Hong et al., 2021), often on the ground of agricultural land expansion (Raihan et al., 2022; H. Zhang et al., 2023). Not only that, but the conversion of forests into cropland or pasture also implies releasing the tree- and soil-stored carbon into the atmosphere, therefore contributing to the agricultural-related GHG emissions from a $CO_2$ perspective (Chiripuci & Dumitru, 2017; Rytter & Rytter, 2020; Xie et al., 2021).

The necessity to comprehensively assess the carbon footprint of farms emerges as a key element to support decision and policy making in the context of agriculture's substantial GHGs generation. It became imperative to further harmonize strategic policy objectives with agri-environmental practices. Thus, by providing insights into the measurement techniques of farm carbon footprint, this paper was aimed at critically discussing various farm GHG quantifying frameworks. Identifying the most suitable assessment method to calculate farm carbon footprints serves as the foundation for implementing sustainable agricultural practices (Kumara et al., 2023; Strat et al., 2024).

**Carbon Footprint Assessment Frameworks – A Review of Three Case Studies**

Life-cycle assessment frameworks has been proposed by Peng et al. (2021), who developed a technique to quantify the carbon footprint in a comparative manner: carbon emissions and carbon sequestration. The proposed LCA model from Figure 1 was designed around mapping production and consumption patterns of rural household, by incorporating agricultural and livestock-related processes, as well as the input-output LCA concerning the consumption of energy, food, and transporation. A cornerstone in the quantification framework proposed by Peng et al. (2021) was the evaluation of emissions resulting from direct energy. Moreover, the carbon emissions attributable to the consumption of various fuels used at local levels were also taken into account, while considering the specific type and quantity of fuel utilized. Beyond this, the proposed assessment framework encompassed the emissions associated with indirect carbon consumption, by paying attention to the lifetimes of durable goods, strategically positioning this aspect into the framework. Through this design, the framework advocates for reducing carbon footprints by advocating for sustainable consumption patterns.

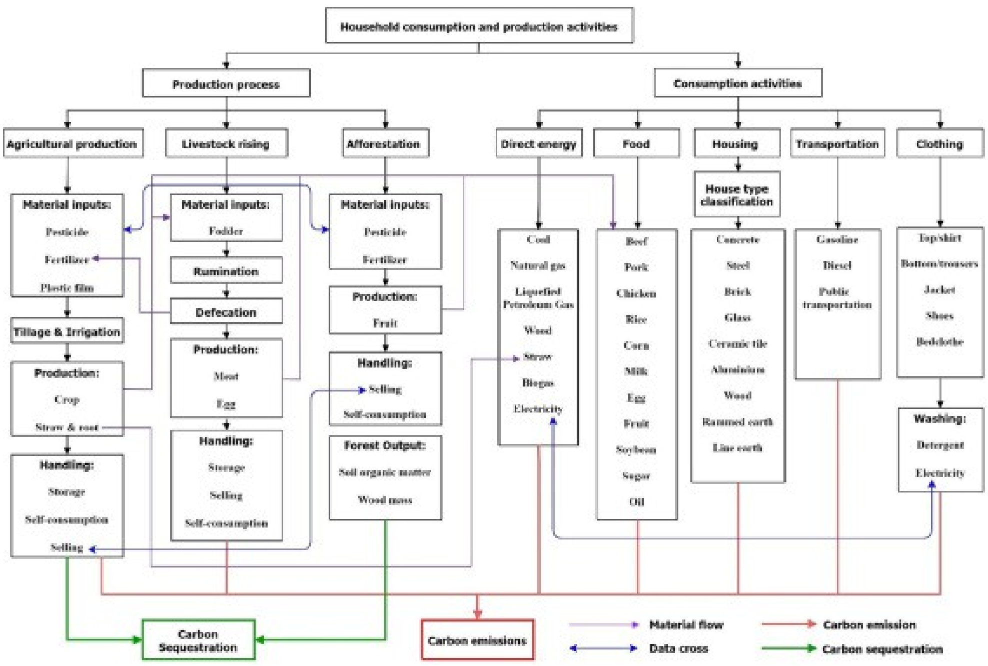


**Figure 1. Carbon footprint assessment framework applied to rural areas**

*Source: Peng et al. (2021)*

Because it was focused on rural settings and agriculture is a primary livelihood activity in such settings, the work of Peng et al. (2021) dualistically examined the resulted carbon emissions from agricultural material inputs and the potential for carbon sequestration through the growth of crops and biomass. Thus, by including these factors into the research model, the framework underscores more than the environmental impact of conventional farming techniques; it empowers the adoption of sustainable agricultural practices that are capable of carbon sequestration, thereby contributing to climate change mitigation.

Lastly, the assessment framework of Peng et al. (2021) put the spotlight on the carbon footprint of livestock raising, considering its significant contribution to the generation of methane emissions due to enteric fermentation processes. By including this evaluation agri-environmental element into the model, the carbon footprint assessment framework provides a comprehensive perspective on the impact of livestock production on GHG generation.

Another carbon footprint assessment framework identified in the literature was applied to a banana supply chain (Craig & Blanco, 2009). In this framework, the empirical approach involved data collection, carrying out interviews, supply chain mapping. In the overview, the authors explained that bananas destined for the United States market predominantly originate from Central America, and, as a result, the supply chain encompasses various stages, from cultivation, which includes fertilizers, pesticides, and fungicides application, to harvesting, packaging, and transportation. Significant amounts of GHGs are produced, since the bananas are then transported to the United States, undergoing several stages including shipment, distribution, and retail, as shown in Figure 2.

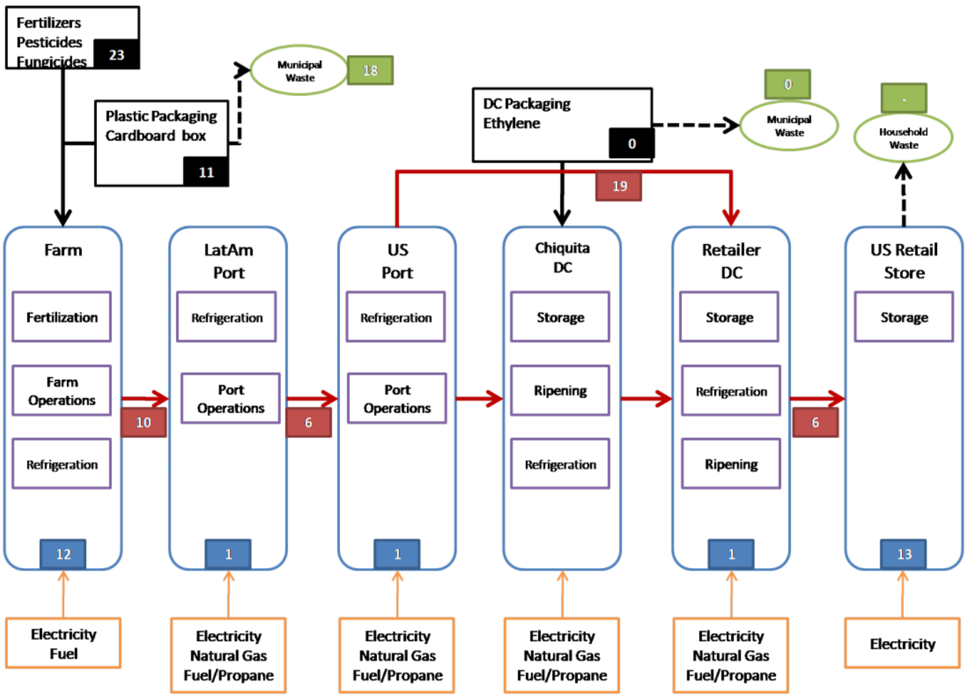


**Figure 2. A carbon footprint assessment framework applied to a banana supply chain**

*Source: Craig and Blanco (2009)*

Although primarily from electricity, energy use in distribution and retail facilities were considered in the banana carbon footprint assessment framework, through the explanation of allocation challenges in multi-product scenarios. Packaging materials and agricultural chemicals were also included in the framework, aiming to identify GHGs quantities from these sources. Additionally, the LCA study provided GHG estimates, pinpointing manners to decrease emissions. Lastly, Craig and Blanco's model underscored the variability in carbon footprint estimations across distribution networks and banana farming practices, emphasizing the complex nature of precise carbon footprint quantifications techniques.

Carbon footprint assessment frameworks were designed for other types of farming, such as in the case of a dairy farm. In this regard, the work of Seigl et al. (2023) was aimed at describing a procedure for the development of GHG quantification model specific for dairy farms, based on the data gathered from a case study of Bavaria. This detailed model in Figure 3 incorporated various emission sources, including direct energy consumption (similarly with the model proposed by Peng et al.), the utilization of consumables like fertilizers and feed (as noticd in the framework of Craig and Blanco), and biological processes such as enteric fermentation in livestock. As a result, there are plenty of similarities with the previously-described carboon footprint assessment frameworks.

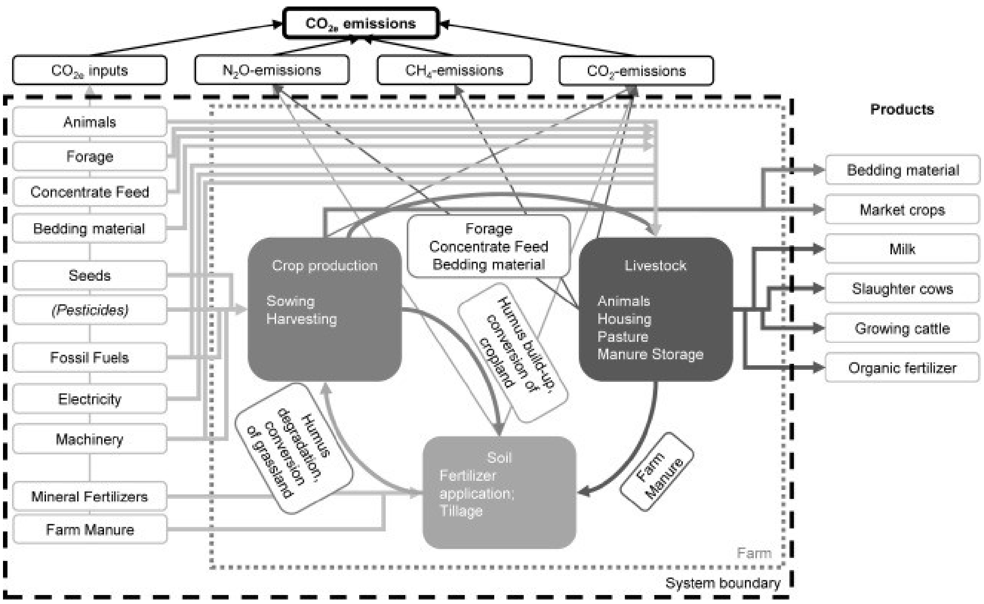


**Figure 3. Carbon footprint assessment framework in the case of a dairy farm**

*Source: Siegl et al. (2023)*

By designing a useful tool that encompasses analytical insights, the framework of Siegl et al. supports the Bavarian dairy industry's efforts to transition towards more sustainable and environmentally-friendly farming practices through a model that empowers: closed designs for slurry or liquid manure storage facilities (to reduce methane emissions); solid manure composting under aerobic conditions (to lower GHGs); increasing the productive dairy cows livespan and increase milk production efficiency (to reduce GHG per unit of milk produced), increasing the use of renewable energies and sources diversification (to lower GHGs), tree planting in the farm (to sequester carbon dioxide and reduce GHGs); and other practices.

All three case studies presented—Peng et al. (2021) focusing on rural settings; Craig and Blanco (2009) on the banana supply chain; and Siegl et al. (2023) on Bavarian dairy farms—offer insightful perspectives on carbon footprint assessment frameworks, each meticulously crafted to specific agri-environmental contexts, yet sharing common quantifying purposes, as well as the strategic general objective of farm carbon footprint minimization. All three assessment frameworks adopt an LCA approach, including both direct and indirect GHG emissions generated from production processes, energy consumption, and the use of inputs like fertilizers, feed, and fuels. While the framework of Peng et al. (2021) was rooted in the rural context, emphasizing the importance of carbon sequestration through biomass growth, Craig and Blanco's work (2009) was much more dedicated to incorporating the complexities of international logistics into the carbon footprint assessment framework. Due to the nature of the sample (dairy farm), the framework of Siegl et al. (2023) had manure management as key variable of analysis concerning GHG emission sources. However, all three framework stand for improving agricultural farm practices towards sustainability.

**Conclusions**

The measurement of farm carbon footprints is an essential tool that can be used by scholars, practitioners, and decision makers to ensure the transition towards a more environmentally-friendly agricultural sector by mitigating the negative agri-environmental impacts associated with food production and agricultural support activities, based on GHG computation. The significance of crafting efficient carbon footprint quantification models lays in the necessity to adopt disruptive practices that contribute to the global efforts under the 2030 Agenda for Sustainable Development, the European Green Deal, and the Farm to Fork Strategy.

This investigation into carbon footprint assessment frameworks was based on reviewing three different studies. One was centered on rural settings, another was focused on a banana supply chain, and the last one was dedicated to Bavarian dairy farms. All these studies detail valuable GHG assessment methodologies, collectively advocating for the importance of employing LCA techniques in the quantification models. Despite their shared strategic objective of GHG minimization, each framework was distinctly nuanced and particularly crafted to respect the characteristics of different agri-food chain, putting the complex nature of environmental sustainability into the research spotlight.

This cross-sectional approach to some of the papers identified in the literature to undertake the objective of designing farm carbon footprint assessment frameworks showcases the application of LCA techniques in addressing the unique challenges posed by different agricultural practices. In addition, this paper complements the knowledge by successfully synthesizing the findings and mapping a common thread for the assessment framework of farm carbon footprints, no matter the agri-food chain. Such a comparative analysis marks a valuable addition to confirm the most important variables that should be included in any research framework, underscoring variable applicability across diverse agricultural contexts.

By design, this paper inherited a notable limitation, namely the reliance on existing research frameworks, since there was no introduction of primary research to test novel farm carbon footprint assessment models on empirical data or in unexplored agricultural contexts. This limits the capacity to provide insights beyond what has been already tested in the literature. Thus, future research could tap into testing augmented assessment methods of farm carbon footprint.

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