E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; SP-8(9): 61-65
Received: 22-07-2025
Accepted: 24-08-2025

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Carbon footprint of Robusta based coffee agroforests of Kodagu in the Central Western Ghats region of India

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DOI: https://www.doi.org/10.33545/2618060X.2025.v8.i9Sa.3730

Abstract
Kodagu district in the central Western Ghats of India, known for its unique coffee agroforests represents a significant opportunity for studying carbon footprints. The study was carried out to assess the carbon footprint associated with the different management practices followed in the coffee agroforests by small (<10 ha.) and large (>10 ha.) farmers. A questionnaire survey was carried out to assess the carbon footprint. The results revealed that small land holdings had less carbon footprint than large land holdings which accounted for 1.44 Mg CO_2e ha^{-1} y^{-1} and 1.75 Mg CO_2e ha^{-1} y^{-1} respectively. The study highlighted traditional shaded coffee agroforests, significantly contributed to sustainable agroforestry practices.

Keywords: Carbon footprint, small farmer, large farmer

Introduction
Coffee, often referred to as "Brown Gold," stands as one of the most widely consumed beverages, deeply embedded in the daily lives of millions. Its transformation from a regional agricultural product to a globally traded commodity underscores its immense economic importance and cultural significance. As an essential agricultural resource, coffee is cultivated in approximately 80 tropical countries, supporting the livelihoods of an estimated 125 million people across Latin America, Africa, and Asia, thereby playing a crucial role in global trade and economic sustainability (Krishnan, 2017) [11]. Indian coffee is renowned globally for its quality and is becoming a prominent producer of top-tier shade-grown coffee. Coffee the perennial plantation crop of the family *Rubiaceae* in coffee-based agroforestry is often the main source of income for small-scale producers, who are among the most vulnerable to climate hazards (Bacon *et al.*, 2014) [3]. Kodagu, often referred to as the Coffee Cup of India, is among the smallest districts in Karnataka, situated in the Western Ghats, a global biodiversity hotspot. Spanning a total area of 4106 sq. km, coffee cultivation occupies 1,06,921 hectares. In India, almost all coffee is grown under shade, often alongside other economically valuable crops. Indian coffee systems serve as global models when exploring solutions for the climate crisis and the economic sustainability of coffee. In Kodagu, coffee-based shaded perennial systems are the cornerstone of traditional agroforestry (Dhanya *et al.*, 2016) [7]. These coffee agroforests with high species diversity play a vital role in biodiversity conservation, sustainability and carbon sequestration. The shade trees in these coffee agroforests significantly enhance carbon storage on coffee plantations, aiding in climate change mitigation (Lugo-Perez *et al.*, 2023) [10] compared to unshaded coffee plantations. Beyond their primary role, shade trees provide additional ecosystem services such as fruit production, timber, and soil fertility maintenance. They also act as a climate adaptation strategy for smallholder farmers, reducing both ecological and economic vulnerability (Nasiro, 2024) [14].

Climate change is increasingly exerting a profound impact on agricultural production worldwide. In tropical regions, it manifests through heightened uncertainty in rainfall patterns and more frequent and intense floods and droughts, significantly affecting agriculture in multiple ways. Climate change significantly affects coffee, which is highly sensitive to environmental shifts by inducing substantial impact on coffee quality and yield (Jawo *et al.*, 2022) [9].

Additionally, the coffee industry itself contributes to greenhouse gas emissions. Therefore, it is crucial to recognize that various agricultural practices, including coffee farming's contribution to GHG emissions and thus to climate change.

The region of Kodagu is primarily dedicated to farming. Traditionally and historically, rice paddies are located in the valley bottoms, while the surrounding hills are home to coffee and pepper agroforests. Coffee cultivation is being done depending on the region-specific environmental condition. Coffee agroforests exhibit a continuum of structural and floristic diversity, from species-rich complex agroforests quite similar to natural secondary forests to simple coffee plantations planted with shading trees (Toledo and Moguel, 2012) [18].

Understanding the carbon footprint of coffee is crucial for farmers. By evaluating these distinct groups, this study sought to uncover the differential impacts of farm size on greenhouse gas (GHG) emissions within the robusta-based coffee agroforests of Kodagu. Such comparative analysis provides critical insights into the environmental footprint associated with each farming practice, thereby guiding strategies for sustainable agricultural management and carbon mitigation.

Material and Methods

The study was carried out in the robusta-based coffee agroforests of Kodagu district, Karnataka state located in the Central Western Ghats region during 2022. A preliminary study was conducted in the robusta-based coffee agroforests (Fig. 1) of Kodagu District. A stratified random sampling approach was adopted. The study area was stratified (categorised) based on land holdings size into small farmer (<10 ha) and large farmer (> 10ha) as classified by *Anon.*, 2022 [1]. Plantations with the plantation age of more than 10 years were selected randomly in different locations within Kodagu.

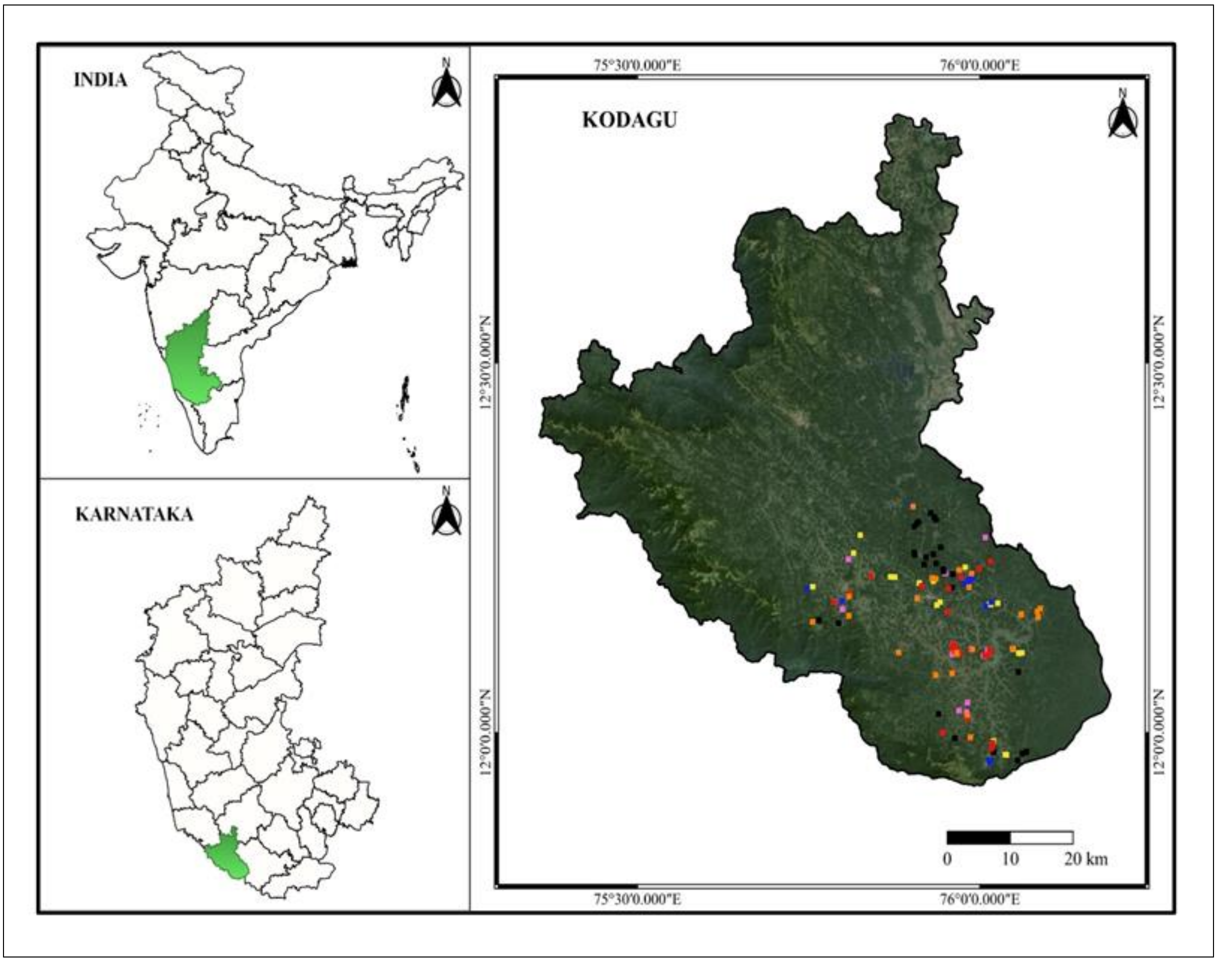

Fig 1: Location of the study sites in Kodagu

Carbon Footprint Estimation

The Carbon Footprint of the coffee agroforests of small farmers and large farmers includes the total amount of GHGs emitted from the various management practices employed in the coffee agroforests. The emission calculations were based on the on-farm activities, such as fertilizers (N, P, K, FYM) application, agrochemicals required for coffee cultivation, farm power used for field preparation, intercultural operations and fuel power for operating pumps for irrigation. On-farm emissions were calculated based on the "Guidelines for National Greenhouse Gas Inventories (*Anon.*, 2006) [1] and expressed in carbon equivalent (CE) units. It is estimated using the following relationship, according to Cheng *et al.*, 2011 and Patel *et al.*, 2019 [5, 15].

Carbon Footprint = Agricultural Input × Emission factor

Where "Carbon Footprint" represents the GHG emission induced by inputs (in Megagram carbon dioxide equivalent expressed as Mg CO_2e). "Agricultural Input" is the total amount of inputs such as fertilizer, pesticide, soil amendments, fuel, electricity, etc. "Emission Factor" is the individual carbon intensity in kilo gram of carbon dioxide equivalent (Kg CO_2e) per unit volume or mass, when manufactured and/or applied as individual inputs. Thus, the estimation of the Total Carbon

Footprint (CF_t) in coffee production was calculated by summing of all the individual carbon costs from different inputs:

Total Carbon Footprint (CF_t) = $CF_F + CF_P + CF_{IR} + CF_D$

Where, CF_F, CF_P, CF_{IR} and CF_D represents the individual carbon footprint from fertilizers, pesticides, irrigation and mechanical operations involved in crop production, respectively.

Calculation of Carbon Emission from Fertilizers

The emission from fertilizers was calculated by multiplying the quantity of fertilizer used in the production system with the respective emission factor and the GHG emission obtained was expressed as carbon dioxide equivalent (CO_2e).

Calculation of Carbon Emission from Pesticides

The emission from the application of pesticides was calculated in a similar way as for emission from fertilizer application. Total GHG emission from pesticides was calculated by multiplying the quantity of pesticide applied to the crop with the emission factor for pesticides. The total GHG emission thus obtained was reported in terms of carbon dioxide equivalent (CO_2e).

Calculation of Carbon Emission from Mechanical Operations

To calculate the emission from mechanical operations performed during crop cultivation, the fuel (diesel) consumed per unit area for different operations was computed. The GHG emission from the fuel consumed in terms of carbon dioxide equivalent (CO2e) was computed by multiplying the quantity of fuel used with respective emission factors.

Calculation of Carbon Emission from Irrigation

The emission from the irrigation operation was calculated based on the total fuel (diesel) or units of electricity consumed for irrigating the coffee plantation. It was quantified based on the frequency of irrigation and the number of hours a machine operated in a day and was multiplied by the emission factor of the fuel (diesel) or electricity used and expressed in terms of carbon dioxide equivalent (CO_2e).

Results and Discussion

Carbon Footprint of small and large farmers in Robusta-based Coffee Agroforests

The results pertaining to the carbon footprint of small and large farmers in the robusta-based coffee agroforests of Kodagu are presented in Table 1. The analysis revealed a significant difference in carbon footprint between small and large landholdings. Small landholdings exhibited a carbon footprint of 1.44 Mg CO_2e ha^{-1} y^{-1}, whereas large landholdings showed a substantially higher value of 1.75 Mg CO_2e ha^{-1} y^{-1}. In Latin American countries, the carbon footprint of robusta coffee in the traditional polyculture maintained by small growers was 7.3 kg CO_2e kg^{-1} (7.02 Mg CO_2e ha^{-1} yr^{-1}) of parchment coffee (50 percent was contributed by post-harvest processing). In contrast, commercial monocultures had a carbon footprint of 9 kg CO_2e kg^{-1} parchment coffee (Rikxoort *et al.*, 2014) [16] which was much higher than the results obtained in the present study. In another study by Maina *et al.*, (2016) [12] reported the carbon footprint decreased with increase in production level and the mean farm level carbon footprints for 1 kg of fresh coffee cherries were 0.05 kg CO_2e, 0.24 kg CO_2e and 0.54 kg CO_2e for high, medium and low producers along Small - Holder Coffee Supply Chain.

Table 1: Carbon Footprint of small farmers and large farmers Robusta based coffee agroforests

Land holdings	Carbon Footprint Mg CO_2e ha^{-1} yr^{-1}	SE.m (±)	P value	t value
Small Farmer	1.44	0.10	0.01520*	-2.50
Large Farmer	1.75	0.08		
* Significant at 0.05				

The substantial disparity in the carbon footprint between small and large Robusta-based coffee agroforests in Kodagu District highlights the impact of farm size on greenhouse gas (GHG) emissions. This difference could be due to the heterogeneity in the agricultural practices employed by small and large farmers. Some large farms use more intensive farming techniques, including higher fertiliser, pesticide, and machinery inputs (Burney *et al.*, 2010) [4] which contribute to elevated GHG emissions. In contrast, small farms may rely more on traditional and sustainable practices (De, 2021) [6], which results in lower emissions. The higher variability in the carbon footprint of large farms, as indicated by the larger standard error, suggests that these farms may have diverse management practices and levels of resource use efficiency.

The Fig. 2 elucidates the percentage contributions of various inputs to the carbon footprint in robusta-based coffee agroforests of small farmers. Nitrogen (N) fertiliser is the most significant contributor, accounting for 54.48% of the total carbon footprint, highlighting the substantial emissions from its production and application. Diesel has a 12.31% contribution, reflecting its extensive use in farm machinery, while dolomite contributes 11.81%, likely due to its role in soil pH adjustment processes that emit carbon dioxide. This highlights the critical role of synthetic fertilisers in greenhouse gas emissions, as their production and application are linked to substantial nitrous oxide emissions, which is a potent greenhouse gas (Hillier *et al.*, 2011) [8]. Phosphorus (P) fertilizer adds 8.90%, indicating the energy-intensive nature of its production.

Other inputs such as petrol (1.58%), electricity (1.67%), Farmyard Manure (FYM) at 4.15%, potassium (K) fertiliser (4.97%), and pesticides (0.14%) have relatively minor contributions, but collectively add to the overall emissions. Despite their smaller individual percentages, these inputs still played a role in the total carbon footprint. To mitigate these emissions, it is essential to optimise the use of N fertilisers, adopt renewable energy sources, improve machinery efficiency, and explore alternative soil amendments. Additionally, promoting organic farming practices and using bio-based inputs can contribute to sustainable agricultural practices and lower emissions. Understanding the specific contributions of each input allows for targeted efforts to reduce the carbon footprint of these coffee agroforests, thereby aiding climate change mitigation efforts in the agricultural sector.

The Fig. 3 presents the percentage contributions of various inputs to the carbon footprint in robusta-based coffee agroforests with large landholdings. Nitrogen (N) fertiliser was the dominant contributor, accounting for 58.89% of the total carbon footprint, highlighting the substantial emissions from its production and application. Diesel contributed to 11.68%, primarily because of its extensive use in farm machinery and transportation. Dolomite, at 8.15%, played a significant role due to its use in soil pH adjustment. Phosphorus (P) fertilizer contributed 10.40%, reflecting the energy-intensive nature of its production. Other inputs such as petrol (0.32%), electricity (4.80%), Farmyard Manure (FYM) 0.03%, potassium (K) fertiliser (5.71%), and pesticides (0.01%) had relatively minor contributions, but collectively added to the overall emissions.

The results of the present study indicated the dominance of the use of nitrogen in both small and large land holdings and is in line with the studies by Salanamca *et al.* (2017) [17] which indicated that nitrogen is the most essential and extensively applied fertiliser in coffee production because of its significant impacts on vegetative growth stage, yield, and sustainability. Furthermore, Menegat *et al.* (2022) [13] noted that the production, transportation, and field application of N fertilisers resulted in substantial emissions, with China, India, the USA, and EU28 being the top emitters.

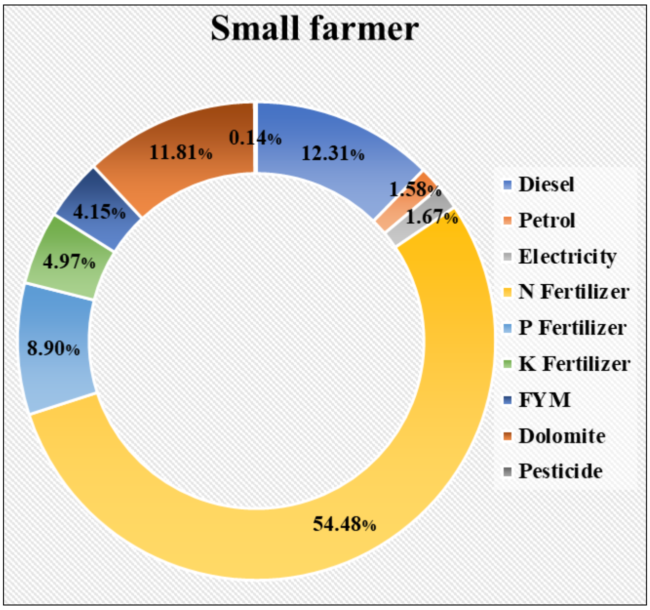

Fig 2: Carbon footprint of different management inputs in Robusta-based coffee agroforests of small farmers

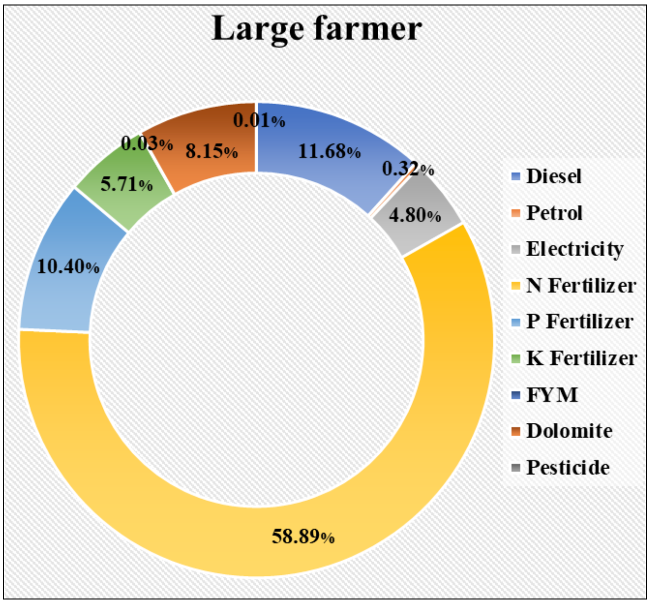

Fig 3: Carbon footprints of different management inputs in Robusta-based coffee agroforests of large farmers

Conclusion

India's coffee production is primarily observed in the hilly tracts of South Indian states, with Karnataka contributing nearly 70%. This study demonstrated that the carbon footprint of small farmers coffee agroforests was less than that of large farmers in Kodagu and highlighted the significant factors contributing to the carbon footprint of Robusta coffee. Thus, quantifying GHG emissions in the Robusta coffee agroforests helps farmers, researchers and policymakers to understand and manage these emissions and develop strategies to achieve food security and stabilize the environment highlighting their potential as a significant tool in climate change mitigation.

Acknowledgement

The authors gratefully acknowledge KSNUAHS, Shiomogga for the support and providing permission to carry out the research work.

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