# Carbon assessment for Robusta coffee production systems in Vietnam

## A case study in Dak Lak

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# Content



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## Introduction

The Central Highlands of Vietnam is the most important Robusta coffee producing area in the nation, reflected via its significant share of about 88% of an estimated 622,200 hectares of all Robusta growing areas (as of 2016/2017 production season, (USDA Foreign Agricultural Service, 2017). Yield and production of Robusta coffee in Vietnam have been well known worldwide to be very high. The important drivers behind this are production intensification with high fertilizer use and the expansion of monoculture coffee growing area with many cases linked to deforestation in recent decades, among others. As a consequence, the greenhouse gas (GHG) emission contributed from coffee production to the atmosphere which adversely affects the environment is assumed to be high.

The Central Highlands has faced a challenge posed by a changing climate characterized by increasing temperature, more severe and longer drought in dry season, and longer rainy seasons with increasing severity. The projection of climate change and its impact has been studied by various researchers such as Baker (2016), CIAT (2012), Haggar (2011), and Phan et al. (2013). It is forecasted that by 2050, climatic suitability will be greatly reduced by about 80% for coffee production in all coffee areas in Central Highlands with the exception of suitability gained in only a few high altitude areas (CIAT, 2012). The latter does not, however, suggest that farmers can or should migrate to higher altitudes due to the risks of deforestation and subsequent ecological disturbance it will pose. Variability in annual precipitation in terms of total quantity and heavy rainfall events is forecasted to be large and unpredictable; moreover, rainfall tends to reduce during coffee productive stage while increase during harvesting season (Baker, 2016). These changes in climate in sync with other important biotic and abiotic threats of aging coffee trees, pests and diseases, limited water availability especially at higher altitudes, excessive fertilizer use, soil degradation, poor drying facilities, lack of irrigation infrastructure, and limited access to finance would threaten the sustainability and viability of coffee production and the sector as a whole.

Growing shade trees has been considered a good practice because it not only facilitates coffee tree development and yield via provision of a favorable micro-climate that helps buffer coffee trees against negative impacts of excessive sun light intensity, high temperature, big winds, and heavy rainfall, especially in a changing climate but also provides various ecosystem services. One of the important ecosystem services is carbon sequestration, which is thought to help off-set GHG emissions produced during farm management. Other benefits of growing shade trees include nutrient cycling (especially leguminous trees), soil erosion reduction, water retention, risk reduction and economic efficiency increase via diversification of income sources on the same area of land (especially fruit trees), and even sometimes farm tenure demarcation.

Carbon assessments have been conducted across Latin America and Africa to identify climate friendly practices in Arabica producing systems, though little attention is given to Robusta. In this study, we evaluated the climate impact of Robusta production via quantification of carbon stock and greenhouse gas (GHG) emissions in the intensive shaded and unshaded coffee farms of the world’s largest Robusta producing region, Vietnam’s Central Highlands.

# Methodology

The study was conducted in six districts of Buôn Đôn, Buôn Mê Thuột, Cư Kuin, Krông Buk, Krông Năng, and Krông Pắk of Đắk Lắk province in Vietnam's Central Highlands in November 2016 by Hanns R. Neumann Stiftung Vietnam and CIAT Asia. The data collection work included field inventory with tree measurements for biomass and thus carbon stock estimation and semi-structured survey on coffee management practices for input data for carbon footprint calculation. In total, 50 farms (26 coffee monocropping farms (with or without perennial trees at the borders), and 24 coffee-shade tree intercropping) were surveyed with GPS locations shown in Figure 1. From 50 surveyed farms, 46 farms (23 monocropping and 23 intercropping farms) were selected for the analysis after data cleaning. The representative farms were selected based on consultation of Hanns R. Neumann Stiftung Vietnam's field staff and agricultural extension officer based at the communes and/or villages. The household member who knew the most about the household's coffee management practices was selected to be interviewed for the production input use.

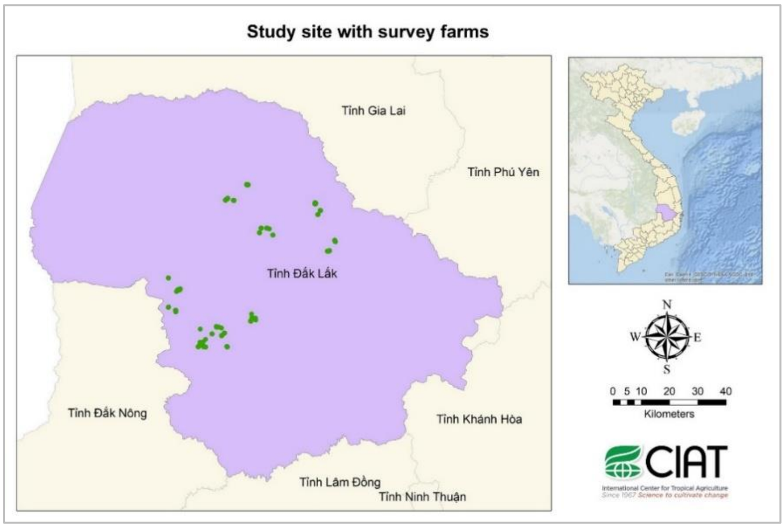


*Figure 1. The study site with 50 surveyed farms*

## Farm typology

The objective of the study was to assess the environmental impact of two major typical Robusta coffee production systems in the Central Highlands: coffee monocropping and coffee-shade tree intercropping systems (hereafter called coffee unshaded and shaded systems, respectively). Therefore, commercial polyculture system (coffee intercropped with multiple shade tree species) and shaded monoculture system (coffee intercropped with only one specific shade species) as classified by Moguel and Toledo (1999) were grouped into shaded (coffee) systems. Six farms with windbreak trees at borders together with those without those trees were considered being unshaded (coffee) system due to insignificant shade value that windbreak trees could provide for the coffee trees. Figure 2 below illustrates the farm typologies in our study compared with Moguel and Toledo's. Within each system, the farms applied with more than two tons of inorganic fertilizers per hectare were further classified as intensive coffee production systems while those with less than two tons $ha^{-1}$ were clustered into less intensive systems, according to Marsh (2007). Therefore, eventually four systems of intensive and less intensive shaded systems and intensive and less intensive unshaded systems were taken into the analysis.

## Carbon stock methodology

In this study, above ground and below ground biomass were estimated via a tree inventory based on the methodology by Rügnitz et al. (2009) where a sample plot of 50m × 20m was selected in each farm for tree measurements. Coffee tree density and pruning patterns, shade tree density and species component, and tree health were taken into consideration when determining a sample plot to capture as much representativeness as possible with regard to the overall plot. This is important because the result calculated for the sample plot is extrapolated for the entire farm. An example of a sample plot is shown in Figure 3.

Due to the uniformity of coffee trees with regard to major parameters of tree height, stem girth at 15 cm above the soil surface, and canopy structure in all studied farms, fifteen coffee trees were selected together with all shade trees with DBH larger than 10 cm in the sample plot, wherein they were measured for height and DBH based on the methodology by Rügnitz et al. (2009). Diameter of coffee trees was registered at 15 cm above the soil surface and at 1.3 m above the soil surface for shade trees (hereafter referred to as diameter at breast height or DBH). In this sample plot, the data on tree count, species name, age, height and DBH were documented. DBH, height and wood density were used to estimate tree above-ground biomass based on allometric equations (Table 1).

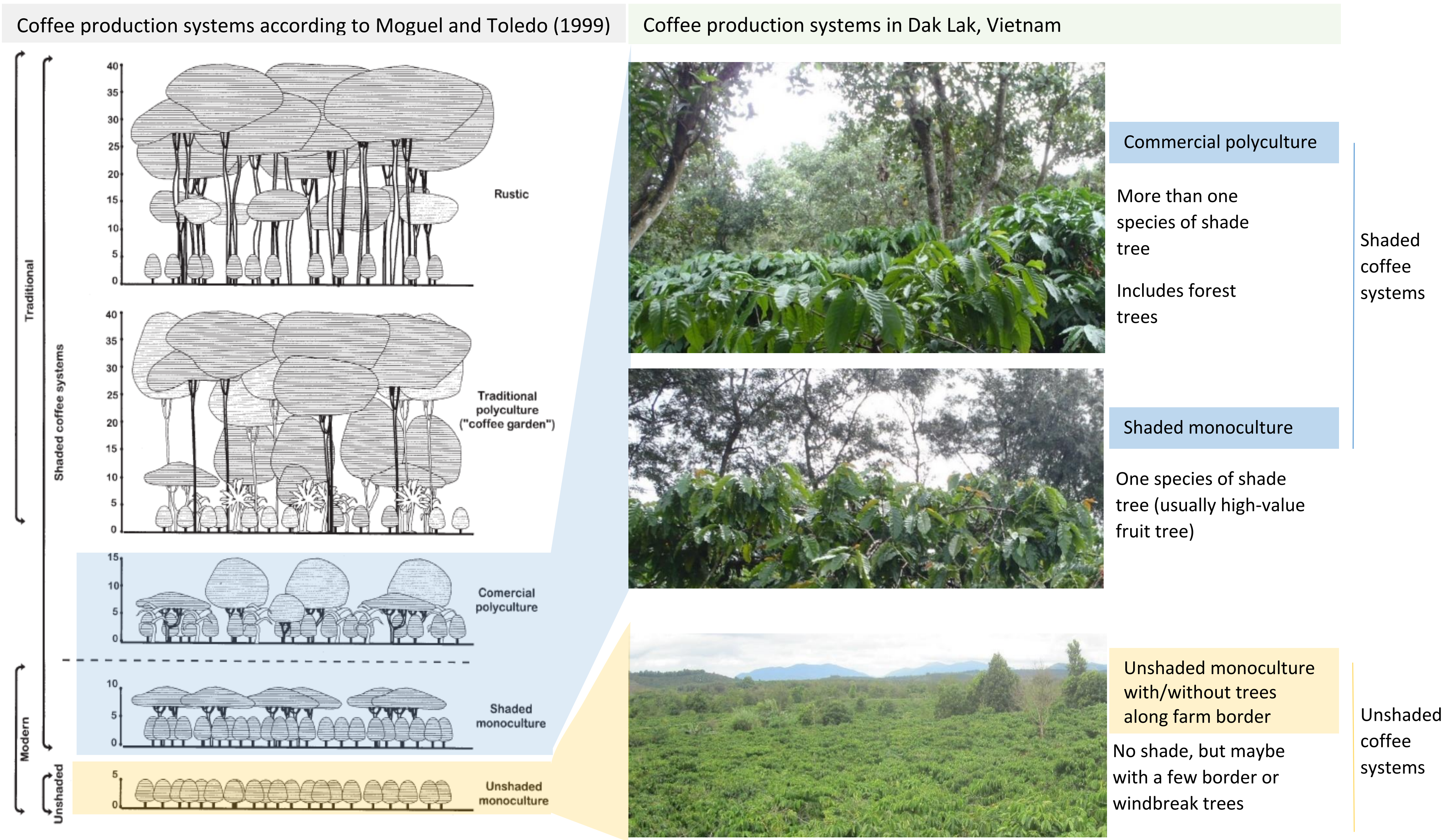


*Figure 2 Coffee production systems in literature (left) and in Dak Lak province, Vietnam*

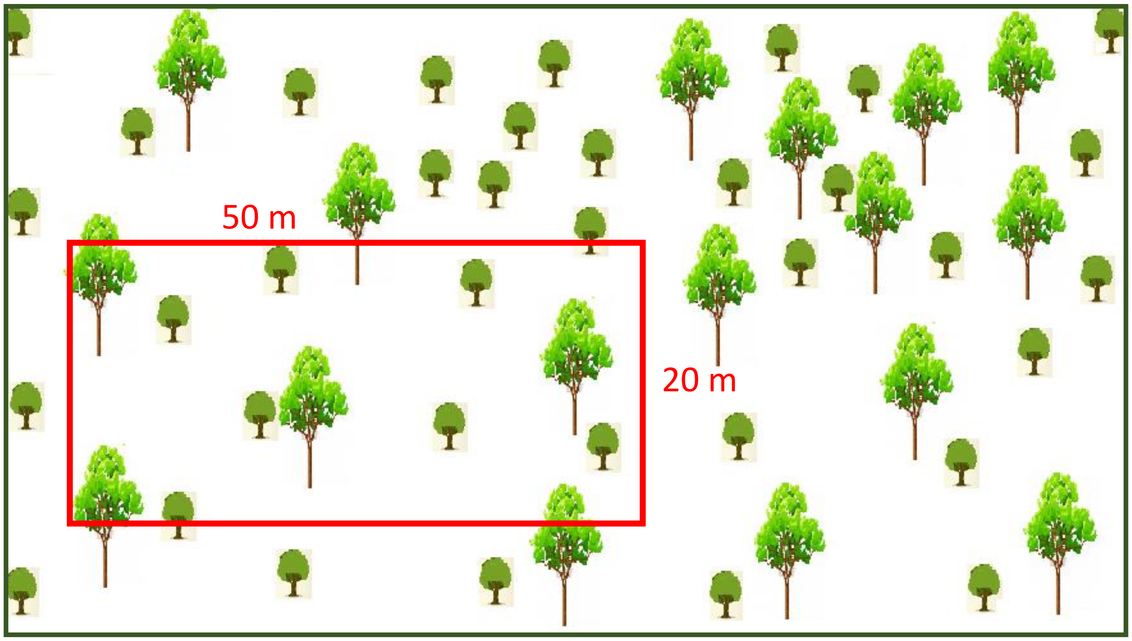


*Figure 3. An example of a representative sample plot (red rectangle) in terms of coffee and shade tree density. Shorter and taller tree illustrate coffee and shade trees, respectively.*

Wood density was extracted from ICRAF's Tree Functional Attributes and Ecological Database (http://db.worldagroforestry.org//wd). The tree biomass of the sample plot is the total biomass of all measured trees it contains and then converted into per hectare unit (Mg biomass $ha^{-1}$). Subsequently, a conversion factor of 0.47 (IPCC, 2006) was employed to derive carbon (C) stock (Mg C $ha^{-1}$) from biomass.

*Table 1 List of allometric equations used for above- and below-ground (root) biomass estimation*

| Tree type | Allometric equation | Reference |
|---|---|---|
| **Coffee** | B = 10(-1,18+1,99*log(d15)) | Segura et al., 2006 |
| **Fruit trees** | Log AGB = (−1.11 + 2.64 * Log(DBH)) | CATIE, unpublished |
| **Palms** | AGB = 4.5+7.7*H | Frangi and Lugo, 1985 in Hairiah et al., 2001 |
| **Coconut** | AGB = ((π /4) *(DBH*0.5) ^2) *H*0.4 | Hairiah et al., 2001 |
| **Banana** | AGB = 0.030*DBH2.13 | van Noordwijk et al., 2002 |
| **Rubber** | AGB = Exp[-3.1426]*[DBH^2.69273]] | Rojo etal., 2015 |
| **Other shade trees** | AGB = 0.0509*WD*(DBH)^2 *H | Chave et al., 2005 |
| **Root biomass** | RB = Exp( - 1.0587 + 0.8836 * LN(AGB)) | Cairns et al., 1997 |

AGB: above-ground biomass, kg $tree^{-1}$; $D_{15}$, dimeter at 15 cm above soil surface, cm; H, height, m; DBH, diameter at breast height, cm; CATIE, Centro Agronómico Tropical de Investigación y Enseñanza; WD, wood density, g $cm^{-3}$; RB, root biomass, kg $tree^{-1}$.

## GHG emission quantification

For the estimation of GHG emissions produced during the production of coffee, data on coffee productivity, on-farm practices, including input use (lime, organic and inorganic fertilizer – type, application rate and application method), crop residue management, total field energy use (in water irrigation, foliar fertilizer and pesticide spraying, weeding, coffee berry dehusking), distance and means of transportation of input and products, and soil drainage condition were collected via a semi-structured questionnaire for the same plot for which tree inventory was done. These data were collected for the calendar year of 2015 according to the methodology of CoolFarmTool (CFT) requiring a full calendar year of data. Soil data (texture, pH, soil organic matter) for different locations were extracted from literature study. These data were inputted in CFT, an online GHG calculator (Hillier et al., 2011; CFT: https://www.coolfarmtool.org/) to estimate the GHG emissions for the study. Emissions from transportation of was calculated based on the guidance by The Catalan Office for Climate Change (2013) based on the distance and means of transportation. This method was used because there is no option for calculating GHG emissions from motorbikes but other transportation vehicles in CFT tool. However, for a consistent estimation, emissions from latter vehicles were also estimated using the guidance by the Catalan Office. CFT has been used in various studies to estimate the GHG emissions at farm level such as van Rikxoort et al. (2014), Gaitán et al. (2016), Vetter et al. (2017), and Ortiz-Gonzalo et al. (forthcoming). The carbon (C) stock was converted into $CO_2$ equivalent ($CO_{2e}$) amount in order to calculate the net $CO_{2e}$ emission C footprint. The GHG emission was presented in the form of $CO_2$ equivalent or $CO_{2e}$.

# Results and discussions

## General information

This paragraph is to provide general information for 46 analyzed households. The farm area averages 0.8 ha and varies widely from 0.2 to 2.4 hectares. The average age of coffee trees in 2015 was 17.5, ranging largely from 3 to 36 years. Coffee bean yield spans from 0.42 to 5.0 tons $ha^{-1}$, averaging at 2.46 tons $ha^{-1}$. The average coffee tree density across all farms is 1066 tree $ha^{-1}$ (average planting density of 3.06m × 3.06m), with the respective figures of 1084 and 1047 tree $ha^{-1}$ in unshaded and shaded system. The average shade tree density of shaded coffee farms is 86 tree $ha^{-1}$. In general fruit trees, cassia and cashew are the most popular shade trees species. Inorganic fertilizer use is widespread with regard to both volumes and variety of inputs applied. The share of surveyed farmers applying inorganic fertilizers such as NPK, urea, ammonium sulfate, potassium, fused calcium magnesium phosphate and YV nitrabor are 96, 50, 30, 37, 33, and 2%, respectively. Still in this order, the quantity shares of these fertilizers in the total average applied amount of 2.14 tons $ha^{-1}$ are 66, 7, 6, 6, 13, and 2%, respectively. 67% of farmers applied compost manure either homemade or bought, which averages 3.2 tons $ha^{-1}$, ranging from 0.3 to 8 tons $ha^{-1}$. All farmers practice tree pruning with removal of dead and unproductive branches and desuckering of young sprouts.

## Farm typology

In this report, other than the four main systems of intensive and less intensive shaded systems and intensive and less intensive unshaded systems, the results of the four systems of simplified shaded and unshaded systems (classification based on shade tree intercropping practice, regardless of inorganic fertilizer use intensiveness) and simplified intensive and less intensive systems (classification based on inorganic fertilizer use, regardless of shade tree intercropping practice) are also presented. The characteristics of the four main systems and simplified shaded and unshaded systems are presented in Table 2 below. The four main systems were quite similar in terms of farm area (ranging from 0.8 to 1.1 ha) and crop residue volume (mostly from 3.5 to 3.6 Mg ha$^{-1}$, with exception of intensive shaded system with 4.6 Mg ha$^{-1}$ of crop residue). Generally, compared to less intensive unshaded and shaded systems, intensive unshaded and shaded systems had relatively but not significantly older coffee trees (19.7 and 18.4 versus 15.6 and 15.8 years, respectively), significantly higher amount of applied inorganic fertilizers (2.7 and 2.9 versus 1.2 and 1.3 Mg ha$^{-1}$, respectively), and possibly thus significantly higher yield (3.2 and 2.9 versus 1.9 and 1.7 Mg ha$^{-1}$, respectively). Coffee density in unshaded systems was clearly higher than those in shaded systems because of the space demand occupied by shade trees in the latter systems.

*Table 2 Basic characteristics of four main coffee production systems in Dak Lak and simplified shaded and unshaded systems (regardless of inorganic fertilizer use intensity). Mean values are in bold and standard deviations in brackets. Figures followed by different letters in one column of the same color differ significantly (Tukey test at 5%). These letters are shown where there are significant differences only.*

| | System | n | Farm size (ha) | Coffee age (years) | Coffee DBH (cm) | Coffee density (tree ha$^{-1}$) | Shade/ windbreak tree density (tree ha$^{-1}$) | Coffee bean yield (Mg ha$^{-1}$) | Total inorganic fertilizers (Mg ha$^{-1}$) | Total organic fertilizer (Mg ha$^{-1}$) | Total crop residue (Mg ha$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Unshaded | Less -intensive | 11 | **0.8** (0.5) | **15.6** (10.9) | **12.9$^{ab}$** (3.7) | **1,045** (524) | **5$^{b}$** (13) | **1.9$^{b}$** (1.1) | **1.2$^{b}$** (0.5) | **1.6** (2.6) | **3.6** (1.9) |
| | Intensive | 12 | **1.0** (0.6) | **19.7** (1.9) | **16.4$^{a}$** (2.8) | **1,119** (154) | **11$^{b}$** (25) | **3.2$^{a}$** (1.3) | **2.7$^{a}$** (0.7) | **1.7** (2.3) | **3.5** (1.5) |
| Shaded | Less -intensive | 9 | **1.1** (0.5) | **15.8** (11.1) | **11.9$^{b}$** (3.1) | **1,018** (171) | **93$^{a}$** (33) | **1.7$^{b}$** (1.1) | **1.3$^{b}$** (0.6) | **1.0** (1.2) | **3.5** (1.5) |
| | Intensive | 14 | **0.8** (0.4) | **18.4** (7.4) | **15.1$^{ab}$** (3.4) | **1,066** (82) | **79$^{a}$** (36) | **2.9$^{ab}$** (1.3) | **2.9$^{a}$** (0.5) | **2.3** (1.9) | **4.6** (2.5) |
| **Simpl. unshaded** | | 23 | 0.9 | 17.7 | 14.7 | 1,084 | 8 | 2.6$^{a}$ | 2.0$^{a}$ | 1.6$^{a}$ | 3.5 |
| **Simpl. shaded** | | 23 | 0.9 | 17.3 | 13.5 | 1,041 | 85 | 2.4$^{a}$ | 2.3$^{a}$ | 1.7$^{a}$ | 4.1 |

## Tree inventory

The statistics on shade tree species (categorized into five groups) registered from 23 shaded coffee farms and 6 farms with shade trees only at farm's borders are presented in Table 3 below. Shade tree trees in latter type of farm also provides information about farmer's preference toward shade trees and contributes to carbon stock so they were included in the table.

It can be seen in Table 3 that legume, fruit and industrial trees are the tree groups with highest encountered frequency (percentage of farms with these tree species in the total number of farms with shade trees (either within or at border of farms)), at about 55, 45, and 35%, respectively. When it comes to individual tree species, *Cassia siamea* is the most popular one which was found in about 52% of surveyed farms, followed by cashew (31%), avocado (28%), durian (24%), and mango (24%), explaining their high shares in the total tree counts across all farm, except for *Holarrhena antidysenterica* due to high density of black pepper plants which it supports. Taking the abundance of tree groups/species into account, it can be seen that fruit trees, legumes, and industrial trees had the largest share in the total tree count with 30.4% each with large contribution from durian (11.1%), cassia (27.6%), and cashew (25.8%), respectively for those groups.

*Table 3 Information on shade trees found in investigated farms.*

| Name | Scientific name | Group | Average age | Frequency for species (%)[d] (nr of farms) | Frequency for group (%)[e] | Share of total tree counts for species across farms (%)[f] (tree count/ha) |
|---|---|---|---|---|---|---|
| Avocado | *Persea americana* | *Fruit* | 4.4 | **27.6** (8) | **44.8** | 6.5 (18) |
| Burmese grape | *Baccaurea ramiflora* | *Fruit* | 13.0 | 3.4 (1) | | 0.9 (20) |
| Durian | *Durio zibethinus* | *Fruit* | 9.6 | **24.1** (7) | | **11.1** (34) |
| Fig | *Ficus racemosa*[b] | *Fruit* | 5.0 | 3.4 (1) | | 0.9 (20) |
| Jackfruit | *Artocarpus heterophyllus* | *Fruit* | 14.0 | 3.4 (1) | | 0.9 (20) |
| Mango | *Mangifera indica* | *Fruit* | 10.0 | **24.1** (7) | | 5.1 (16) |
| Sapodilla | *Manilkara zapota* | *Fruit* | 8.0 | 3.4 (1) | | 0.5 (10) |
| Pomelo | *Citrus maxima* | *Fruit* | 3.0 | 3.4 (1) | | 0.5 (10) |
| Rambutan | *Nephelium lappaceum* | *Fruit* | 5.0 | 10.3 (3) | | 1.4 (10) |
| Soursop | *Annona muricata* | *Fruit* | 9.5 | 13.8 (4) | | 2.8 (15) |
| Cassia | *Cassia siamea* | *Legume* | **14.9** | **51.7** (15) | **55.2** | **27.6** (40) |
| Leucaena | *Leucaena leucocephala* | *Legume* | 12.1 | 10.3 (3) | | 2.8 (20) |
| Ceiba | *Ceiba pentandra* | *Specialized*[c] | 6.0 | 3.4 (1) | 17.2 | 0.9 (20) |
| Kurchi | *Holarrhena antidysenterica* | *Specialized* | 6.2 | 10.3 (3) | | 5.5 (40) |
| Oroxylum | *Oroxylum indicum* | *Specialized* | 11.0 | 3.4 (1) | | 0.9 (20) |
| Chinaberry | *Melia azedarach*[b] | *Wood* | 5.0 | 3.4 (1) | 6.9 | 0.5 (10) |
| Clove | *Syzygium aromaticum* | *Wood* | 12.0 | 3.4 (1) | | 0.5 (10) |
| Burma Ironwood | *Xylia xylocarpa* | *Wood* | 3.0 | 3.4 (1) | | 0.5 (10) |
| Cashew | *Anacardium occidentale* | *Industrial* | 11.7 | **31.0** (9) | **34.5** | **25.8** (62) |
| Rubber | *Hevea brasiliensis* | *Industrial* | 6.0 | 3.4 (1) | | 4.6 (100) |
| Black pepper[a] | *Piper nigrum* | *Vine* | - | **28.6** | - | - |

[a], black pepper is not considered as shade plant in this case but presented here to show farmer's preference towards plants being intercropped; [b], those tree species only found at borders of coffee monoculture farms; [c], these specialized shade trees in this case are living support trees for black pepper; [d,e], this frequency is the percentage of farms with these tree species and tree group in the total number of farms with shade trees (either within or at border of farms), respectively. Note that frequency for each group does not equal the sum of those for individual species in that group because they are treated the same as one category of group;, this share presents percentage of trees counts of each group in the total number of shade trees cross all farms with shade trees.

Cassia, fruit trees, and cashew are the most preferred shade species in shaded coffee systems in the Central Highlands. The reason why *Cassia siamea* is the most popular shade tree species is very likely due to the history of Robusta coffee cultivation in the Central Highlands dating back 15-20 years to when a French company introduced to cooperatives the practice of planting one row of cassia trees per every several rows of coffee trees. This practice has been then gradually adopted by coffee farmers, especially by those who live near contract-farming companies' plantation. This is shown by the average

age of cassia trees of some 15 years (most tree ages range from 13 to 30 years) compared to most of other shade tree species.

In summary, the density of coffee and shade tree groups are presented in Table 4 below. The coffee densities range from 1018 (planting density of 3.13m x 3.13m) in less intensive shaded system to 1,119 (~ 3m x 3m) in intensive unshaded system. Shade tree densities in intensive and less intensive shaded systems are 79 and 93 trees ha$^{-1}$, respectively. On average, there are some 8 trees at the border in unshaded systems.

*Table 4 Coffee and shade tree group densities (trees ha$^{-1}$) across studied coffee production system. Figures in each column of the same color followed by different letters differ significantly (Tukey test at 5%). These letters are shown where there are significant differences only.*

| System | | Coffee | Fruit | Industrial | Legume | Specialized | Wood | Total shade | Coffee + shade |
|---|---|---|---|---|---|---|---|---|---|
| Unshaded | Less -intensive | 1,045 | 0 | 0 | 5 | 0 | 0 | 5$^{b}$ | 1,050 |
| | Intensive | 1,119 | 3 | 0 | 0 | 8 | 1 | 11$^{b}$ | 1,137 |
| Shaded | Less -intensive | 1,018 | 27 | 44$^{a}$ | 22$^{ab}$ | 0 | 0 | 93$^{a}$ | 1,111 |
| | Intensive | 1,066 | 28 | 19$^{ab}$ | 29$^{a}$ | 3 | 1 | 79$^{a}$ | 1,145 |
| Unshaded | | 1,084 | 1.3 | 0 | 2.2 | 3.9 | 0.4 | 7.8 | 1093.4 |
| Shaded | | 1,047 | 27.4 | 28.7 | 26.1 | 1.7 | 0.9 | 84.8 | 1131.9 |

## Carbon footprint

### *Carbon footprint per hectare*

The GHG emissions from different sources of input and product transportation (donated as transportation for short), organic and inorganic fertilizer application, soil emission (background), organic and inorganic fertilizer production, crop residues, and field energy use were respectively referred to as $E_{Trans}$, $E_{OrgFerAppl}$, $E_{InorgFerAppl}$, $E_{soil}$, $E_{OrgFerProd}$, $E_{InorgFerProd}$, $E_{Residue}$, $E_{Energy}$ in following discussion. The general information on different components of emission measured per hectare of the four main coffee production systems and four simplified systems is presented in Table 5.

*Table 5 GHG emissions (Mg $CO_2e$ ha$^{-1}$) from various components across four main studied coffee production systems ($^{++}$) and simplified (simpl.) cropping systems of shaded and unshaded* (regardless of inorganic fertilizer use intensity) and intensive and less intensive** (regardless of shade tree growing practices). Mean values are in bold and standard deviations in brackets. Figures followed by different letters in the same column of the same color differ significantly (Tukey test at 5%). These letters are shown where there are significant differences only.*

| System | | $E_{Trans}$ | $E_{OrgFer-Appl}$ | $E_{InorgFer-Appl}$ | $E_{soil}$ | $E_{OrgFer-Prod}$ | $E_{InorgFer-Prod}$ | $E_{Residue}$ | $E_{Energy}$ | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| Unshaded$^{++}$ | Less -intensive | **0.011** (0.016) | **0.05** (0.07) | **0.99$^{c}$** (0.76) | **0.36** (0.07) | **0.51** (0.94) | **0.31$^{b}$** (0.51) | **0.31** (0.29) | **0.50** (0.34) | **3.01$^{b}$** *(1.52)* |
| | Intensive | **0.020** (0.049) | **0.05** (0.07) | **4.16$^{a}$** (2.34) | **0.41** (0.11) | **0.59** (0.82) | **0.85$^{a}$** (0.73) | **0.38** (0.39) | **0.79** (0.56) | **7.22$^{a}$** (3.16) |
| Sh | Less -intensive | **0.020** (0.045) | **0.03** (0.04) | **1.4$^{bc}$** (1.12) | **0.39** (0.1) | **0.27** (0.45) | **0.32$^{ab}$** (0.32) | **0.41** (0.41) | **0.45** (0.21) | **3.25$^{b}$** (1.61) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Intensive** | **0.020** | **0.070** | **3.34[ab]** | **0.41** | **0.41** | **0.55[ab]** | **0.53** | **0.94** | **6.25[a]** |
| | (0.017) | (0.06) | (2.09) | (0.11) | (0.67) | (0.23) | (0.59) | (0.58) | (2.1) |
| ***Simpl. unshaded**** | ***0.016*** | ***0.047*** | ***2.64*** | ***0.38*** | ***0.55*** | ***0.59*** | ***0.35*** | ***0.65*** | ***5.21*** |
| ***Simpl. shaded**** | ***0.020*** | ***0.051*** | ***2.58*** | ***0.40*** | ***0.36*** | ***0.46*** | ***0.48*** | ***0.75*** | ***5.08*** |
| **Simpl. less intensive**** | **0.015** | **0.037** | **1.2[b]** | **0.37** | **0.41** | **0.31[b]** | **0.36** | **0.48[b]** | **3.2[b]** |
| | (0.032) | (0.058) | (1.0) | (0.08) | (0.75) | (0.42) | (0.34) | (0.28) | (1.6) |
| **Simpl. intensive**** | **0.020** | **0.058** | **3.8[a]** | **0.41** | **0.49** | **0.69[a]** | **0.46** | **0.87[a]** | **6.7[a]** |
| | (0.035) | (0.061) | (2.2) | (0.11) | (0.73) | (0.54) | (0.51) | (0.57) | (2.7) |

It can be seen in Table 5 that across the four main systems inorganic fertilizer application is the most important GHG emission source with $E_{InorgFerAppl}$ ranging from 0.99 to 4.16 Mg $CO_2$e $ha^{-1}$, accounting for 31.7-56.9% of the total emission produced. The ranges of $E_{Energy}$, $E_{soil}$, $E_{Residue}$, $E_{InorgFerProd}$, $E_{OrgFerProd}$, $E_{OrgFerAppl}$, and $E_{Trans}$ were respective 0.45-0.94, 0.36-0.41, 0.31-0.53, 0.31-0.85, 0.27-0.59, 0.03-0.07, and 0.011 to 0.020 Mg $CO_2$e $ha^{-1}$, with the total emission being from 3.01 to 7.22 Mg CO2e $ha^{-1}$ across all coffee production systems.

Intensive unshaded and shaded systems had significantly higher total GHG emissions compared to the less intensive unshaded and shaded ones, being (7.22, 6.25, 3.01, and 3.25 Mg $CO_2$e $ha^{-1}$ respectively in that order). Those four main systems also differed significantly in inorganic fertilizer-related emission of $E_{InorgFerProd}$ and $E_{InorgFerAppl}$ with the values of 4.16, 3.34, 0.99, and 1.4 Mg $CO_2$e $ha^{-1}$, respectively for the latter. $E_{InorgFerAppl}$ contributes the largest parts to the total emission in those systems, being 56.9, 49.2, 31.7, and 38.4 % of the total emissions, respectively in that order and as a consequence, the differences in $E_{InorgFerAppl}$ are the driver of the differences in total emission. Also, the high values of $E_{InorgFerAppl}$ were resulted from high amount of applied inorganic fertilizers in these systems as shown in Table 2. These are confirmed by very high and moderate positive correlation of $E_{InorgFerAppl}$ with the total GHG emission ($r = 0.92$) and with applied amount of inorganic fertilizers ($r = 0.66$), respectively, implying the important negative effects of inorganic fertilizer application on the environment.

Generally, emission from on-field energy use, $E_{Energy}$ is the second largest component of emission with the values of 0.79 (11.3%), 0.94 (16.4%), 0.5 (18.8%), and 0.45 (15.4%) Mg $CO_2$e $ha^{-1}$ to the total emissions in intensive unshaded and shaded systems, and less intensive unshaded and shaded systems, respectively. In these systems of that order, other emission components (except for $E_{OrgFerAppl}$ and $E_{Trans}$) are contributors of relatively similar importance to total amount of emissions, with ranges of 6.1-11.5%, 6.4-10.2%, 9.4-13.5%, and 8.7-14.0%, respectively. In general, $E_{OrgFerAppl}$ and $E_{Trans}$ only contribute insignificantly, being roughly at or less than 0.02 (0.5%) and 0.07 (1.1%) Mg $CO_2$e $ha^{-1}$, respectively to the total emissions, across the four main systems.

Interestingly, there were no significant differences in the total emission (5.21 and 5.08 Mg $CO_2$e $ha^{-1}$, respectively) and in all other emission components between simplified unshaded and shaded systems with $E_{InorgFerAppl}$ being major emission component (both 45% of total emission), $E_{Trans}$ (<0.5%) and $E_{OrgFerAppl}$ (about 1%) being insignificant emission components in total amount of emissions. These results and those showed in Table 2 indicate that the management practices and thus GHG emissions are very similar for simplified unshaded and shaded systems as a whole. Simplified intensive system had significantly higher total emission, $E_{InorgFerProd}$, $E_{InorgFerAppl}$ as a natural result of classification definition, and higher $E_{Energy}$.

### *Carbon footprint per unit product*

GHG emissions per unit of dry coffee bean is presented in Table 6 below. As showed in this table, the total emissions per unit dry coffee bean from less intensive and intensive unshaded, less intensive and intensive shaded systems were 1.89, 2.63, 2.73, and 2.78 kg CO2e kg-1, respectively with no significant difference among these values. This is completely contrary with the existence of the significant difference in total emission per hectare among those four systems as presented in previous paragraph. This is explained by the fact that emission per unit product can be calculated by dividing emission per hectare by coffee bean yield as in the equation follows:

$$Emission\ per\ unit\ product = \frac{Total\ emision\ per\ farm}{Coffee\ productivity} = \frac{Emission\ per\ hectare}{Coffee\ yield} \quad (1)$$

Among the four above mentioned main systems, their relative values of yield are similar to those of total emission per hectare as shown in Figure 5. Take intensive and less intensive shaded systems as an example, yield ratio of those two systems is 1.7 and their ratio of total emission per hectare is 1.9. As a result, the total emissions per unit dry coffee bean do not differ for those two systems (2.73 and 2.78 kg $CO_2e$ $kg^{-1}$, respectively). This explains why there are significant differences in total emission per hectare but not in total emission per unit product among the four systems.

Within each of the four main systems, $E_{InorgFerAppl}$ again contributes the largest to the total emission per unit product with the same shares as described in the section just above because of the way emission per unit product was calculated.

*Table 6 GHG emissions per unit dry coffee bean (kg $CO_2e$ $kg^{-1}$) from different components of the coffee production system (++ and simplified (simpl.) shaded and unshaded* (regardless of inorganic fertilizer use intensity) and simplified intensive and less intensive** cropping systems (regardless of shade tree growing practices). Mean values are in bold and either standard deviations (++) or percentage emission share in total emission of systems (*, **) in brackets. Figures followed by different letters in the same column of the same color differ significantly (Tukey test at 5%). These letters are shown where there are significant differences only.*

| System | | $E_{Trans}$ | $E_{OrgFerAppl}$ | $E_{InorgFerAppl}$ | $E_{Soil}$ | $E_{OrgFerProd}$ | $E_{InorgFerProd}$ | $E_{Residue}$ | $E_{Energy}$ | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| Unshaded++ | Less intensive | **0.008** (0.011) | **0.024** (0.036) | **0.62** (0.41) | **0.28** (0.21) | **0.30** (0.48) | **0.19** (0.27) | **0.17** (0.09) | **0.34** (0.26) | **1.89** (0.77) |
| | Intensive | **0.005** (0.011) | **0.020** (0.03) | **1.53** (0.98) | **0.15** (0.08) | **0.26** (0.38) | **0.31** (0.26) | **0.14** (0.12) | **0.32** (0.2) | **2.63** (1.54) |
| Shaded++ | Less intensive | **0.012** (0.018) | **0.023** (0.027) | **1.10** (1.15) | **0.34** (0.22) | **0.27** (0.37) | **0.34** (0.5) | **0.28** (0.11) | **0.39** (0.31) | **2.73** (2.12) |
| | Intensive | **0.010** (0.013) | **0.032** (0.044) | **1.47** (1.11) | **0.19** (0.13) | **0.24** (0.6) | **0.23** (0.14) | **0.19** (0.15) | **0.45** (0.38) | **2.78** (1.89) |
| *Simpl. unshaded** | | **0.007** (0.32) | **0.022** (0.87) | **1.09** (45.29) | **0.22** (10.47) | **0.28** (10.04) | **0.25** (9.91) | **0.15** (8.47) | **0.33** (14.81) | **2.27** (100) |
| *Simpl. shaded** | | **0.011** (0.38) | **0.029** (0.96) | **1.32** (44.75) | **0.25** (9.74) | **0.25** (7.18) | **0.28** (8.98) | **0.22** (12.24) | **0.43** (15.82) | **2.76** (100) |
| Simpl. less intensive** | | **0.010** (0.45) | **0.024** (1.05) | **0.83[b]** (34.47) | **0.31** (14.03) | **0.28** (11.16) | **0.26** (9.00) | **0.22** (12.92) | **0.36** (17.03) | **2.27** (100) |
| Simpl. intensive** | | **0.008** (0.27) | **0.026** (0.82) | **1.49[a]** (53.13) | **0.17** (7.09) | **0.25** (6.65) | **0.27** (9.78) | **0.17** (8.39) | **0.39** (13.99) | **2.71** (100) |

Simplified shaded and unshaded systems had the total emission of 2.76 and 2.27 kg $CO_2$e kg$^{-1}$, respectively, without being significantly differed. Relatively speaking, the difference in $E_{InorgFerAppl}$ between these two systems (0.23) explains 46% of their difference in the total emission (0.49 kg $CO_2$e kg$^{-1}$). Simplified intensive and less intensive coffee production systems had the total emission of respective 2.71 and 2.27 kg $CO_2$e kg$^{-1}$, being not significantly differed. However, there are indeed difference in $E_{InorgFerAppl}$ between these two systems with the respective values of 1.49 and 0.83 kg $CO_2$e kg$^{-1}$. This emphasizes that reducing emission (measured in per unit product) from inorganic fertilizer application will be an effective way to mitigate emission from management practices on coffee farms.

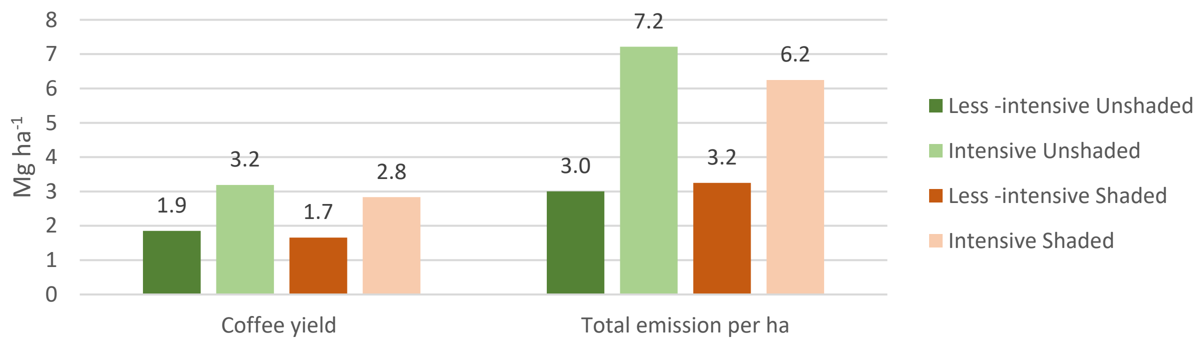


*Figure 2 Coffee yield and total emission per hectare of the studied systems*

## Carbon stock

### *Total carbon stock*

The results of shade tree carbon (C) stock of the studied systems are presented in Table 7 below.

*Table 7 C stock (Mg C ha$^{-1}$) of shade tree groups across the studied coffee production systems. Figures followed by different letters in the same column of the same color differ significantly (Tukey test at 5%). These letters are shown where there are significant differences only.*

| System | | Coffee | Fruit | Industrial | Legume | Specialized | Wood | Total shade | Coffee + shade |
|---|---|---|---|---|---|---|---|---|---|
| Unshaded | Less -intensive | 7.6[ab] | 0 | 0 | 0.03 | 0 | 0 | 0.025[b] | 7.63[c] |
| | Intensive | 12.3[a] | 0.3 | 0 | 0 | 0.2 | 0 | 0.6[b] | 12.9[bc] |
| Shaded | Less -intensive | 6.2[b] | 3.2 | 4.5 | 6.2 | 0 | 0 | 13.9[a] | 20.1[ab] |
| | Intensive | 10.4[ab] | 3.5 | 6.0 | 5.9 | 0.1 | 0.4 | 16.0[a] | 26.3[a] |
| Simpl. unshaded | | 10.1 | - | - | - | - | - | 0.3[b] | 10.4[b] |
| Simpl. shaded | | 8.7 | - | - | - | - | - | 15.2[a] | 23.9[a] |

Because of the small C stock values of windbreak trees at the border in the unshaded systems, the focus of the discussion will be for the shaded ones. In both intensive and less intensive shaded systems, fruit, industrial, and legume trees dominate in the shade tree density and hence C stock. The C stock of coffee, legume, industrial, and fruit trees are 6.2, 6.2, 4.5, and 3.2 Mg C ha$^{-1}$, respectively for less intensive shaded system and are 10.4, 5.9, 6.0, and 3.5 Mg C ha$^{-1}$, respectively for intensive one. The C stock of coffee and shade trees are relatively larger in intensive shaded system than in less intensive shaded system.

Generally, C stock of coffee trees in the simplified unshaded systems (10.1 Mg C $ha^{-1}$) was larger than that in the simplified shaded systems (8.7 Mg C $ha^{-1}$). This can be explained by the fact that the coffee tree density and DBH in shaded systems (1,041 tree $ha^{-1}$, 13.5 cm, respectively) are relatively lower than in unshaded systems (1,084 tree $ha^{-1}$, 14.7 cm, respectively; Table 2). The lower coffee tree density was because part of the land in the former systems is scarified for growing shade trees. However, the tradeoff for space between coffee and shade trees in the shaded coffee systems is worthwhile in terms of C sequestration as can be shown by the nearly 2-fold larger of shade tree's C stock (15 Mg C $ha^{-1}$) compared to coffee tree's (8.7 Mg C $ha^{-1}$) in the simplified shaded systems.

In both intensive and less intensive shaded systems, fruit trees, industrial trees, and legume are important shade trees in terms of both density and C stock contribution. This may imply that small household farmers prefer to invest in those species that provide benefits that can be recognized in the short term rather than in the long term since their establishment period. It will take shorter time for fruit, cashew, rubber, and legume trees to bring about benefits either in the form of income or ecosystem service compared to woody trees. Also, it should be noticed that quite a number of the surveyed farms are close to farmer's house or home gardens where fruit and cashew trees are preferred because farmers might not prefer to grow commercial fruit and nut trees at farms further away from home due to risk of theft.

### *Annual carbon stock*

The total annual carbon stock of less intensive and intensive unshaded systems were 0.61 and 0.73 Mg C $ha^{-1}$, respectively, lower than those of less intensive and intensive shaded systems, being 1.76 and 1.81 Mg C $ha^{-1}$, respectively (Table 8). For the two latter systems, shade tree contributed a significant share of carbon stock, being 71% and 68%, respectively. The total annual carbon stocks of the simplified unshaded system and shaded system were 0.68 and 1.79 Mg C $ha^{-1}$. The C stock per unit coffee bean of the less intensive and intensive unshaded systems, and less intensive and intensive shaded systems were 0.43, 0.32, 2.13, and 0.94 Kg C $kg^{-1}$, respectively. Among the shaded systems, the much higher carbon stock per unit product of less intensive system compared to the intensive one was due to the lower yield of this system than the other, being 1.7 Mg $ha^{-1}$ versus 2.9 Mg $ha^{-1}$ (Table 2). Though the intensive and less intensive shaded systems have relatively similar total annual carbon stock (1.81 and 1.76 Mg C $ha^{-1}$, respectively), the C stock per unit product of the latter was 2.3-fold higher compared to that of the former due to the lower (1.6-fold) yield of the latter.

*Table 8 Annual carbon stock and C stock per unit dry coffee bean across coffee production systems*

| Systems | | Coffee C stock | Shade C stock | Total C stock | C stock per unit dry coffee bean |
|---|---|---|---|---|---|
| | Unit | | Mg C $ha^{-1}$ | | Kg C $kg^{-1}$ |
| Unshaded | Less -intensive | 0.60 (0.22) | 0.02 (0.03) | 0.61 (0.23) | 0.43 (0.29) |
| | Intensive | 0.64 (0.22) | 0.10 (0.20) | 0.73 (0.39) | 0.32 (0.34) |
| Shad | Less -intensive | 0.51 (0.28) | 1.26 (0.84) | 1.76 (1.00) | 2.13 (2.63) |

| | | | | |
|---|---|---|---|---|
| **Intensive** | 0.59 (0.17) | 1.23 (0.85) | 1.81 (0.95) | 0.94 (0.97) |
| **Simpl. unshaded** | 0.62 (0.22) | 0.06 (0.15) | 0.68 (0.32) | 0.37 (0.31) |
| **Simpl. shaded** | 0.56 (0.22) | 1.24 (0.83) | 1.79 (0.95) | 1.40 (1.85) |

## Net carbon emissions

### *Net carbon emissions per hectare*

In order to calculate the net carbon emissions, carbon stock was converted into $CO_2$ equivalent ($CO_2e$) using a factor of 3.67 (molecular weight of $CO_2$ dividing by atomic weight of C). Net C emissions are derived by subtracting $CO_2e$ carbon stock from $CO_2e$ emissions with results being presented in Figure 5.

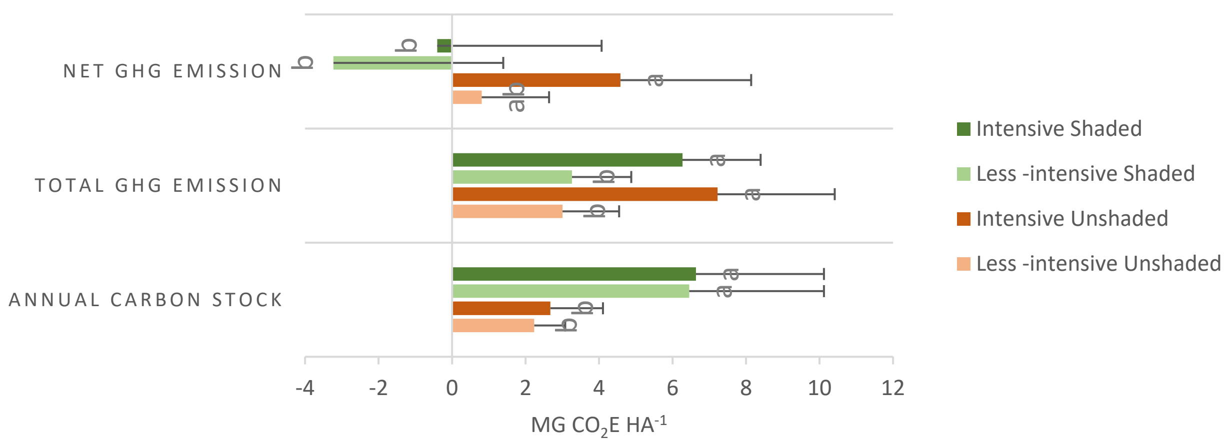


*Figure 5 Total carbon emissions, annual carbon stock, and net carbon emissions (Mg $CO_2e$ $ha^{-1}$) across studied systems. The bars with caps represent (upper) standard deviation. The values represented by thick bars with the same letter on the right side do not differ significantly (Tukey test at 5%).*

Figure 5 showed significant difference in net $CO_2e$ emissions among systems with intensive and less intensive shaded systems having negative net $CO_2e$ emissions values (-0.4 and -3.2 Mg $CO_2e$ $ha^{-1}$, respectively) whereas the intensive and less intensive unshaded systems had positive values (4.6 and 0.8 Mg $CO_2e$ $ha^{-1}$, respectively), attributed to higher carbon stock in the two former systems. Though having similar annual carbon stock (6.5 and 6.6 Mg $CO_2e$ $ha^{-1}$, respectively), less intensive shaded system had lower net emissions values compared to those of intensive shaded systems, due to the higher emissions of the latter systems. These results imply that across the four main systems, both shade tree growing and inorganic fertilizer use intensity affect the net GHG emission but in positive and negative ways, respectively. The effects of these factors can be quickly recognized as implied by the results for simplified unshaded and shaded systems (shade tree growing) and for simplified intensive and less intensive systems (inorganic fertilizer use intensity) in Table 9(a): the lower (and negative) net emission of the simplified less intensive system (-1.0 Mg $CO_2e$ $ha^{-1}$) compared to that of the simplified intensive system (1.9 Mg $CO_2e$ $ha^{-1}$) was due to the higher emission of the latter system; whereas, the lower (and negative) net emission of the simplified shaded system (-1.5 Mg $CO_2e$ $ha^{-1}$) compared to that of the simplified unshaded system (2.8 Mg $CO_2e$ $ha^{-1}$) was due to the higher carbon stock of the former system.

*Table 9 Net carbon emissions per hectare and per unit product across coffee production systems. Figures in each column of the same color followed by same letters do not differ significantly (Tukey test at 5%)*

| System | Annual carbon stock | Total GHG emissions | Net GHG emissions | Annual carbon stock | Total GHG emissions | Net GHG emissions |
|---|---|---|---|---|---|---|
| | (a) | | | (b) | | |
| **Measures (Unit)** | Per hectare (Mg $CO_2e$ $ha^{-1}$) | | | Per unit product (kg $CO_2e$ $kg^{-1}$) | | |
| **Unshaded** | **2.5** (0.1.2) $^{b}$ | **5.2** (3.3) $^{a}$ | **2.8** (3.4) $^{a}$ | **1.4** (1.1) $^{b}$ | **2.3** (1.3) $^{a}$ | **1.0** (1.4) $^{a}$ |
| **Shaded** | **6.6** (3.5) $^{a}$ | **5.1** (2.4) $^{a}$ | **-1.5** (4.7) $^{b}$ | **5.1** (6.8) $^{a}$ | **2.8** (1.9) $^{a}$ | **-2.4** (6.1) $^{b}$ |
| **Intensive** | **4.8** (3.3) $^{a}$ | **6.7** (2.6) $^{a}$ | **1.9** (4.7) $^{a}$ | **2.4** (2.9) $^{a}$ | **2.7** (1.7) $^{a}$ | **0.3** (2.3) $^{a}$ |
| **Less intensive** | **4.1** (3.3) $^{a}$ | **3.1** (1.5) $^{b}$ | **-1.0** (3.8) $^{b}$ | **4.4** (7.1) $^{a}$ | **2.2** (1.6) $^{a}$ | **-2.1** (6.4) $^{a}$ |

The net GHG emissions of simplified shaded and unshaded systems were respective -1.5 and 2.8 Mg $CO_2e$ $ha^{-1}$.

## *Net carbon footprint per unit product*

Similar to net $CO_2e$ emissions per hectare, the net $CO_2e$ emissions per unit dry coffee bean were negative for shaded systems, being -0.7 and -5.1 kg CO2e $kg^{-1}$ (4-fold difference) for intensive and less intensive systems, respectively. Meanwhile, the net CO2e emissions per unit dry coffee bean were positive for unshaded systems, being 1.5 and 0.4 kg CO2e $kg^{-1}$, for intensive and less intensive systems, respectively (Figure 6).

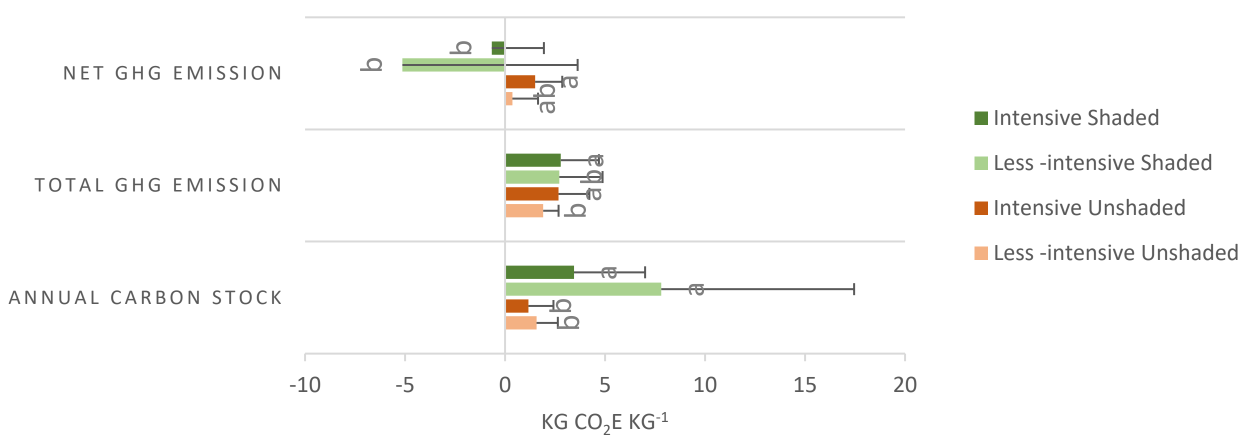


*Figure 6 Total carbon emissions, annual carbon stock, and net carbon emissions per unit dry coffee bean (kg CO2e $kg^{-1}$) across studied systems. The bars with caps represent (upper) standard deviation. The values with the same letter on the right side do not differ significantly (Tukey test at 5%).*

Within the shaded systems, the much lower net carbon emissions of the less intensive shaded system were because of its very high annual carbon stock compared to the intensive shaded one as discussed in section on carbon stocks.

Therefore, although less intensive systems have lower net CO2e emissions on a per hectare basis, emissions from input use on a per unit product basis are not significantly different between the intensive and less intensive systems (Figure 6). However, when accounting for carbon sequestered in biomass, the less intensive systems are negative emitters on a per unit product basis.

The lower (negative) net emission per unit product of simplified shaded than that of simplified unshaded (-2.4 versus 1.0 kg CO2e $kg^{-1}$, respectively) was also because of the higher carbon stock per unit product of the former system. These net emissions values suggests that production of 1 kg dry coffee bean in the simplified unshaded system will consequently release 1.0 kg CO2e while helps sequester 2.4 kg CO2e in the simplified shaded system, thanks to the off-setting effects of shade trees grown in coffee farms (Table 9(b)).

### *Discussion on coffee yield*

Among the four main coffee production systems, there were significant differences in total emissions per hectare while not so in total emissions per unit product. This is because yield values tend to vary in relation to total emissions per hectare. Therefore, we take yield into account for a simple correlation analysis. Due to the small sample size, the correlation analysis is for indicative purposes only. Correlation between yield and factors that might affect yield are presented in the Table 10.

*Table 10 Pearson correlation between coffee yield and yield-related factors (***indicates very significant at p-value of <0.001; ns indicates not significant)*

| | Inorganic fertilizer quantity | Organic fertilizer quantity | Coffee density | Coffee age | Coffee residue volume | Shade density |
|---|---|---|---|---|---|---|
| Green coffee yield | 0.50*** | $0.11^{ns}$ | $0.21^{ns}$ | $0.24^{ns}$ | $0.14^{ns}$ | $-0.20^{ns}$ |

Only inorganic fertilizer quantity had moderately positive correlation (r = 0.50) with green coffee yield. It has been noted that inorganic fertilizer quantity had positive correlation with GHG emission from application of this kind of fertilizer $E_{InorgFerAppl}$ (r = 0.66). This means that the more inorganic fertilizer is applied to coffee trees, the more coffee yield as well as GHG emissions will be produced. Our modest data sample size, however does not allow deeper analysis of the relationship between diminishing return of yield and incremental inorganic fertilizer quantity.

## Conclusion

As discussed in the previous section, the lower (and negative) net emissions measured both in per hectare or per unit product of the shaded systems compared to the positive net emissions of unshaded system was due to the higher carbon stock in the former systems. This is attributed to the significantly large contribution of carbon stock by shade trees (accounting for 68 - 71%) to the systems' total carbon stock (see section *Annual carbon stock*). In our study, it has been shown that there was no significant difference in green coffee yields between shaded and unshaded systems. Therefore, growing shade trees (with a tree density of 85 trees $ha^{-1}$, in our study) appears to be an effective way to increase carbon stock of coffee production systems which in turn significantly help off-set GHG emissions produced from those systems without reducing coffee yield. It has been found that farmers in the Central Highlands prefer high value fruit trees (especially avocado, durian, mango, and cashew), in addition to *Cassia siamea* as shade trees for intercropping with coffee.

As of 2017, the total Robusta coffee production area in the Vietnam's Central Highlands was estimated at 622,200 hectares (USDA Foreign Agricultural Service, 2017), of which about 25% of is coffee-shade tree intercropping system. Given the target of 70% coffee growing area under shaded systems is achieved (HRNS and CIAT, unpublished), with a shade tree density of 85 trees $ha^{-1}$, an additional 1.2 million Mg $CO_2e$ $year^{-1}$ would be sequestered[1]. Therefore, the potential of increasing carbon stock via growing shade trees in coffee farms is of great significance.

Reducing inorganic fertilizer use is another approach to reduce GHG emission from its production as well as application in the soil. A detailed recommendation on specific reduction inorganic fertilizer quantities is out of the scope of this study. Further study should be prioritized to explore the relationship between diminishing return of yield and incremental inorganic fertilizer quantities, types and timing to derive a rational threshold of inorganic fertilizer application rate and thus suitable reduction in its quantity and in consequent GHG emission without compromising coffee yield.

[1] This simple calculation assumed a baseline of net GHG emissions in simplified shaded and unshaded systems of -1.5 and 2.8 Mg $CO_2e$ $ha^{-1}$ respectively. Note that their carbon footprints were relatively similar at 5.1 and 5.2 Mg $CO_2e$ $ha^{-1}$ respectively, indicating that growing about 85 trees in one hectare of a coffee monocropping farm would sequester 4.3 Mg $CO_2e$ $year^{-1}$ from the atmosphere.

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