PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(sp4): 01–07
https://doi.org/10.14719/pst.5213

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RESEARCH ARTICLE

Assessing the carbon footprint of marginal and smallholders farming systems: A typology driven approach

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ARTICLE HISTORY
Received: 25 September 2024
Accepted: 15 October 2024
Available online
Version 1.0 : 28 December 2024

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

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Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Arivukkumar N, Shanmugam PM, Kannan B, Sumathi CS, Prahadeeshwaran M, Sangeetha SP, Raghavi G. Assessing the carbon footprint of marginal and smallholders farming systems: A typology driven approach. Plant Science Today.2024;11(sp4):01-07. https://doi.org/10.14719/pst.5213

Abstract

Agriculture is a significant contributor to greenhouse gas (GHG) emissions, with practices such as fertilizer application, soil tillage and livestock management releasing carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). To meet the demands of a growing population, it is essential to identify agricultural practices that boost food production while simultaneously reducing greenhouse gas emissions, contributing to climate change mitigation and adaptation. This study aimed to quantify GHG emissions from various farm typologies of marginal and smallholder households in the western regions of Tamil Nadu, India, using the Cool Farm Tool (CFT). Data was collected from 250 households in Coimbatore, Tiruppur and Erode districts during 2022-2023 and farm typologies were identified through multivariate analysis, revealing four farm types: (i) cereal crop-dominated marginal farms, (ii) livestock-dominated marginal farms, (iii) cash crop-dominated marginal farms and (iv) plantation crop-dominated small farms. The results show that cash crop and plantation crop dominated farms had the highest emissions, particularly from crop residue burning, fertilizer production and fertilizer application. In contrast, cereal crop-dominated farms recorded lower emissions. Livestock dominated farm type exhibited higher GHG emission from enteric fermentation and manure management due to higher number of livestock. The results of this study highlight the importance of developing farm-specific mitigation strategies to reduce emissions. The study also underscores the value of using tools such as CFT for comprehensive GHG quantification to ensure sustainable agricultural practices.

Keywords

cool farm tool; enteric fermentation; farm types; greenhouse gases; sustainability

Introduction

Agricultural practices emit greenhouse gases (GHG) such as carbon-di-oxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) which is the major reason for climate change which in turn adversely effects crop production (1). The GHG emission from agricultural practices contributed for 14-17 percentage (2) and crop production is considered as an entry point for emission of greenhouse gases (3,4). In India, fertilizer recommendations are typically based on crop response across large geographic regions, which may not account for the spatial variability in the soil's nutrient-supplying capacity which results in lower input efficiency and increased pollution (5,6). The emission of CO_2(77%) and N_2O (60%) are mainly due to the anthropogenic agents in Indian agriculture (7). Agricultural activities such as soil tillage and fertilizer application are significant sources of CO_2 and N_2O emissions across various crops (8). Additionally, methane (CH_4) emissions primarily arise from rice cultivation due to the flooded conditions in rice paddies and from enteric fermentation in livestock, particularly ruminants like cows (9). The mitigation of GHGs from the crop production is significant in term of sustainability. The policies and measures for the mitigation of GHGs is dependent on the quantification of the GHG emission from the agricultural crops (10). The need to quantify greenhouse gas emissions from marginal and smallholder farming systems is becoming more critical. However, direct measurement of agricultural GHG emissions to support national and regional GHG budgets is costly and impractical for nations with highest percentage of marginal and small farming households (11). Additionally, the marginal and small holders exhibit a high degree of heterogeneity (12). Marginal households are typically defined as those owning or cultivating a land area of less than 2 hectares. On the other hand, smallholders are characterized by having land areas ranging from 2 to 3 hectares (13). Thus, developing farm typologies and utilizing GHG estimation methods may be viable strategies for identifying emissions from marginal and small households and exploring mitigation options. GHG can be measured using several tools viz., Cool Farm Tool, Farm DESIGN model and Climate Change, Agriculture, Food Security Mitigation Options Tool (CCAFS MOT) for whole-farm quantification (14). The tools required data on the on-farm level activities for quantification of GHG. The Cool Farm Tool (CFT) used to measure GHG balances across various systems such as maize-wheat cropping system in India (15). The GHG emission at the farm level as impacted by various agricultural management practices has been assessed using the CFT. Thereby, the main objective of the study is to identify farm types and quantify the GHG balance for various farm typologies of marginal and small farm households in western parts of Tamil Nadu, India by using the Cool Farm Tool.

Materials and Methods

Description of the study area and data collection

The study was conducted at marginal and small farm households in Coimbatore, Tiruppur and Erode districts of Tamil Nadu, India (Fig. 1). The research survey was conducted during 2022-2023 among 250 marginal and small farm households in western parts of Tamil Nadu using survey questionnaire. The data collected pertains to the baseline condition of farms during 2020-2021. The questionnaire includes information on household characteristics, labour, land use patterns, livestock, cost of production and income aimed at identifying the heterogeneity within the farming system. Based on the data collected from 250 samples during the survey, significant and key variables are identified based on experts in study area for further multivariate analysis (16,17). To avoid errors in the statistical analysis, the data collected were carefully examined for missing data and outliers in the data set. The outliers in the data were detected by the box plot (18). Typology were constructed using multivariate analysis in R software (version 4.3.2) with the ade4 package (19). The variables used for multivariate analysis is given in Supplementary Table 1. The multivariate analysis used were principle component analysis and cluster analysis. The principal components (PCs) are selected based on criteria (i) Kaiser criterion- eigen value >1 (20) (ii) scree plot showing variations and (iii) interpretation based on the correlation of PCs (21). The cluster analysis was performed by hierarchical clustering for identifying the number of clusters using Wards method (22). The multivariate analysis identified four farm types. Dendrogram also supports four farm types (Fig. 2). In the current study, four

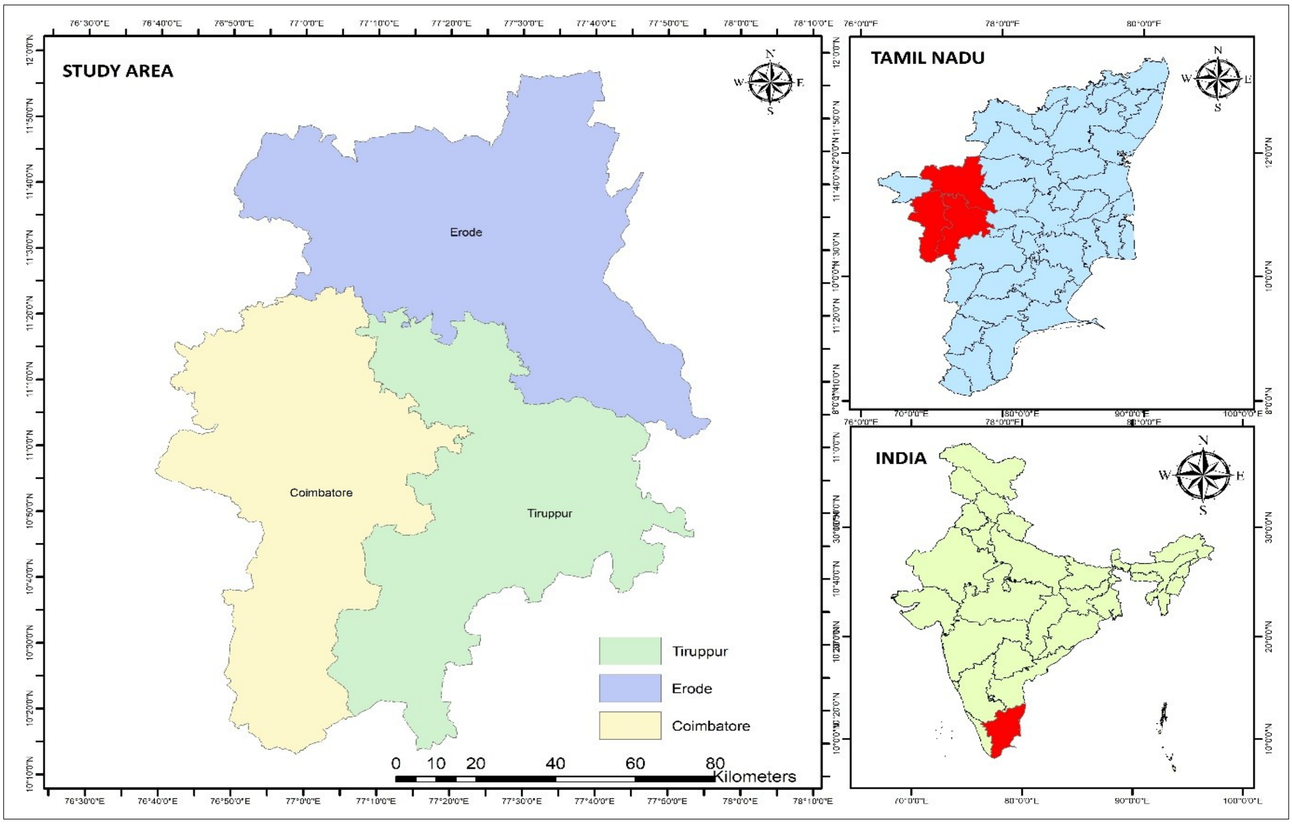

Fig. 1. Map showing the study area location

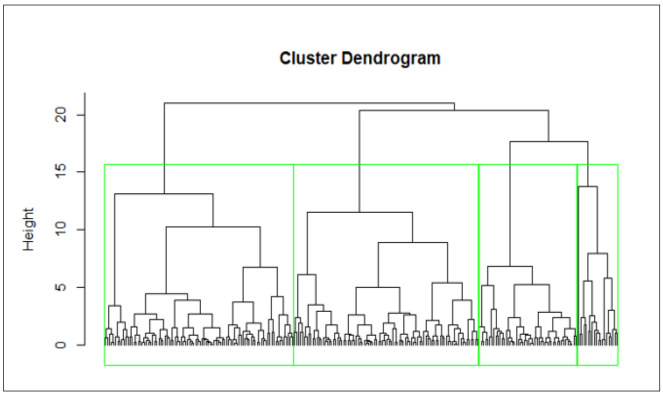

Fig. 2. Dendrogram showing four cluster groups

representative farms have been identified based on centre of cluster circle (Fig. 3) for the estimation of the GHG balance. An in-depth survey with each representative farm households was conducted during February to April, 2024 for the collection of information on the whole-farm regarding crop and livestock production which emits GHG directly and indirectly.

Quantification of greenhouse gas (GHG)

The representative farms from each type were subjected to usage of cool farm tool (CFT) calculator, an approachable farm-level greenhouse gas calculator for calculating the greenhouse gas emission from agricultural crop-livestock management (23). The CFT model applies simple emission factor empirical equations between Intergovernmental Panel on Climate Change (IPCC) Tier 1 and 2 methodologies. Without requiring additional data beyond what farmers often know, CFT provides GHG emission estimates based on source and sinks (24). Soil carbon sequestration acts as a sink, while the sources of emissions include CH_4, CO_2 and N_2O. The overall greenhouse gas (GHG) balance is expressed in terms of CO_2 equivalents (CO_2e). In crop production, data regarding residue management, fertilizer production, application of fertilizers, application pesticides, energy usage and carbon sequestration are used for GHG quantification. Data on residue management covers how leftover plant material is handled: whether it's removed, mixed into the soil, or burned. Fertilizer production refers to the greenhouse gases (GHG) released when fertilizers are made, while fertilizer application looks at the emissions that occur when fertilizers are applied to the soil. Pesticide use includes the emissions from spraying herbicides, insecticides and fungicides. Energy usage mainly involves the diesel burned during soil preparation. Carbon sequestration is the process of storing carbon in the soil through certain plants, which helps lower GHG emissions. The information on emission from trees, electricity consumption, irrigation and post-harvest processing of crops are not considered for quantification of GHG In term of livestock, the GHG emission derived from the enteric fermentation and manure management depend on the size, milk yield, milks fat and protein per cent, body weight of the livestock. The information is collected through the personal interview with each representative farm household (25). The soil parameters like soil pH, texture and organic matter of representative four farms also determinants of GHG balances which have been analysed in the Agronomy laboratory, Tamil Nadu Agricultural University, Coimbatore. The carbon footprint for each crop and livestock is assessed individually, allowing for a detailed evaluation of the emissions associated with each agricultural operation. After calculating the carbon footprint for every specific crop and livestock, these values are aggregated to derive the total carbon footprint for each farm type (26). The estimated GHG emission from farm types have been expressed in kg CO_2 equivalent per year for the area of representative farms (kg CO_2e yr^{-1}) in term of area. Tukey's Honestly Significant Difference (HSD) test (27) have been done in agri-analyze for showing the significant differences among GHG emission of four farm types.

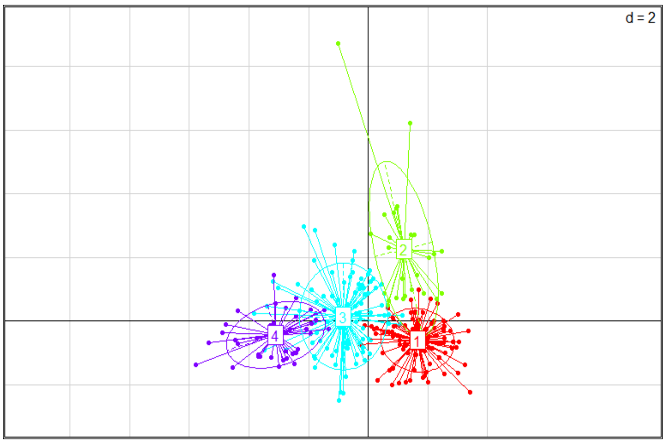

Fig. 3. Distribution of four farm types as a result of agglomerative hierarchical cluster analysis

Results and Discussion

Farm typologies

Principal component analysis (PCA) of the data collected from survey of 250 marginal and small farmers resulted in three PCs (eigen value >1) (Supplementary Fig. 1). PC1 showed variability of 56.7%, while PC2 has 22.3% variation and PC3 has 12.5 % variation as a result of scree plot (Fig. 4). Traditionally, the classification of farm households can be done using one or two variables. Based on land size (marginal, semi-medium, medium and large), farms were classified into five type (28). In contrast, this study classifies farms using a large set of variables. But typology studies have been developed from the heterogenous variability. We employed PCA to reduce the quantitative variables into principal components (PCs) and agglomerative hierarchical cluster analysis to group key quantitative variables into smaller clusters. Many researchers have similarly utilized PCA and cluster analysis for constructing typologies (29,30). Hierarchical clustering resulted in four farm types (Fig. 3) Likewise, typology is formed based on the available resources, technology and socio-economic parameters (31). The four farm types were discussed below.

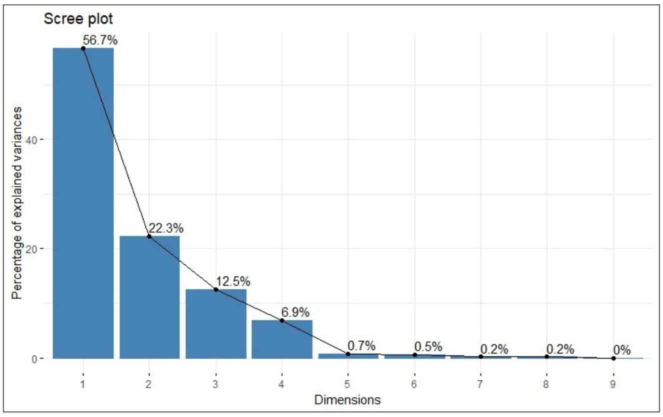

Fig. 4. Scree plot showing cumulative variation among PCs

Farm Type-1: Marginal farmers with cereals crops domination

This group had the second highest number of households (n=79) compared to other farm types and was characterized by a larger cereal cultivation area (0.40 ha) with less owned area (0.90 ha), a smaller livestock count (15 animals) and lower income from both crop and livestock production (Table 1). Smaller land holdings tend to be associated with lower income levels due to restriction of farm households to grow diversified crops (32).

Farm type-2: Marginal farmers with livestock domination

This is the largest farm type (n=90), characterized by marginal households with a larger fodder area (0.20 ha) and cereal area than other farm types with the owned area of 1.3 ha (Table 1). The higher livestock population (22 animals) and greater income from livestock along with the extensive fodder area, distinguish this group from other farm types. Higher income from livestock might be due to higher livestock population especially improved cows. This finding is supported by the previous study conducted typology analysis for cattle farm at Serbia and Canada (33,34).

Farm type-3: Marginal farmers with cash crops domination

This farm type consists of moderate farm households (n=55), second highest owned area (1.90 ha) higher cash crop area (0.94 ha) followed by plantation crop area (0.45 ha) as presented in Table 1. The livestock number was medium (18 numbers) similar to type- 4. The farm type-3 was getting the highest income in term of marginal farmer (<2.0 ha). The higher income might be due to the higher production with cultivation of diversified crops. A similar study conducted on typology assessment in coastal areas of West Bengal and other parts of Asia also demonstrated that greater diversification leads to higher income (35,36).

Farm type-4: Small farmers with plantation crops domination

The farm type-4 cluster was the smallest grouping (n = 24) among all other farm types and had a higher land area (2.3 ha). This farm type-4 has various cropping systems dominated by plantation crops (1.4 ha) contributed to higher income with medium no. of livestock (n = 16) which contributed to lower livestock income (Table 1). The higher income is due to the higher production with larger area of plantation crops and higher market availability with cultivation of diversified crops. Similarly, smallholders practicing sorghum cultivation in larger area have higher market availability and higher productivity results in higher income (37).

GHG quantification

For the comparison of greenhouse gas emission, various operations of four farm types were statistically computed by Tukey HSD test ($p < 0.005$). The GHG emission among the four farm types were quantified based on various operations on the farm using CFT. CFT calculated for each crop cultivated and livestock for each representative farm types. The arable crops grown in each farm type is presented in Table 1. The GHG emission from various operations in crop production and from livestock production are present in Table 2.

GHG emission of four farm types based on various operations

In residue management, farm type-3 and 4 recorded the highest GHG emissions (1475.20 and 1087.73 kg CO_2e yr^{-1}), primarily due to the burning of sugarcane and banana residues with higher area (Table 1). Crop residue burning is a well-known contributor to GHG emissions, particularly in India and other developing countries (38). In contrast, farm types-1 and 2 had lower emissions due to lower owned area (Table 1) and greater portion of their cereal crop residues were used for livestock feed, reducing the need for burning. This aligns with previous study that marginal farms with smaller land areas tend to emit lower GHG (39). There is a significant difference among the farm types ($p < 0.05$) for the residue management ($P = 0.024$).

Regarding fertilizer production, farm types showed that significant differences among them (P value = 0.014). The fertilizer production was considered as off-farm source of GHG emission. The highest emission of GHG on fertilizer production was observed on farm type- 4 (2153.33 kg CO_2e yr^{-1}) followed by farm type-3 (1850.56 kg CO_2e yr^{-1}) and farm type-2 (1440.66 kg CO_2e yr^{-1}) Higher emissions are largely attributed to higher area with high fertilizer consuming crops (Table 1) results in higher use of chemical fertilizers on farm. Similar findings have been reported in previous studies, which showed that increased fertilizer application rates lead to higher GHG emissions during manufacturing processes (40). While the lowest emission was recorded on farm type-1 (414.26 kg CO_2e yr^{-1}). The lower emissions in farm type-1 can be explained by the smaller land area and dominance of cereal crops (Table 1), which generally require fewer nitrogen inputs. This aligns with studies on maize and wheat, which indicate that lower nitrogen fertilizer application rates in cereal crops result in reduced GHG emissions (41). The same trend was observed on all four farm types regarding soil application of fertilizers (Table 2). The soil application also shows significant differences across four farm types (P value =0.004). The higher application of nitrogen fertilizer increased the GHG emission in farm type-3 and type-4 due to higher owned area which contributed higher emission. It is similar with the study showing that the higher soil application of chemical fertilizers increased the GHG emission (42). In contrast, type-1 and type-2 had the lower emission due to lower application of fertilizers with less owned area (Table 1). Similar to our results, low application rates of synthetic fertilizer have reduced GHG emission (43).

The differences across the four farm types regarding crop protection (P value = 0.001) is depicted in table 2. Farm type-4 had higher GHG emission of 21.56 kg CO_2e $yr^{-1}$and followed by farm type-3 (16.83 kg CO_2e yr^{-1}) which is that is on par with it. This might be due higher owned area (Table 1) results in higher application of pesticides for higher production. The farm type-2 has observed lower GHG emission of 8.90 kg CO_2e yr^{-1} and it is on par with farm type-1 (5.31 kg CO_2e yr^{-1}) due to the lower owned area (Table 1). The emission from energy usage includes use of fossil fuels like diesel for tillage operation. Farm type-4 had highest emission (1084.66 kg CO_2e yr^{-1}) followed by farm type-3 and farm type-2. The higher emission might be attributed to a greater number of tillage operation which needs higher fuel consumption for higher area. The lowest emission was recorded in type-1 farm household about 388.42 kg CO_2e yr^{-1} due to lower area and less consumption of diesel for tillage operation. The usage of diesel for tillage operation is considered as important contributor of GHG emission (44).

In term of animal production system, the GHG emission has influence on the four farm types. Both the enteric fermentation and a manure management are similar in showing significant differences (p value < 0.005). Regarding enteric fermentation the farm type-2 had the highest GHG emission of 10,500 kg CO_2e yr^{-1} and it was followed by farm type-3 which has emission of 7823.33 kg CO_2e yr^{-1}. Both the type-4 and type-1 had lowest GHG emission of 5888.2 and 5813.33 kg CO_2e yr^{-1}, respectively. The similar trend was also found in the manure management of all four farm types (Table 2). The higher GHG emissions from livestock in farm types-2 and 3 are due to larger livestock populations, particularly improved breeds of cows, which contribute more to GHG emissions compared to smaller livestock like goats or poultry (Table 1). These results align with findings from smallholder farms in Kenya, where livestock, particularly cattle influence GHG emissions (45). Carbon sequestration in crop production reveal significant differences among the farm types ($p=<0.001$). Farm type-4 observed the highest soil carbon sequestration, with 15,905.11 kg CO_2e yr^{-1}, while farm type-1 had the lowest, sequestration of 6,071.38 kg CO_2e yr^{-1}. Higher carbon sequestration in farm type-4 can be attributed to practices such as diversified crop rotation, incorporation of crop residues, minimal soil disturbance. Furthermore, the inclusion of perennial crops contributes to higher carbon sequestration rates (Table 1). On the other hand, the lower carbon sequestration observed in farm type-1 could be due to less intensive farming practices, smaller land areas and a focus on cereal production (Table 1), which generally contributes less to soil carbon accumulation compared to more diverse or perennial cropping systems. Similar findings have been reported in in East Africa where perennial crops and fodder crops significantly increased soil carbon stocks (46).

Conclusion

This study aimed to quantify greenhouse gas emissions from various farm types of marginal and smallholder households in western Tamil Nadu, India using CFT. The research revealed significant differences in GHG emissions across four farm types, influenced by farm practices such as residue management, fertilizer application and livestock production. Higher GHG emissions were observed in farm type-4 and type-3 dominated by plantation and cash crops due to higher owned area and farm activities like crop residue burning, higher fertilizer usage, while

Table 1. Characteristics of the four farm types

Variables	Units	Farm type 1 (n=79)		Farm type 2 (n=90)		Farm type 3 (n=55)		Farm type 4 (n=26)	
		Mean	SeM ±	Mean	SeM ±	Mean	SeM ±	Mean	SeM ±
HH members	Number	4.00^{b}	0.11	5.00^{a}	0.12	4.00^{ab}	0.16	6.00^{a}	0.30
Age	Year	54.93^{b}	1.00	47.70^{c}	0.60	59.98^{a}	0.90	54.6^{bc}	1.08
Owned area	Hectare	0.90^{d}	0.03	1.30^{c}	0.05	1.90^{b}	0.06	2.29^{a}	0.07
Crop diversity	Crop year^{-1}	4.00^{a}	0.09	4.00^{a}	0.13	5.00^{a}	0.17	6.00^{a}	0.23
Cereal area	Hectare	0.40^{a}	0.02	0.33^{b}	0.03	0.26^{bc}	0.04	0.21^{c}	0.04
Other crops area	Hectare	0.10^{a}	0.02	0.08^{ab}	0.02	0.12^{ab}	0.03	0.05^{b}	0.03
Vegetable area	Hectare	0.14^{a}	0.02	0.27^{a}	0.03	0.26^{a}	0.04	0.47^{a}	0.04
Plantation area	Hectare	0.20^{c}	0.03	0.32^{ab}	0.06	0.45^{b}	0.08	1.20^{a}	0.14
Cash crop area	Hectare	0.03^{c}	0.04	0.15^{ab}	0.04	0.94^{a}	0.05	0.41^{b}	0.10
Fodder area	Hectare	0.10^{c}	0.03	0.20^{a}	0.06	0.14^{ab}	0.05	0.10^{b}	0.08
Total Cost of Production (X 10^4)	INR year^{-1}	10.00^{d}	0.40	15.90^{c}	0.80	22.20^{b}	0.80	34.30^{a}	1.30
Family labour on-farm	Number	1.94^{a}	0.03	1.87^{a}	0.04	2.00^{a}	0.06	2.06^{a}	0.07
Hired labours	Numbers year^{-1}	150.00^{d}	6.90	196.00^{c}	10.60	284.00^{b}	12.10	420.00^{a}	18.00
Livestock	Number	15.00^{ab}	1.00	22.00^{a}	1.80	18.00^{ab}	1.57	16.00^{b}	2.65
Improved cows	Number	2.00^{c}	0.10	6.00^{a}	0.17	4.00^{b}	0.16	2.00^{ab}	0.12
Calves	Number	1.00^{c}	0.08	3.00^{a}	0.12	2.00^{b}	0.09	2.00^{ab}	0.07
Goats	Number	5.00^{a}	0.38	4.00^{a}	0.58	4.00^{a}	0.61	3.00^{a}	0.06
Poultry	Number	7.00^{c}	0.98	9.00^{a}	1.70	8.00^{ab}	1.42	9.00^{b}	2.03
Feed quantity (X 10^3)	kilogram year^{-1}	4.20^{c}	0.19	8.5^{a}	0.43	5.8^{b}	0.47	6.8^{ab}	0.49
Feed expenses (X 10^4)	INR year^{-1}	5.98^{c}	0.38	10.24^{a}	0.76	8.24^{ab}	0.61	6.53^{b}	0.76
Milk yield (X 10^3)	Litres year^{-1}	5.39^{c}	0.26	10.85^{a}	0.65	8.22^{ab}	0.57	7.57^{b}	0.48
Crop income (X 10^4)	INR year^{-1}	35.80^{d}	1.60	58.70^{c}	3.03	80.20^{b}	3.10	125.90^{a}	2.54
Livestock income (X 10^4)	INR year^{-1}	11.60^{c}	0.81	30.45^{a}	0.26	22.63^{ab}	0.19	17.31^{b}	0.17
Arable crops		Tomato, Cowpea, okra, Maize, Sorghum, Fodder, Coconut		Chilli, Tomato, Cauliflower, Coconut, Fodder, Maize		Daincha, Banana, Turmeric + Onion, fodder, Fodder maize, Tobacco, Sugarcane		Chilli, Tomato, Cauliflower, Coconut, Fodder, Daincha, Banana, Turmeric	

Table 2. GHG emission from various operations for four representative farms (kg CO_2e yr^{-1})

Variables	Residue management	Fertilizer production	Soil application	Crop protection	Energy usage	Enteric fermentation	Manure management	Carbon sequestration
Farm type-1	128.66^{c}	545.76^{c}	414.26^{c}	5.13^{c}	388.42^{d}	5813.00^{c}	477.30^{c}	6071.38^{d}
Farm type-2	98.06^{c}	1440.66^{b}	1094.36^{b}	8.90^{b}	570.54^{c}	10500.00^{a}	1221.83^{a}	9121.23^{c}
Farm type-3	1475.2^{a}	1850.56^{ab}	1565.36^{ab}	16.83^{a}	927.83^{b}	7823.33^{b}	949.40^{b}	10664.06^{b}
Farm type-4	1087.73^{b}	2153.33^{a}	1689.93^{a}	21.56^{a}	1084.64^{a}	5888.23^{c}	618.03^{c}	15905.11^{a}
P value (<0.05)	0.021	0.014	0.004	0.001	0.001	0.002	0.003	0.001

*Table shows GHG emission from four farm types through various operations; **a,b,c,d shows the significant difference based on Tukey's HSD test type-1 and type-2 exhibited lower emissions due to lower owned area in term of crop production. Regarding livestock production, farm type-2 exhibited higher GHG emission due to higher number of livestock. The findings emphasize the need for tailored GHG mitigation strategies for different farm types, particularly those involving high-emission practices. The use of tools like CFT allows for a comprehensive understanding of emissions at the farm level and supports the development of targeted interventions to reduce agricultural GHG emissions in marginal and smallholder farming systems. Addressing GHG emissions is crucial for enhancing the sustainability of agriculture and mitigating climate change impacts.

Acknowledgements

The authors thank the Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore for providing direction and technical support during the research process.

Authors' contributions

NA drafted the original manuscript, conducted survey, collected data and performed the statistical analysis. PMS drafted methodology and carried out the correction of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of the manuscript, first author used Chatgpt for improving language and readability of manuscript. After using this tool, the corresponding author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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