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Carbon stocks and yields in smallholder cocoa agroforestry systems along a climatic gradient in Ghana

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Abstract Cocoa agroforestry systems are recognized for their potential to reconcile agricultural production with climate change mitigation, yet the mechanisms governing carbon storage across environmental gradients remain poorly understood. Here, we examined above- and belowground carbon stocks of cocoa and shade trees as well as soil organic carbon (SOC) in smallholder cocoa agroforestry systems across dry, intermediate (mid), and wet climatic zones in Ghana. Despite pronounced differences in shade tree density, size, and species richness, shade-tree aboveground carbon stocks (108–147 Mg C ha^{-1}) as well as total farm-level carbon stocks were comparable across the climatic gradient (from dry to wet), with no negative effect on cocoa yield, signifying trade-offs in the structural characteristics of shade trees driven by management. Cocoa tree carbon and SOC stocks varied across the climatic zones but individually contributed less to ecosystem carbon stocks. Cocoa tree carbon stocks were highest in the mid climatic zone (41 Mg C ha^{-1}) compared to 22 Mg C ha^{-1} for the dry and 27 Mg C ha^{-1} for the wet zone, reflecting the older cocoa tree stands and larger stem diameters of the mid zone. SOC was lower in the dry zone than in the mid and wet zones, by 23 and 27%, respectively, and mirrored the combined effects of climatic conditions and soil properties. The ratio of cocoa yield to total plant carbon increased from the dry to wet climatic zone, indicating a shift in carbon allocation toward productivity under wetter climatic conditions. Our results highlight the capacity of cocoa agroforestry systems to provide climate-mitigation benefits independent of climatic variations but with greater synergies of achieving high cocoa productivity and ecosystem carbon storage under wetter climatic conditions. Overall, these findings underscore the need for climate-specific management strategies that optimizes both carbon sequestration

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and cocoa productivity in West African agroforestry systems.

Keywords Aboveground biomass · Belowground biomass · Cocoa production · Carbon credit · Carbon sequestration · Soil organic carbon · Sustainable agriculture · West Africa

Introduction

As a globally important commodity, cocoa (*Theobroma cacao*) production and associated markets contribute to the livelihoods of over 40 million people worldwide (Beg et al. 2017; Fotiadis and Huan 2022). Out of the nearly 4−5 million metric tons of cocoa beans produced annually across the tropics, about 95% is contributed by smallholder farms ranging 0.26–14.7 ha in size (Carr and Lockwood 2011; ICCO 2023). The global land area covered by cocoa farming is estimated to be around 11.7 million hectares, of which West Africa accounts for nearly 70% of these lands (~8.09 million hectares) and production (Otekunrin 2025). As the global demand for cocoa and cocoa-based products increases, the expansion of cocoa cultivation into forested areas intensify, often driving up tropical deforestation, and loss of biodiversity and ecosystem services (Steffan-Dewenter et al. 2007; Gockowski and Sonwa 2011; Obeng and Aguilar 2015). Smallholder cocoa agroforestry systems, which integrate cocoa with diverse shade tree species, present a promising approach to mitigate these challenges, potentially fostering both agricultural productivity and ecological resilience (Asare 2006; Wu et al. 2016). Moreover, these agroforestry systems are increasingly recognized for their potential to stock significant amounts of carbon through their enhanced accumulation of biomass and soil organic matter, thereby contributing to climate change mitigation and improved soil health (Jose 2009; Somarriba et al. 2013; Veldkamp et al. 2023). Understanding the dynamics of carbon storage in these smallholder cocoa agroforestry systems is critical for the global carbon cycle and important for quantifying its response to increasing land use changes (Houghton 2005).

Moreover, cocoa agroforestry systems are also widely regarded as a climate adaptation strategy, that can accrue diversified financial returns for smallholder farmers while enhancing ecosystem multifunctionality through increased biodiversity, improved nutrient cycling and nutrient-use efficiency, and greater carbon sequestration (Tscharntke et al. 2011; Monroe et al. 2016; Abdulai et al. 2018, 2025). Despite such benefits, the interaction between cocoa trees and the associated shade trees have not always been positive regarding climate adaptation as they significantly affect water and nutrient dynamics. For example, if cocoa and shade tree combinations are not well chosen, this can result in adverse hydrological and nutritional limitations to cocoa plant growth, their productivity, and the rate of biomass accumulation (Abdulai et al. 2017). Whereas canopy interactions may determine light interception levels, root distribution between cocoa and shade trees may express competition or complementarity in their water and nutrient use, all of which may vary under different climatic conditions, and thus influence the performance and adoptability of cocoa agroforestry systems (Cannavo et al. 2011; Padovan et al. 2015; Abdulai et al. 2017). For instance, under extreme seasonal drought conditions, competition for water between cocoa and shade trees in agroforestry systems are likely to lead to stalled or reduced growth, and mortality of the cocoa plant (Abdulai et al. 2017; Gateau-Rey et al. 2018; Kompas et al. 2024). The physiological responses of tropical plants to seasonal drought, may sometimes be confounded by soil nutrient availability (Manu et al. 2024), which influences their carbon assimilation and mortality risk.

Climate significantly controls plant biomass productivity and the carbon sequestration potential in agroforestry systems (Läderach et al. 2013; Schroth et al. 2016a). Variations in temperature, precipitation, and other environmental factors across a climatic gradient can affect tree growth rates, species composition, and overall ecosystem functioning (Toledo et al. 2011; Wagner et al. 2016; Green et al. 2019; Humphrey et al. 2021; Manu et al. 2022; Higgins et al. 2023). These variations can lead to significant differences in biomass production and the carbon sequestration potential across ecological zones (Toledo et al. 2011; Wagner et al. 2016; Green et al. 2019; Humphrey et al. 2021; Higgins et al. 2023). Such variability raises important questions about the adaptability of smallholder cocoa agroforestry systems to changing climatic conditions and their capacity to serve as effective carbon sinks. For instance, regions with

higher rainfall and optimal temperature ranges significantly enhance plant growth, thereby facilitating greater carbon storage. In drier and hotter regions, water availability may limit plant growth, induce nutrient limitations and constrain potential carbon storage (Manu et al. 2024). This relationship underscores the need for site-specific studies that consider local climatic conditions and management strategies that may optimize carbon storage in cocoa agroforestry systems. Furthermore, despite the recognized potential of smallholder cocoa agroforestry systems to sequester carbon, there is a lack of comprehensive studies examining carbon stocks along climatic gradients, with the interaction between climatic factors and agroforestry practices that determines productivity and carbon stocks poorly understood (Schroth et al. 2016b; Lynch 2022).

Across the tropics, significant proportion of aboveground carbon of cocoa agroforestry systems is stored in non-cocoa shade trees. Previous studies in Central America and Africa show that shade trees typically account for 60–70% of aboveground carbon compared to cocoa trees (Somarriba et al. 2013; Dawoe et al. 2016; Mohammed et al. 2016; Miharza et al. 2023). Moreover, SOC stocks also represent a substantial carbon pool but vary widely with climate, soil depth, land use history, and farm management (Mohammed et al. 2016; Miharza et al. 2023). Understanding how carbon stocks are distributed among biomass and soil pools across environmental gradients is therefore critical for evaluating the mitigation potential and economic viability of cocoa agroforestry systems within emerging carbon finance frameworks. Notwithstanding, only very few studies examine how carbon partitioning among shade trees, cocoa biomass, and soils responds to climatic gradients within smallholder systems. Our study addresses this gap by quantifying component-level carbon stocks across contrasting climatic zones in Ghana. Here, we investigate variations in carbon stocks as well as its relationship with cocoa yield in nearly 150 smallholder cocoa agroforestry systems across dry, mid, and wet climatic zones in Ghana.

By examining how different climatic conditions interact with agroforestry practices in modulating their influence on carbon storage, we aim to generate greater insights into how smallholder farmers can enhance carbon storage while maintaining productivity. We hypothesize that (1) total carbon stocks (soil organic carbon, cocoa tree biomass, and shade tree biomass) will be higher in wet than in drier zones, (2) higher shade tree biomass will not negatively impact yields. Our research findings will contribute crucial information on sustainable agricultural practices, agroforestry and carbon dynamics, and appraise of agroforestry systems as effective climate change mitigation strategies for sustainable cocoa cultivation.

Materials and methods

Study location and design

This study was conducted across three distinct climatic zones (dry, mid, and wet) in the cocoa cultivation belt of Ghana (Fig. 1), classified according to the different climate suitability zones for cocoa production in West Africa (Schroth et al. 2017). The dry zone is located near Akumadan in the Ashanti region of Ghana, where vegetation has over time transitioned from semi-deciduous forests to forest savannas due to recurrent wildfires and widespread intensive agriculture (Amisah et al. 2010; Abdulai et al. 2018). This zone encounters an extended dry period from November to March (Abdulai et al. 2017). The mid climatic zone occurs mostly within the moist semi-deciduous forest region around Goaso in the Brong-Ahafo region, while the wet climatic zone was mostly within the moist evergreen forest region around Asankragua in the Western region. For both mid and wet zones, the dry season persists from November to February, coupled with a southward surge in humidity. Mean annual temperatures ranged between 27–30 °C, 26–30 °C, and 27–30 °C for the dry, mid, and wet regions, respectively (Asante et al. 2021). Soils in the three zones are largely loamy-textured Acrisol, Alfisol, and Oxisol (see Table 1 for physicochemical characteristics). The cocoa agroforestry systems were distinguished by contrasting land-use histories (Abdulai et al. 2018). In the dry zone, cocoa farms occurred on previous cocoa farmlands, typically following short fallows intercropped with annual crops such as maize and vegetables. In contrast, most farms in the mid and wet zones were established after forest clearing (Gockowski and Sonwa 2011; Abdulai et al. 2018).

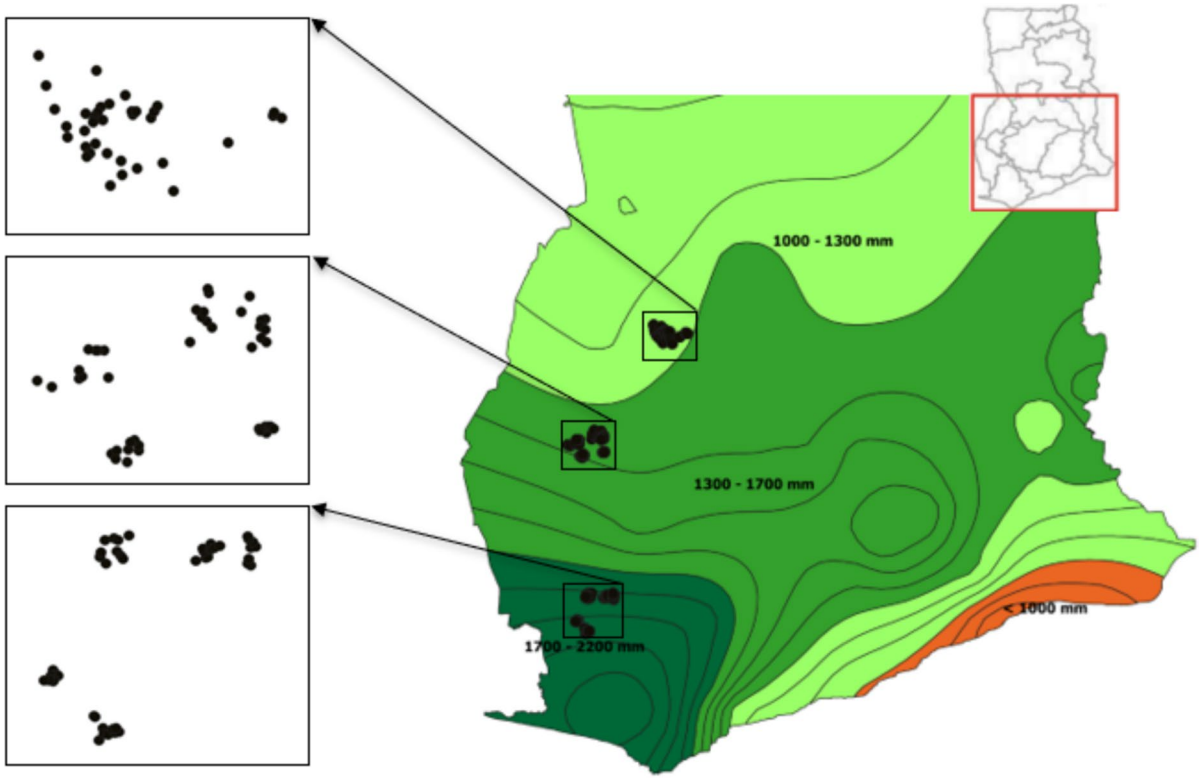


Fig. 1 Map of southern Ghana showing annual rainfall (mm) and the distribution of cocoa agroforestry systems (n = 50 farms) in the dry, mid, and wet climatic zones. Annual rainfall in the dry, mid, and wet climatic zones ranges from 1000–1300 mm, 1300–1700 mm, and 1700–2200 mm, respectively. Each black dot represents an individual cocoa agroforestry system

Estimations of tree biomass and carbon stocks

In total, our study consisted of 150 matured cocoa agroforestry farms in the three climatic zones (50 farms per climatic zone). Each farm within a climatic zone represented a replication unit (Fig. 1). Tree inventories were conducted in all farms across the three climatic zones (Table 1). Within each farm, we measured the tree height and diameter at breast height (DBH) of all shade trees. For cocoa trees, these measurements were conducted on a fixed area transect of 40 m^2 in the middle of the cocoa agroforestry plantation. With the help of local botanists, shade tree species were taxonomically identified, except for 0.5% of the trees which could not be identified to the species level. A total of 2447 individual shade trees consisting 85 species (62 species in the dry zone, and 66 in the mid zone and 64 in the wet zones) were measured in the 150 farms (Table 2). Across zones, the average number of cocoa trees expressed in hectares were 1570 ± 82 trees ha^{-1} in the dry zone, 1620 ± 67 trees ha^{-1} in the mid zone, and 1740 ± 58 trees ha^{-1} in the wet climatic zones (Table 1). To estimate the aboveground wood biomass (AWB) of shade trees, we used a pan-tropical allometric equation (Chave et al. 2014), expressed as $AWB = 0.0673 \times (pD^2H)^{0}.976$ using measured DBH and height values. Where p represents species-specific wood density (g cm^{-3}), D represents diameter at breast height (cm), and H represents total tree height (m). The species-specific wood density was taken from the global wood density database of the R package BIOMASS and other published literature (Zanne et al. 2009; Chave et al. 2009; Donegan et al. 2014; Manu et al. 2022). For cocoa trees, with only DBH measured, we used a pan-tropical allometric equation built only for tree diameter (Chave et al.

Table 1 Site characteristics (mean ± SE, n = 50 farms) of soils (0–30 cm depth) and vegetation of cocoa agroforestry farms in dry, mid, and wet climatic zones in Ghana. Within rows, mean values with different letters indicate statistically significant difference ($P < 0.05$) between the climatic zones

Soil / vegetation characteristics	Climatic zones		
	Dry zone	Mid zone	Wet zone
Soil physical and chemical characteristics			
Soil texture class	Sandy-loam	Loam	Silt-loam
Sand (%)	59.8 ± 1.6 a	41.3 ± 1.3 b	31.4 ± 1.3 c
Silt (%)	27.9 ± 1.6 c	46.0 ± 1.3 b	56.1 ± 1.2 a
Clay (%)	12.3 ± 0.8 a	11.7 ± 0.6 a	12.5 ± 0.7 a
Soil organic matter (%)	2.3 ± 0.1 b	2.8 ± 0.1 a	3.0 ± 0.1 a
Bulk density (g cm^{-3})	1.46 ± 0.01 a	1.41 ± 0.01 b	1.40 ± 0.01 b
pH (1:1H_20)	6.9 ± 0.1 a	6.8 ± 0.1 a	5.3 ± 0.1 b
C:N ratio	10.7 ± 0.3 b	12.1 ± 0.7 a	11.26 ± 0.1 ab
Total N (g N m^{-2})	519 ± 15 b	592 ± 25 a	639 ± 20 a
CEC (cmolc kg^{-1})	10.9 ± 0.7 ab	14.4 ± 1.3 a	9.3 ± 0.5 b
Base saturation (%)	98.8 ± 0.2 a	98.8 ± 0.2 a	93.7 ± 0.5 b
Calcium (mg Ca kg^{-1})	1624 ± 107 a	2080 ± 205 a	798 ± 69 b
Magnesium (mg Mg kg^{-1})	282 ± 21 b	389 ± 33 a	188 ± 16 c
Potassium (mg K kg^{-1})	89.2 ± 5.6 a	87.3 ± 5.5 ab	71.5 ± 5.2 b
Sodium (mg Na kg^{-1})	19.0 ± 1.0 b	29.4 ± 1.8 a	25.4 ± 1.5 a
Bray phosphorus (mg P Kg)	6.2 ± 0.5 a	3.3 ± 0.6 b	8.6 ± 1.2a
Vegetation characteristics			
Cocoa yield (kg ha^{-1} $year^{-1}$)	282 ± 34 c	712 ± 43 b	849 ± 47 a
Plantation size (ha)	1.1 ± 0.2 b	1.7 ± 0.2 a	0.9 ± 0.1 b
Cocoa plantation age (years)	16 ± 1 b	20 ± 1 a	16 ± 1 b
Cocoa plant DBH (cm)	9.6 ± 0.4 b	12.1 ± 0.4 a	10.0 ± 0.4 b
Cocoa plant density (trees ha^{-1})	1570 ± 82 a	1620 ± 67 a	1740 ± 58 a
Shade cover (%)	23.6 ± 1.7 a	13.1 ± 1.2 b	16.8 ± 1.5b
Shade tree DBH (cm)	50.5 ± 1.8 b	56.3 ± 1.6 a	51.0 ± 2.5 b
Shade tree height (m)	17.3 ± 3 b	19.5 ± 0.4 a	19.7 ± 0.8 a
shade tree density (trees ha^{-1})	42 ± 3 a	23 ± 2 c	32 ± 3 b
Shade tree diversity (species ha^{-1})	20 ± 2 a	11 ± 1 c	16 ± 1 b
Shade tree basal area (m^2 ha^{-1})	4.4 ± 0.6 b	6.7 ± 0.8 a	3.5 ± 0.5 b

2005) expressed as $\mathrm{AWB} = p \times \exp(-1.499 + 2.148ln(D) + 0.207(ln(D))^2 - 0.0281(ln(D))^3)$. To determine the total tree biomass (TBM), a root-to-shoot conversion factor for secondary tropical forest of 0.24 is applied and expressed as: *TWB = AWB + (AWB *0.24)*. This factor was chosen because of its relevance to tropical and subtropical secondary forest stands, according to the widely used guidelines (IPCC 2006). For carbon fraction, we assumed 50% carbon in wood biomass (Schultz et al. 2008; Lewis et al. 2009; Petersson et al. 2012; Manu et al. 2022). Furthermore, following widely used guideline (IPCC 2006; Schultz et al. 2008; Petersson et al. 2012), the carbon fraction was converted into CO_2-equivalents (CO_2eq) and the unit converted from kg to tons (t) as follows: $\mathrm{CO2eq} = (TBM * 0.5 * 44/12)/1000$.

Soil sampling and analysis

Within each cocoa plantation, soil samples from the top 0–30 cm depth were taken from the midpoint and four locations of the transects using a soil auger (at least 5 m from the boundary to avoid edge effect). The five samples were mixed to form a composite sample, dried at 105 °C, sieved through a 2 mm sieve and ground. From the composite sample, a sub-sample was taken and analyzed for its physical and chemical properties (Table 1) at the Soil Research Institute of Ghana (CSIR-SRI). Soil organic carbon (SOC) was

Table 2 Aboveground carbon stocks contributions from different shade tree species in cocoa agroforestry systems in dry, mid, and wet climatic zones in Ghana

Serial number	Dry zone			Mid zone			Wet zone		
	Shade tree species	Carbon stock (Mg C ha^{-1})	Share (%)	Shade tree species	Carbon stock (Mg C ha^{-1})	Share (%)	Shade tree species	Carbon stock(Mg C ha^{-1})	Share (%)
1	*Alstonia scholaris*	54.6	7.7	*Ceiba pentandra*	44.8	6.6	*Celtis mildbraedii*	69.8	8.7
2	*Ceiba pentandra*	54.2	7.6	*Hannoa klaineana*	41.5	6.1	*Ceiba pentandra*	57.2	7.1
3	*Cassia rotundifolia*	53.0	7.5	*Entandrophragma candollei*	37.5	5.5	*Milicia excelsa*	38.1	4.7
4	*Entandrophragma utile*	27.4	3.9	*Nauclea diderrichii*	31.0	4.6	*Petersianthus macrocarpus*	33.0	4.1
5	*Cola gigantia*	25.7	3.6	*Cola gigantia*	26.5	3.9	*Hannoa klaineana*	31.6	3.9
6	*Entandrophragma candollei*	25.6	3.6	*Terminalia superba*	25.6	3.8	*Irvingia gabonensis*	24.3	3.0
7	*Milicia excelsa*	22.5	3.2	*Pterygota macrocarpa*	24.8	3.7	*Piptadeniastrum africanum*	24.3	3.0
8	*Cynometra megalophylla*	20.2	2.8	*Celtis mildbraedii*	23.0	3.4	*Guibourtia ehie*	21.5	2.7
9	*Terminalia ivorensis*	19.0	2.7	*Milicia excelsa*	20.7	3.0	*Aningeria robusta*	21.0	2.6
10	*Celtis mildbraedii*	18.1	2.5	*Amphimas pterocarpoides*	18.5	2.7	*Pericopsis laxiflora*	20.7	2.6
11	*Hannoa klaineana*	18.1	2.5	*Pycanthus angolese*	16.6	2.5	*Terminalia superba*	19.8	2.5
12	*Alstonia boonei*	16.8	2.4	*Antiaris toxicaria*	15.4	2.3	*Cola nitida*	18.3	2.3
13	*Guibourtia ehie*	16.5	2.3	*Morinda lucida*	14.8	2.2	*Cylicodiscus gabunensis*	17.7	2.2
14	*Terminalia superba*	16.1	2.3	*Alstonia boonei*	14.6	2.1	*Morinda lucida*	17.6	2.2
15	*Triplochiton scleroxylon*	15.7	2.2	*Ficus capensis*	14.1	2.1	*Combretum glutinosum*	17.6	2.2
16	*Ficus capensis*	14.9	2.1	*Ficus capensis*	14.1	2.1	*Alstonia boonei*	17.4	2.2
17	*Morinda lucida*	13.2	1.9	*Sterculia oblonga*	13.5	2.0	*Terminalia ivorensis*	15.9	2.0
18	*Entandrophragma angolense*	13.1	1.9	*Sterculia tragacantha*	13.2	1.9	*Bombax buonopozense*	14.8	1.8
19	*Petersianthus macrocarpus*	12.4	1.7	*Bombax buonopozense*	12.9	1.9	*Nauclea diderrichii*	14.3	1.8

Table 2 (continued)

Serial number	Dry zone			Mid zone			Wet zone		
	Shade tree species	Carbon stock (Mg C ha^{-1})	Share (%)	Shade tree species	Carbon stock (Mg C ha^{-1})	Share (%)	Shade tree species	Carbon stock(Mg C ha^{-1})	Share (%)
20	*Ricinodendron heudelotii*	12.2	1.7	*Entandrophragma angolense*	12.2	1.8	*Entandrophragma angolense*	13.7	1.7
21	*Chlorophora excelsa*	11.7	1.6	*Entandrophragma utile*	12.0	1.8	*Amphimas pterocarpoides*	12.9	1.6
22	*Antiaris toxicaria*	11.6	1.6	*Petersianthus macrocarpus*	11.9	1.8	*Vitex rivularis*	12.8	1.6
23	*Nesogordonia papaverifera*	11.5	1.6	*Bighia sapida*	11.1	1.6	*Unknown* spp.	12.0	1.5
24	*Spathodea campanulata*	11.1	1.6	*Guibourtia ehie*	11.0	1.6	*Aucoumea klaineana*	11.4	1.4
25	*Cola nitida*	10.1	1.4	*Cylicodiscus gabunensis*	10.2	1.5	*Lannea welwitschii*	11.4	1.4
26	*Bighia sapida*	10.0	1.4	*Mansonia altissima*	10.2	1.5	*Khaya ivorensis*	10.9	1.3
27	*Pycanthus angolese*	9.6	1.3	*Ricinodendron heudelotii*	10.0	1.5	*Pycanthus angolese*	10.7	1.3
28	*Cordia millenii*	8.5	1.2	*Aningeria robusta*	9.9	1.5	*Treculia africana*	10.2	1.3
29	*Albizia ferruginea*	8.1	1.1	*Blighia unijugata*	9.7	1.4	*Lophira alata*	10.1	1.3
30	*Sterculia oblonga*	7.5	1.1	*Triplochiton scleroxylon*	9.0	1.3	*Triplochiton scleroxylon*	10.1	1.3
31	*Antrocaryon micraster*	7.4	1.0	*Albizia zygia*	8.5	1.3	*Bighia sapida*	9.9	1.2
32	*Lannea welwitschii*	7.2	1.0	*Heritiera utilis*	8.3	1.2	*Funtumia elasstica*	9.5	1.2
33	*Citrus sinensis*	6.7	0.9	*Combretum glutinosum*	7.9	1.2	*Albizia ferruginea*	8.7	1.1
34	*Margaritaria discoidea*	6.5	0.9	*Lannea welwitschii*	7.9	1.2	*Antiaris toxicaria*	8.7	1.1
35	*Sterculia tragacantha*	6.5	0.9	*Discoglypremna caloneura*	7.8	1.1	*Blighia unijugata*	8.3	1.0
36	*Bombax buonopozense*	6.4	0.9	*Spathodea campanulata*	6.5	1.0	*Newboudia larvis*	7.9	1.0
37	*Persia americana*	6.4	0.9	*Holarrhena floribunda*	6.4	0.9	*Entandrophragma utile*	7.8	1.0

Table 2 (continued)

Serial number	Dry zone			Mid zone			Wet zone		
	Shade tree species	Carbon stock (Mg C ha^{-1})	Share (%)	Shade tree species	Carbon stock (Mg C ha^{-1})	Share (%)	Shade tree species	Carbon stock(Mg C ha^{-1})	Share (%)
38	*Unknown* spp.	6.3	0.9	*Daniellia ogea*	6.4	0.9	*Milicia regia*	7.8	1.0
39	*Samanea saman*	6.0	0.8	*Terminalia ivorensis*	6.1	0.9	*Cedrela odorata*	7.1	0.9
40	*Amphimas pterocarpoides*	6.0	0.8	*Pericopsis laxiflora*	5.9	0.9	*Pterygota macrocarpa*	6.8	0.8
41	*Tectona grandis*	5.8	0.8	*Newboudia larvis*	5.5	0.8	*Citrus sinensis*	6.5	0.8
42	*Albizia zygia*	5.8	0.8	*Albizia ferruginea*	5.1	0.7	*Discoglypremna caloneura*	6.5	0.8
43	*Cedrela odorata*	5.7	0.8	*Tectona grandis*	4.9	0.7	*Albizia zygia*	6.3	0.8
44	*Newboudia larvis*	5.6	0.8	*Magnifera indica*	4.8	0.7	*Persia americana*	6.2	0.8
45	*Albizia adianthifolia*	5.4	0.8	*Samanea saman*	4.8	0.7	*Ficus sur*	6.1	0.8
46	*Magnifera indica*	5.3	0.7	*Anthocleista nobilis*	4.8	0.7	*Ficus exasperata*	5.4	0.7
47	*Holarrhena floribunda*	4.4	0.6	*Unknown* spp.	4.4	0.6	*Allanblackia parviflora*	5.3	0.7
48	*Piliostigma thonningii*	4.1	0.6	*Tetrapleura tetraptera*	4.2	0.6	*Albizia adianthifolia*	5.2	0.6
49	*Pericopsis laxiflora*	3.8	0.5	*Persia americana*	4.0	0.6	*Sterculia rhinopetala*	5.2	0.6
50	*Anthocleista nobilis*	3.4	0.5	*Ficus exaperata*	3.8	0.6	*Ricinodendron heudelotii*	5.1	0.6
51	*Ficus exaperata*	3.0	0.4	*Piptadeniastrum africanum*	3.2	0.5	*Musanga cecropioides*	5.0	0.6
52	*Khaya senegalensis*	3.0	0.4	*Albizia adianthifolia*	3.1	0.5	*Rauvolfia vomitoria*	4.9	0.6
53	*Discoglypremna caloneura*	3.0	0.4	*Treculia africana*	2.9	0.4	*Spathodea campanulata*	4.4	0.5
54	*Aningeria robusta*	2.8	0.4	*Cola nitida*	2.9	0.4	*Anthocleista nobilis*	3.9	0.5
55	*Blighia unijugata*	2.5	0.3	*Aucoumea klaineana*	2.6	0.4	*Ficus exaperata*	3.8	0.5
56	*Diospyros abyssinica*	2.3	0.3	*Citrus sinensis*	2.3	0.3	*Magnifera indica*	3.5	0.4

Table 2 (continued)

Serial number	Dry zone			Mid zone			Wet zone		
	Shade tree species	Carbon stock (Mg C ha^{-1})	Share (%)	Shade tree species	Carbon stock (Mg C ha^{-1})	Share (%)	Shade tree species	Carbon stock(Mg C ha^{-1})	Share (%)
57	*Piptadeniastrum africanum*	2.2	0.3	*Musanga cecropioides*	2.3	0.3	*Sterculia tragacantha*	3.5	0.4
58	*Funtumia elasstica*	2.1	0.3	*Funtumia elasstica*	2.3	0.3	*Myrianthus arboreus*	3.0	0.4
59	*Citrus reticulata*	1.7	0.2	*Ficus sur*	2.0	0.3	*Alstonia scholaris*	2.8	0.3
62	*Voacanga africana*	1.4	0.2	*Margaritaria discoidea*	1.9	0.3	*Antrocaryon micraster*	2.5	0.3
61	*Tetrapleura tetraptera*	1.4	0.2	*Piliostigma thonningii*	1.8	0.3	*Ficus capensis*	2.5	0.3
62	*Erythrina senegalensis*	0.9	0.1	*Khaya ivorensis*	1.7	0.3	*Turraeanthus africanus*	2.4	0.3
63				*Nesogordonia papaverifera*	1.7	0.3	*Tetrapleura tetraptera*	1.9	0.2
64				*Antrocaryon micraster*	1.5	0.2	*Piliostigma thonningii*	1.1	0.1
65				*Canarium schweinfurthii*	1.4	0.2			
66				*Cordia millenii*	1.1	0.2			

determined by the wet oxidation method (Walkley and Black 1934) and total N by the modified Kjeldahl method (Bremner 1996). Exchangeable bases were extracted with 1.0 M ammonium acetate solution (Thomas 1982). Soil texture was determined using the hydrometer method whilst extractable soil P was determined using the Bray I method (Bray and Kurtz 1945). Soil organic carbon stocks was calculated from SOC concentration (SOC %), soil layer thickness (in meters) and bulk density (Solomon et al. 2002; Adiyah et al. 2023) and expressed as: SOC stocks (Mg C / ha) = (SOC %) × bulk density (Mg / m^3) × soil depth (m) × 10,000.

Bulk density was estimated from soil organic matter (% OM) for each farm following a widely used approach (Post and Kwon 2000; Chatterjee et al. 2018): $\text{Bulkdensity} = 100/((\%\text{OM}/0.244) + ((100 - \%\text{OM})/1.64))$.

Statistical analysis

For comparison of carbon stocks, vegetation, and physicochemical soil characteristics across the dry, mid, and wet climatic zones, we tested each parameter for equality of variances using Levene`s test and for normal distribution using Shapiro–Wilk's test. If these two conditions were met, differences among the climatic zones were tested with a one-way ANOVA followed by Tukey HSD test. If normal distribution was not met, a Kruskal–Walli's test with multiple comparison extension was used. If the assumption of equality of variances was not met, we used a one-way T test pairwise comparison with a Holm-correction. Additionally, to assess the relationship between production and carbon storage, we calculated the ratio between cocoa yield (Mg/ha) and total plant carbon stocks (Mg/ha). Such ratios provide an integrated indicator of production relative to biomass carbon

storage within the cocoa agroforestry system across the different climatic zones. Spearman correlation was also used to test relationships between yield and carbon stocks for different compartments of ecosystem carbon storage across the three zones. All data were analyzed using R (version 4.0.4) with statistical significance level at $P < 0.05$.

Results

Characterization of cocoa agroforestry systems across wet, mid and dry climatic zones

Like shade trees, mean DBH of cocoa trees was 19–23% higher in the mid climatic zone than in the dry and wet zones. Similarly, average DBH of the shade trees was 10–11% higher in the mid zone than in the dry and wet climatic zones. Consequently, the shade tree basal area was about twice as high in the mid zone than in the dry or wet zones. Higher shade tree density (by 36–72%), canopy cover (by 40–70%), and species diversity (by 36–70%) were observed in the dry compared to the mid and wet climatic zones (Table 1), likely reflecting the adaptative management strategy to the marginal climatic conditions of the drier region. We distinguished between low-shaded (shade cover ≤ 25%) and medium-shaded (shade cover > 25%) farms and found that low-shaded farms represented about 53, 94, and 79% of farms in the dry, mid and wet climatic zones, respectively.

Aboveground carbon stock contribution of different shade tree species

A total of 2447 individual shade trees and 85 species were recorded from all the cocoa agroforestry plantations. The eleven most abundant species (*Terminalia superba (9%), Morinda lucida (6%), Ficus capensis (6%), Milicia excelsa (5%), Persia Americana (4%), Ceiba pentandra (4%), Antiaris toxicaria (4%), Sterculia tragacantha (4%), Albizia zygia (3%), Ricinodendron heudelotii (3%),* and *Cola nitida (3%)*) accounted for about half (51%) of all trees but represented only 12% of aboveground carbon stock in the three climatic zones. Considering all species across the three zones, we observed an overlap in species assemblage with about half of the total species pool occurring in all zones (Table 2). However, each of the zones showed largely distinct species composition for the top 15 species with the highest biomass, contributing over half of the zone's total carbon stock (Table 2). Out of these 15 species, only five (*Ceiba petandra*, *Hannoa klaineana, Celtis mildbraedii, Milicia excelsa, and Terminalia superba*) occurred in all three climatic zones and contributed a combined carbon stock of 18%, 23%, and 27% in the dry, mid and wet zones respectively (Table 2). Across climatic zones, the highest aboveground carbon stock of 53 ± 22 Mg C ha^{-1} was recorded for *Cassia rotundifolia* (only occurring in the dry zone), followed by 51 ± 9 Mg C ha^{-1} for *Ceiba pentandra*, and then 33 ± 6 Mg C ha^{-1} for *Hannoa klaineana.* Across the three climatic zones, these species represented the highest individual biomass contributors. Within the dry zone, *Alstonia scholaris, Ceiba pentandra* and *Cassia rotundifolia* were the dominant carbon-storing species, each contributing about 8% (53–55 Mg C ha^{-1}) of the total aboveground carbon. In the mid zone, *Ceiba pentandra, Hannoa klaineana,* and *Entandrophragma candollei* stored the most carbon contributing about 6–8% (38–45 Mg C ha^{-1}) of the total aboveground carbon of this zone. Within the wet zone, *Celtis mildbraedii* contributed the highest share of carbon storage (9%; 70 Mg C ha^{-1}), followed by *Ceiba pentandra* (7%; 57 Mg C ha^{-1}), and then by *Milicia excelsa* (5%; 38 Mg C ha^{-1}) (Table 2).

Aboveground and belowground carbon stocks across the climatic gradient

Carbon storage in the cocoa agroforestry systems varied with compartments (i.e., shade trees, and cocoa trees). Shade trees contributed a higher aboveground carbon stock (108–147 Mg C ha^{-1}), accounting for ~ 78–85% of the total aboveground carbon at the plantation level and did not differ among climatic zones. On the other hand, aboveground C of cocoa trees was higher in the mid climatic zone than the wet zone by 41% and dry zone by 60% (Table 3). However, total aboveground C (shade tree C + cocoa tree C) was 39% higher in the mid zone than the dry zone but comparable to the wet climatic zone (Table 3). Total plant carbon (cocoa tree C + shade tree C) in the dry zone was 32 and 19% lower than in the mid and wet climatic zones, respectively (Table 3). However, similar to cocoa yields (Table 1), the ratio of cocoa

Table 3 Carbon stocks contributions (mean ± SE; Mg C ha^{-1}; n = 50 farms) from different compartments of cocoa agroforestry systems along the climatic gradient in Ghana. Within rows, mean values with different letters indicate statistically significant difference ($P < 0.05$) between the climatic zones

Climatic zone	Dry zone	Mid zone	Wet zone
Aboveground wood carbon (AWB)			
AWB shade trees	108 ± 11 a	147 ± 15 a	132 ± 20 a
AWB cocoa	22 ± 2 b	41 ± 4 a	27 ± 3 b
Total AWB	127 ± 12 b	188 ± 16 a	156 ± 20 ab
Belowground wood carbon (BWB)			
BWB shade trees	26 ± 3 a	36 ± 4 a	32 ± 5 a
BWB cocoa	5.2 ± 0.6 b	9.9 ± 0.8 a	6.5 ± 0.6 b
Soil organic carbon (SOC)	56 ± 3 b	69 ± 3 a	72 ± 2 a
Total belowground carbon (BWB + SOC)	85 ± 5 b	114 ± 5 a	110 ± 6 a
Total plant carbon (cocoa + shade trees)	158 ± 14 b	234 ± 19 a	194 ± 25 a
Cocoa yield: total plant carbon ratio ($\times 10^{-3}$)	2.8 ± 0.4 c	4.5 ± 0.5 b	9.7 ± 1.4 a

yield to total plant carbon increased along the climatic gradient from the dry to the wet zone (Table 3).

Soil organic carbon stocks differed across climatic zones and tended to increase from the dry to wet zones (Fig. 2). Soil C stock in the top 30 cm soil depth was 23–28% lower in the dry zone (56 ± 3 Mg C ha^{-1}) compared to the mid (69 ± 3 Mg C ha^{-1}) and wet (72 ± 2 Mg C ha^{-1}) zones and constitute about 61–66% of total belowground carbon (Table 3). Whereas a comparable belowground biomass of the shade trees was observed among the climatic zones, a higher belowground biomass of cocoa trees was observed in the mid than in the dry and wet climatic zones (Table 3). Together, total belowground carbon (soil organic C + shade tree C + cocoa tree C) was about 27–52% higher in the wet (110 ± 6 Mg C ha^{-1}) and mid (114 ± 5 Mg C ha^{-1}) zones than in the dry climatic zone (85 ± 5 Mg C ha^{-1}). Overall, total farm-level carbon stocks (shade tree C + cocoa tree C + SOC) did not significantly differ among the climatic zones (Fig. 2). Correlation analysis of yield and carbon stocks did not show any clear relationship in the separate zones (Fig. 3). However, combining data from all zones revealed a positive relationship between yield and SOC or total farm level carbon stocks (Fig. 4).

Discussion

We examined carbon allocations among shade trees, cocoa tree biomass, and soils in smallholder cocoa agroforestry systems to understand the mechanisms influencing carbon storage across a dry to wet climatic gradient in Ghana. The conversion of primary forests to cocoa plantations reduces their carbon storage capacity, along with a considerable loss of biodiversity (Steffan-Dewenter et al. 2007; Obeng and Aguilar 2015; van Straaten et al. 2015). Aboveground carbon stocks (shade trees + cocoa) of 127–188 Mg C ha^{-1} at our cocoa agroforestry sites fall within the reported range for tropical agroforestry systems (12–228 Mg C ha^{-1}) (Albrecht and Kandji 2003), and Afrotropical (57–375 Mg C ha^{-1}) and Neotropical (69–229 Mg C ha^{-1}) forests (Quesada et al. 2012; Lewis et al. 2013; Taylor et al. 2019). They are lower than those reported for Bornean forests (229 Mg C ha^{-1}) in Southeast Asia (Quesada et al. 2012; Lewis et al. 2013; Taylor et al. 2019), yet exceed values reported for some secondary forests (104 Mg C ha^{-1}) in southern Ghana and agroforestry systems in Central America (averaging 49 Mg C ha^{-1}) and in Ghana (Dawoe et al. 2016; Mohammed et al. 2016; Afele et al. 2021; Nimo et al. 2021). The similarity of carbon stocks at our sites to reported values for Afrotropical and Neotropical forests likely reflect shared biogeographic characteristics, as these forests generally have fewer very large trees and exhibit lower mean basal area, thereby constraining aboveground biomass. In contrast, Bornean forests typically store substantially greater carbon, due to the dominance of tall dipterocarp species with larger mean DBH and higher wood density (Quesada et al. 2012; Lewis et al. 2013). Moreover, the relatively high carbon stocks observed in our cocoa agroforestry systems compared to the secondary forests can be attributed to the selective retention of large, mature shade

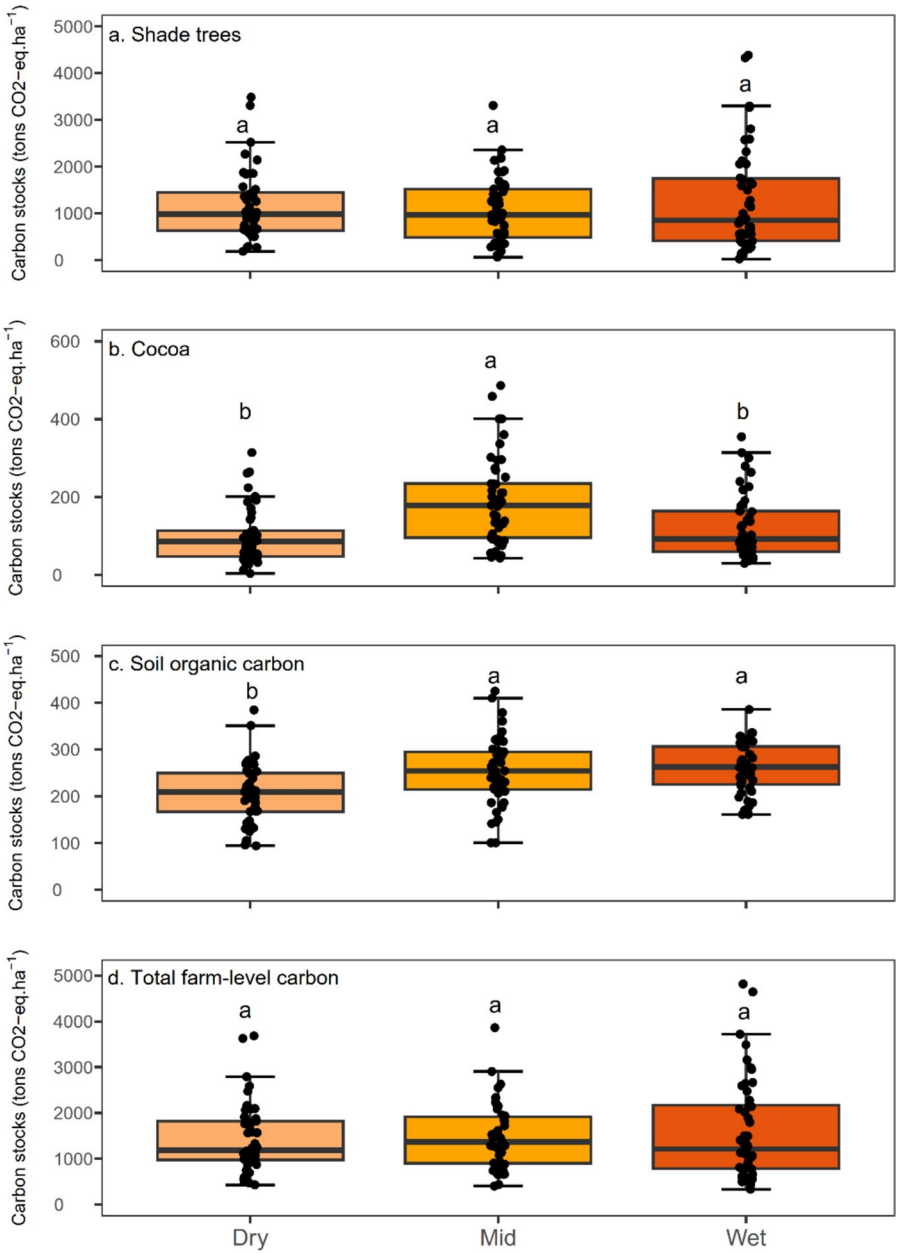


Fig. 2 Carbon stocks (CO_2 equivalent in tons ha^{-1}) in cocoa agroforestry systems in dry, mid, and wet climatic zones in Ghana. Carbon stock estimations for trees include both aboveground and belowground biomass whilst total farm-level carbon is a sum of shade tree carbon, cocoa tree carbon, and SOC. **a–d**, Box plots (25th quartile, median and 75th quartile) and whiskers (1.5 × interquartile range) of carbon stocks (n = 50 farms) in dry, mid, and wet climatic zones. In each panel, different letters above boxplots indicate statistical differences ($P < 0.05$) between the climatic zones

trees of economic or cultural value such as *Ceiba petandra, Terminalia superba, Milicia excelsa,* etc. (Table 2) during forest conversions. These retentions of large shade trees in cocoa agroforestry systems further enhance their overall aboveground carbon relative to secondary forests, which are mostly young in the region, often with a history of repeated disturbance from illegal logging, fuelwood extraction, and shorter recovery periods, thereby limiting their total biomass (Brown et al. 2020).

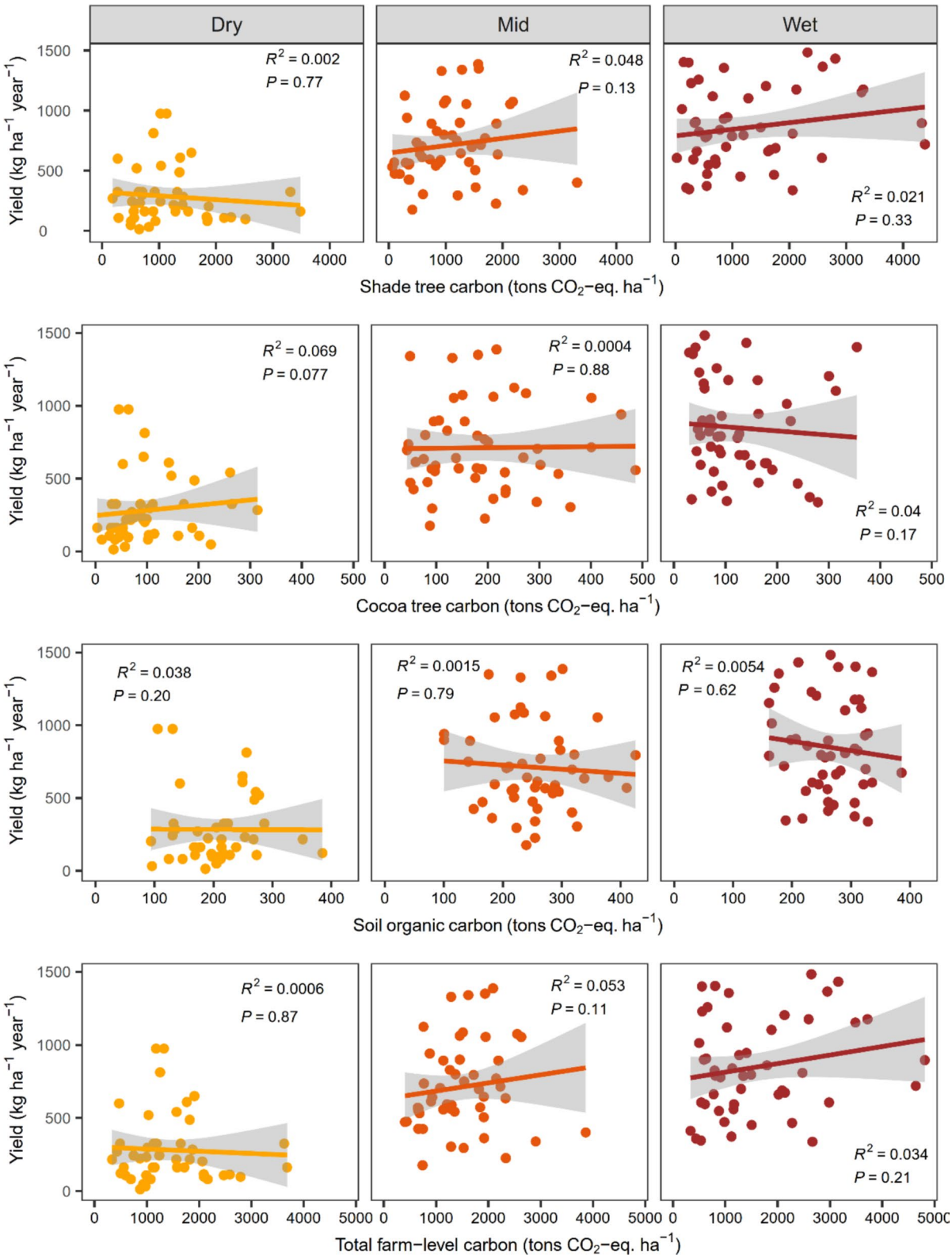
In Southern Ghana, where our study was conducted, Brown et al. (Brown et al. 2020) reported an aboveground carbon stock of 173 Mg C ha^{-1} for intact primary forests. This baseline carbon stock compared to our results show that our studied agroforestry systems has only 31% less carbon in the dry climatic zone and 10% in the wet zone, with the mid zone storing nearly 8% more carbon than the referenced primary forest (Brown et al. 2020). These estimated loss of stored carbon

following forest conversions to cocoa plantation systems are at the lower-end of ranges reported for Ghana (5–73%), Nigeria (69–91%) and Cameroon (5–89%) (Obeng and Aguilar 2015). Higher forest carbon losses from the conversion of primary forests into cocoa agroforestry have also been reported elsewhere in central America and Asia (Steffan-Dewenter et al. 2007; Smiley and Kroschel 2008). Notwithstanding, our results suggest that although cocoa agroforestry cannot substitute primary forests in the provision of ecosystem services, they offer an important strategy and land-use option that prevent significant losses in ecosystem functions such as carbon sequestration and cocoa production when compared to intensive cocoa monoculture or other agricultural land uses (Gockowski and Sonwa 2011; Somarriba et al. 2013; Obeng and Aguilar 2015; Afele et al. 2021).

In our study, total farm-level carbon stocks (shade tree C + cocoa tree C + SOC) did not differ among climatic zones (Fig. 2), although lower cocoa yields were observed in the dry zone than in the mid and wet zones (Table 1). This highlights the capacity of cocoa agroforestry systems, particularly in the dry zone, to continue to provide substantial climate change mitigation benefits through carbon storage at levels comparable to those in the wetter environments, which underscores their value as resilient carbon sinks (Tscharntke et al. 2011; Somarriba et al. 2013; Schroth et al. 2016a; Afele et al. 2021). The maintenance of comparable total carbon stocks under drier conditions of the dry zone reflected the large contributions of the shade tree carbon stocks, which may have buffered the effects of climatic constraints on ecosystem carbon storage (Fig. 2), even in regions where climatic conditions limited crop productivity. This further suggest that, the carbon storage potential of the cocoa agroforestry systems was not solely determined by rainfall availability, but also by the farms' structural characteristics and management practices (Saj et al. 2013). However, given the increased ratio of cocoa yield to total plant carbon from the dry to wet climatic zone (Fig. 2 and Table 3), the wet climatic zone appears to have provided the most favourable conditions for achieving higher cocoa production along with substantial carbon storage (Somarriba et al. 2013; Schroth et al. 2016a).

Limited effect of climatic gradient on shade tree carbon stocks

Despite differences in shade tree structure among climatic zones (Table 1), the aboveground carbon stocks of shade trees were comparable across zones (Fig. 2; Table 3) and were consistent with an earlier central Cameroonian study (Saj et al. 2013). This result suggests a strong structural compensation (a likely trade-off among the growth variables of shade trees) within the cocoa agroforestry systems. For instance, in the dry zone, the higher shade tree density, species richness, and shade cover compensated for the relatively smaller mean tree size and lower basal area (Table 1). Conversely, in the mid climatic zone, fewer but significantly larger shade trees with higher basal area dominated biomass accumulation. The wet zone had intermediate structural attributes with moderate density and diversity but taller shade trees, resulting in comparable carbon stocks across zones. This shade tree density and size trade-offs have been observed in forest communities and agroforestry systems and attributed to the non-linearity of biomass scales with tree diameter and height (Slik et al. 2013; Chave et al. 2014). In natural ecosystems, this density–size trade-offs represent the inverse relationship between tree density and individual size that emerges due to competition for limiting resources such as water, light, and nutrients. Thus, reductions in stem density are compensated by increases in mean tree size, resulting in total aboveground biomass across contrasting environmental or management regimes (Enquist et al. 1998; Pretzsch 2009). In smallholder cocoa agroforestry systems, such comparable carbon stocks across climatic zones may reflect the long-term farm management decisions that tend to balance shade provision and crop productivity rather than maximizing tree carbon storage, and thus inadvertently stabilizing shade tree carbon stocks across the climatic gradient despite large differences in tree density, basal area, or species composition (Dawoe et al. 2016; Abdulai et al. 2018; Asigbaase et al. 2020; Lotz et al. 2026). Consistent with our hypothesis, shade tree biomass had no significant effect on cocoa yield (Fig. 3), suggesting a generally limited negative influence of shade trees on yield (Afele et al. 2021). These findings highlight the role of shade trees as a relatively climate-resilient carbon pool within cocoa agroforestry systems and further suggest that climatic


Dry
Mid
Wet
Yield (kg ha^{-1} year^{-1})
R^2 = 0.002
P = 0.77
R^2 = 0.048
P = 0.13
R^2 = 0.021
P = 0.33
Shade tree carbon (tons CO_2−eq. ha^{-1})
R^2 = 0.069
P = 0.077
R^2 = 0.0004
P = 0.88
R^2 = 0.04
P = 0.17
Cocoa tree carbon (tons CO_2−eq. ha^{-1})
R^2 = 0.038
P = 0.20
R^2 = 0.0015
P = 0.79
R^2 = 0.0054
P = 0.62
Soil organic carbon (tons CO_2−eq. ha^{-1})
R^2 = 0.0006
P = 0.87
R^2 = 0.053
P = 0.11
R^2 = 0.034
P = 0.21
Total farm−level carbon (tons CO_2−eq. ha^{-1})

◂**Fig. 3** Relationship between cocoa yield and carbon stocks in the cocoa agroforestry systems in the dry, mid, and wet climatic zones in Ghana. No significant relationship between yield and carbon stocks of different compartment were observed (Spearman's correlation test; n = 50 farms) in any of the three climatic zones. Each point represents an individual cocoa agroforestry system

constraints on shade tree growth in dry regions can be dampened by management-decisions on tree density and species composition (Table 1).

Climate-mediated cocoa tree carbon allocation and productivity

Cocoa tree aboveground carbon (22–41 Mg C ha^{-1}) was considerably higher than that reported from central America (9 Mg ha^{-1}) and an 8-year old plantation (11–21 Mg C ha^{-1}) in Ghana (Isaac et al. 2007), with this variation likely dependent on site-specific management and plantation characteristics such as farm age and stand density (Jagoret et al. 2017; Asante et al. 2021). In this study, although the share of cocoa tree carbon stocks was low compared to shade trees (Table 3), it varied significantly among climatic zones, with the highest stocks observed in the mid climatic zone compared to the dry and wet zones (Fig. 2; Table 2). This pattern mirrored the growth characteristics of cocoa trees in the mid zone (Jagoret et al. 2017), given its larger cocoa stem DBH, and older plantation stands (Table 1). Therefore, aside from climatic effects, the differences in cocoa carbon stocks were largely driven by cocoa tree size, plantation age, and carbon partitioning rather than by cocoa tree density (Table 1), considering that cocoa plant density did not differ significantly among the zones (1570–1740 trees ha^{-1}). These results also indicate that, unlike shade trees, cocoa tree carbon was more sensitive to climatic conditions and perhaps management that regulated productivity and carbon allocations.

Another plausible reason for the high cocoa tree carbon stock in the mid zone was the low level of shade cover in this zone, which has been shown to be negatively related to cocoa biomass (Steffan-Dewenter et al. 2007; Abdulai et al. 2018). In our study, relative to the dry climatic zone, the high proportion of low-shaded farms (94% of sampled farms in the mid zone had shade cover < 25%), explains the high cocoa tree DBH of the mid zone (Table 1), and the higher cocoa tree biomass carbon stocks observed (Fig. 2 and Table 3). Nevertheless, despite its relatively low cocoa tree carbon stocks and mean stem DBH (Table 1) compared to the mid zone, the wet zone recorded the highest cocoa yields, indicating a shift in carbon allocation that favours greater production efficiency (Somarriba et al. 2013; Schroth et al. 2016a). This allocation strategy is consistent with high soil organic carbon in the wet zone, which likely enhanced nutrient availability and carbon-use efficiency, allowing high yields without substantial investment in woody biomass (Fig. 2) (Somarriba et al. 2013; Schroth et al. 2016a). In contrast, the mid climatic zone had the highest cocoa biomass carbon stock, coinciding with significantly higher cocoa DBH and plantation age, but lower yields than the wet zone (Table 1). These patterns indicate greater carbon retention in woody tissues, likely reflecting moderate seasonal water limitation that necessitate structural investment for hydraulic safety and resilience. The dry zone showed the lowest cocoa carbon stocks (22 ± 2 Mg C ha^{-1}) and yields (282 ± 34 kg ha^{-1} $year^{-1}$) despite comparable planting densities (Table 1). This suggests that water stress and soil conditions limited both growth and reproductive allocation, thereby constraining total carbon gains (Table 3). Overall, these results demonstrate that, high soil carbon availability and wetter climatic conditions promoted an allocation strategy favouring productivity in wet zone, whereas carbon was preferentially retained in woody biomass in mid climatic zone, and both productivity and carbon storage were likely constrained by water limitation in the dry zone.

Moreover, soil properties may have modulated both above- and belowground cocoa carbon stocks. The dry zone was characterized by coarse-textured soils with low soil organic matter, and total nitrogen, as well as higher bulk density (Table 1). These conditions tend to reduce water-holding capacity and nutrient retention, thereby constraining carbon gains and limiting both cocoa productivity and carbon storage (Lal 2004). Although soil pH and base saturation were high, leaching under sandy conditions likely reduced nutrient availability, reinforcing carbon limitation. Conversely, the mid zone exhibited a more balanced soil texture, higher cation exchange capacity, and greater nutrient availability (Table 1), creating conditions for sustained biomass accumulation and carbon retention in cocoa stems. The relatively

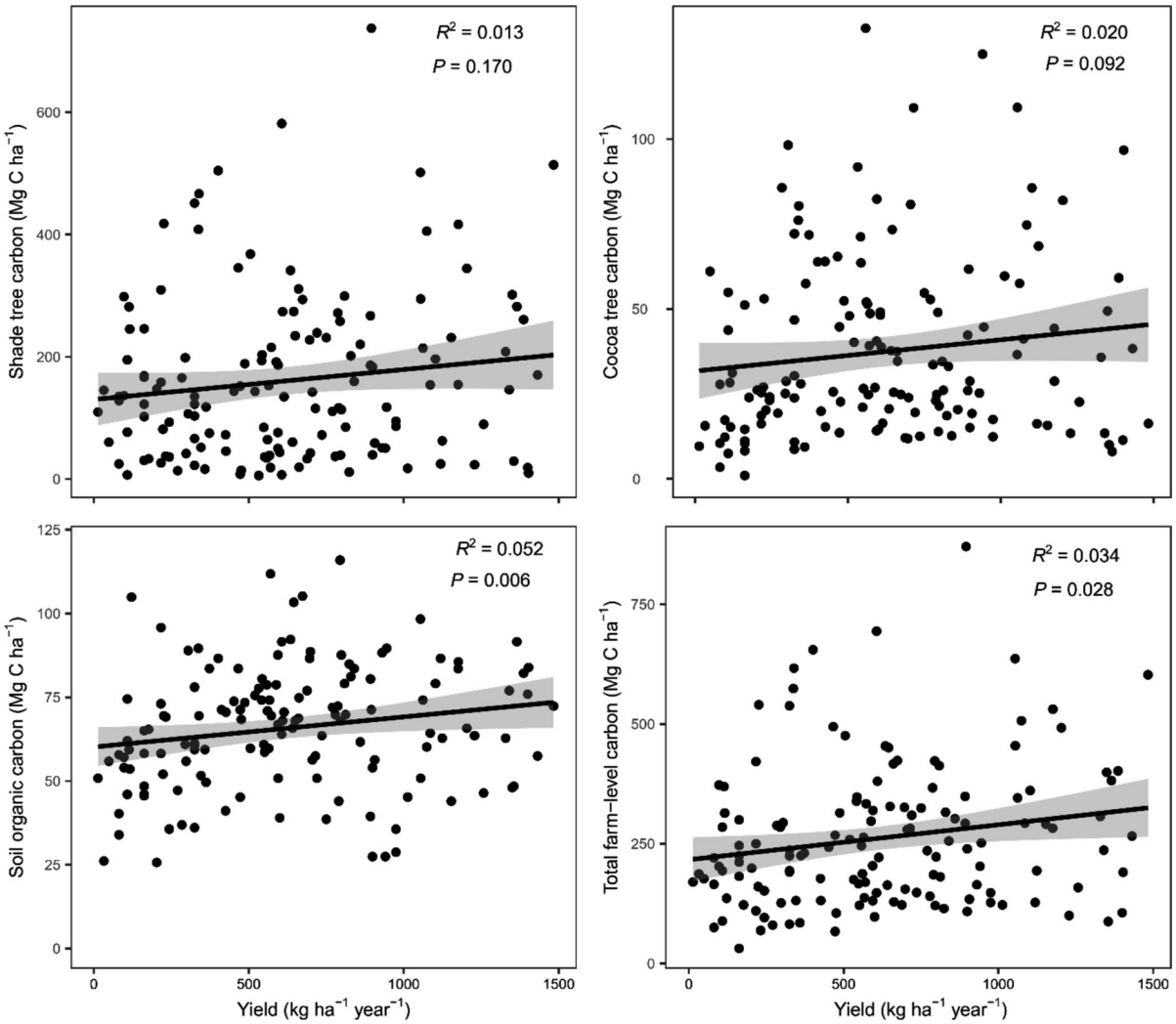


Fig. 4 Relationship between cocoa yield and carbon stocks (Spearman's correlation) in the cocoa agroforestry systems across the cocoa growing belt of Ghana. The lower panels show a significant positive relationship between yield and soil organic carbon or total farm-level carbon stocks (n = 150 farms in all the three climatic zones). Each point represents an individual cocoa agroforestry system

higher C:N ratio suggests slower organic matter turnover, consistent with greater carbon residence time in woody biomass (Six et al. 2002). Wet-zone soils were mostly fine-textured, with the highest soil organic matter, total nitrogen, and SOC stocks (Tables 1 and 3; Fig. 2). These conditions promote nutrient cycling and high productivity but also accelerate carbon turnover, which limits long-term biomass accumulation in the cocoa trees. Lower pH and reduced base saturation may further enhance microbial activity and organic matter decomposition, supporting carbon cycling into yield rather than storage in woody biomass (Gregorich et al. 2017) as was also observed at the system-level.

Climate-mediated soil organic carbon

Some earlier studies on SOC in cocoa agroforestry systems were not directly comparable to our study as they differed in their measured soil depth. For 0–30 cm soil depth, our measured soil organic carbon stocks (56–72 Mg C ha^{-1}) were within range of

values reported in conventional agroforestry systems (50–78) in Ghana (Asigbaase et al. 2020; Agbotui et al. 2023) and followed a clearer climatic signal than aboveground biomass, being significantly lower in the dry zone than in the mid and wet zones (Fig. 2; Table 3). Although the shade tree carbon stocks across zones were comparable in this study, the differing soil organic carbon stocks indicate that soil carbon dynamics were likely controlled by climate-mediated processes such as soil moisture availability, and organic matter decomposition rates than by tree biomass alone. Nonetheless, shade tree structure may have also played an indirect role (Table 1), thus, higher shade tree diversity and density in the dry zone may contribute to sustained litter inputs, but slower decomposition due to limited moisture may have constrained soil organic carbon accumulation. In contrast, wetter conditions in the mid and wet zones may have promoted greater SOC stabilization, allowing soils to retain more carbon even when shade tree biomass does not increase proportionally. This decoupling highlights the importance of considering both above- and belowground carbon pools when evaluating the climate change mitigation potential of cocoa agroforestry systems. The positive relationship between SOC and cocoa yield (Fig. 3) highlights the role of SOC not only as a climate mitigatable pool of carbon but also in soil fertility. However, because our soil carbon sampling was limited to the 0–30 cm depth, potential differences in deeper carbon pools across climatic zones may have been underestimated. Accordingly, we caution against extrapolating these findings to larger spatial scales in cocoa agroforestry systems.

Conclusions

Our study presented patterns of carbon stocks in smallholder cocoa agroforestry systems with data covering the current climatic gradient of the cocoa cultivation belt of Ghana; a major cocoa producing country second only to the Ivory Coast. In converse to our first hypothesis, our results showed that trade-offs in the structural characteristics of cocoa agroforestry systems resulted in large but comparable shade tree carbon stocks and total farm-level carbon stock despite variation in climatic conditions along the dry, mid, and wet zones. Yet, cocoa tree carbon and SOC stocks, which individually represent a smaller share of total carbon, varied across the climatic zones, this was attributable to the combined effects of climate, structural attributes, and soil properties. These results underscore the importance of shade trees as a relatively stable and climate-resilient carbon pool within smallholder cocoa agroforestry systems. They further suggest that, although cocoa trees themselves may contribute less to overall carbon storage, the agroforestry systems they constitute can store substantial amounts of carbon while simultaneously supporting cocoa production. Moreover, whereas the drier sandy soils in the dry zone constrained both carbon storage and productivity, fine-textured, organic-rich soils in the wet zone enhanced SOC and promoted rapid carbon allocation into yield rather than woody biomass. Consistent with our second hypothesis, neither total farm-level carbon nor shade tree carbon had negative effect on cocoa yield. The increasing ratio of cocoa yield to total plant carbon along the dry to wet climatic gradient suggests that the wet climatic zone enhanced the capacity of cocoa agroforestry systems to simultaneously support greater productivity and biomass carbon accumulation and thus showed greater potential for multifunctional agroforestry outcomes. Our data also suggest that while farmer decisions in the design and management of cocoa agroforestry systems may inadvertently lead to comparable carbon stocks in the dry as in the wetter climatic zones and thus offer greater benefit for climate change mitigation in the dry zone, observed yield gap and climate change projections may represent a significant economic challenge to farmers in this zone (Schroth et al. 2017; Abdulai et al. 2020). This may require the adoption of more drought-resistant cocoa breeds or the gradual transitioning to other cash crops. Intensification of cocoa agroforestry is therefore recommended for the mid and wet zones (Abdulai et al. 2020), in line with the proposed regional climate change adaptation strategy (Schroth et al. 2017).

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Authors' contributions RM, AI, MH, and RR conceptualized the study, AI, WAA collected the data, RM, AI, MH, and

OM analyzed the data, RM wrote the manuscript with contribution from all authors.

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Data availability Data for this study will be provided at a reasonable request to the authors.

Declarations

Conflict of interests The authors declare no competing interests.

Ethical approval Not applicable, as this study did not involve animal or human participants.

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References

Abdulai I, Vaast P, Hoffmann MP et al (2017) Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun. Glob Chang Biol 24:273–286. https://doi.org/10.1111/gcb.13885

Abdulai I, Jassogne L, Graefe S et al (2018) Characterization of cocoa production, income diversification and shade tree management along a climate gradient in Ghana. PLoS ONE 13:1–17. https://doi.org/10.1371/journal.pone.0195777

Abdulai I, Hoffmann MP, Jassogne L et al (2020) Variations in yield gaps of smallholder cocoa systems and the main determining factors along a climate gradient in Ghana. Agric Syst 181:102812. https://doi.org/10.1016/j.agsy.2020.102812

Abdulai I, Hoffmann M, Kahiluoto H et al (2025) Functional groups of leaf phenology are key to build climate-resilience in cocoa agroforestry systems. Agric Ecosyst Environ. https://doi.org/10.1016/j.agee.2024.109363

Adiyah F, Csorba Á, Dawoe E et al (2023) Soil organic carbon changes under selected agroforestry cocoa systems. Geoderma Reg. https://doi.org/10.1016/j.geodrs.2023.e00737

Afele JT, Dawoe E, Abunyewa AA et al (2021) Carbon storage in cocoa growing systems across different agroecological zones in Ghana. Pelita Perkeb (a Coffee Cocoa Res Journal) 37:32–49. https://doi.org/10.22302/iccri.jur.pelitaperkebunan.v37i1.395

Agbotui DK, Ingold M, Wiehle M, Buerkert A (2023) Can carbon payments improve profitability of traditional conventional and organic cocoa agroforests? A case study in the Eastern Region of Ghana. Agrofor Syst 97:813–831. https://doi.org/10.1007/s10457-023-00828-0

Albrecht A, Kandji ST (2003) Carbon sequestration in tropical agroforestry systems. Agric Ecosyst Environ 99:15–27. https://doi.org/10.1016/S0167-8809(03)00138-5

Amisah S, Gyampoh A, Sarfo-mensah P, Quagrainie K (2010) Livelihood trends in response to climate change in forest fringe communities of the Offin Basin in Ghana. J Appl Sci Environ Manag. https://doi.org/10.4314/jasem.v13i2.55294

Asante PA, Rozendaal DMA, Rahn E et al (2021) Unravelling drivers of high variability of on-farm cocoa yields across environmental gradients in Ghana. Agric Syst. https://doi.org/10.1016/j.agsy.2021.103214

Asare R (2006) A review on cocoa agroforestry as a means for biodiversity conservation. For Landsc Urban Plan 3:27–38

Asigbaase M, Dawoe E, Lomax B, Sjögersten S (2020) Biomass and carbon stocks of organic and conventional cocoa agroforests, Ghana. Agric Ecosyst Environ. https://doi.org/10.1016/j.agee.2020.107192

Beg MS, Ahmad S, Jan K, Bashir K (2017) Status, supply chain and processing of cocoa-a review. Trends Food Sci Technol 66:108–116

Bray RH, Kurtz LT (1945) Determination of total, organic, and available forms of phosphorus in soils. Soil Sci 59:39–45. https://doi.org/10.1097/00010694-194501000-00006

Bremner JM (1996) Total nitrogen. In: Bartels JM (ed) Methods of soil analysis, part 3 chemical methods. Science Society ofAmerica, Madison, USA, pp 1065–1121

Brown HCA, Berninger FA, Larjavaara M, Appiah M (2020) Above-ground carbon stocks and timber value of old timber plantations, secondary and primary forests in southern Ghana. For Ecol Manage 472:118236. https://doi.org/10.1016/j.foreco.2020.118236

Cannavo P, Sansoulet J, Harmand JM et al (2011) Agroforestry associating coffee and *Inga densiflora* results in complementarity for water uptake and decreases deep drainage in Costa Rica. Agric Ecosyst Environ 140:1–13. https://doi.org/10.1016/j.agee.2010.11.005

Carr MKV, Lockwood G (2011) The water relations and irrigation requirements of cocoa (*Theobroma cacao* L.): a review. Exp Agric 47:653–676. https://doi.org/10.1017/S0014479711000421

Chatterjee N, Nair PKR, Chakraborty S, Nair VD (2018) Changes in soil carbon stocks across the forest-agroforest-agriculture/pasture continuum in various agroecological regions: a meta-analysis. Agric Ecosyst Environ 266:55–67. https://doi.org/10.1016/j.agee.2018.07.014

Chave J, Andalo C, Brown S et al (2005) Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145:87–99. https://doi.org/10.1007/s00442-005-0100-x

Chave J, Coomes D, Jansen S et al (2009) Towards a worldwide wood economics spectrum. Ecol Lett 12:351–366. https://doi.org/10.1111/j.1461-0248.2009.01285.x

Chave J, Rejou-Mechain MI, Alberto B et al (2014) Improved allometric models to estimate the aboveground biomass of tropical trees. Glob Chang Biol. https://doi.org/10.1111/gcb.12629

Dawoe E, Asante W, Acheampong E, Bosu P (2016) Shade tree diversity and aboveground carbon stocks in *Theobroma cacao* agroforestry systems: implications for REDD+ implementation in a West African cacao landscape. Carbon Balance Manag. https://doi.org/10.1186/s13021-016-0061-x

Donegan E, Gael S, Cheng Z et al (2014) GlobAllomeTree's wood density database. Italy, Rome

Enquist BJ, Brown JH, West GB (1998) Allometric scaling of plant energetics and population density. Nature 395:163–165. https://doi.org/10.1038/25977

Fotiadis AK, Huan T-C (2022) Rural development. In: Encyclopedia of tourism management and marketing. Edward Elgar Publishing, pp 769–772

Gateau-Rey L, Tanner EVJ, Rapidel B et al (2018) Climate change could threaten cocoa production: effects of 2015-16 El Niño-related drought on cocoa agroforests in Bahia, Brazil. PLoS ONE 13:1–17. https://doi.org/10.1371/journal.pone.0200454

Gockowski J, Sonwa D (2011) Cocoa intensification scenarios and their predicted impact on CO2 emissions, biodiversity conservation, and rural livelihoods in the Guinea rain forest of West Africa. Environ Manage 48:307–321. https://doi.org/10.1007/s00267-010-9602-3

Green JK, Seneviratne SI, Berg AM et al (2019) Large influence of soil moisture on long-term terrestrial carbon uptake. Nature 565:476–479. https://doi.org/10.1038/s41586-018-0848-x

Gregorich EG, Janzen H, Ellert BH et al (2017) Litter decay controlled by temperature, not soil properties, affecting future soil carbon. Glob Chang Biol 23:1725–1734. https://doi.org/10.1111/gcb.13502

Higgins SI, Conradi T, Muhoko E (2023) Shifts in vegetation activity of terrestrial ecosystems attributable to climate trends. Nat Geosci 16:147–153. https://doi.org/10.1038/s41561-022-01114-x

Houghton RA (2005) Aboveground forest biomass and the global carbon balance. Glob Chang Biol 11:945–958. https://doi.org/10.1111/j.1365-2486.2005.00955.x

Humphrey V, Berg A, Ciais P et al (2021) Soil moisture–atmosphere feedback dominates land carbon uptake variability. Nature 592:65–69. https://doi.org/10.1038/s41586-021-03325-5

ICCO (2023) Quarterly Bulletin of Cocoa Statistics (QBCS). L-No.-1:

IPCC (2006) IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T., and Tanabe K. (eds). Published: IGES, Japan.

Isaac ME, Timmer VR, Quashie-Sam SJ (2007) Shade tree effects in an 8-year-old cocoa agroforestry system: biomass and nutrient diagnosis of *Theobroma cacao* by vector analysis. Nutr Cycl Agroecosyst 78:155–165. https://doi.org/10.1007/s10705-006-9081-3

Jagoret P, Michel I, Ngnogué HT, et al (2017) Structural characteristics determine productivity in complex cocoa agroforestry systems

Jose S (2009) Agroforestry for ecosystem services and environmental benefits: an overview. Agrofor Syst 76:1–10. https://doi.org/10.1007/s10457-009-9229-7

Kompas T, Che TN (2024) Grafton RQ (2024) Global impacts of heat and water stress on food production and severe food insecurity. Sci Reports 141(14):1–9. https://doi.org/10.1038/s41598-024-65274-z

Läderach P, Martinez-Valle A, Schroth G, Castro N (2013) Predicting the future climatic suitability for cocoa farming of the world's leading producer countries, Ghana and Côte d'Ivoire. Clim Change 119:841–854. https://doi.org/10.1007/s10584-013-0774-8

Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627. https://doi.org/10.1126/science.1097396

Lewis SL, Lopez-Gonzalez G, Sonké B et al (2009) Increasing carbon storage in intact African tropical forests. Nature 457:1003–1006. https://doi.org/10.1038/nature07771

Lewis SL, Sonké B, Sunderland T et al (2013) Above-ground biomass and structure of 260 African tropical forests. Philos Trans R Soc B Biol Sci. https://doi.org/10.1098/rstb.2012.0295

Lotz S, Hari B, Peter H, Dirk S (2026) Trade-off between yield and carbon storage in Nepali coffee agroforestry

Lynch JP (2022) Edaphic stress interactions: important yet poorly understood drivers of plant production in future climates. F Crop Res 283:108547. https://doi.org/10.1016/j.fcr.2022.108547

Manu R, Corre MD, Aleeje A et al (2022) Responses of tree growth and biomass production to nutrient addition in a semi-deciduous tropical forest in Africa. Ecology 103:e3659. https://doi.org/10.1002/ecy.3659

Manu R, Iddris NA, Corre MD et al (2024) Response of tropical forest productivity to seasonal drought mediated by potassium and phosphorus availabilifile:///C:/Users/Admin/Downloads/gtr_srs175_317.pdfty. Nat Geosci 17:1–8. https://doi.org/10.1038/s41561-024-01448-8

Miharza T, Wijayanto N, Roshetko JM, Siregar IZ (2023) Carbon stocks and footprints of smallholder cacao systems in Polewali Mandar, West Sulawesi. Front Environ Sci. https://doi.org/10.3389/fenvs.2023.680984

Mohammed AM, Robinson JS, Midmore D, Verhoef A (2016) Carbon storage in Ghanaian cocoa ecosystems. Carbon Balance Manag. https://doi.org/10.1186/s13021-016-0045-x

Monroe PHM, Gama-Rodrigues EF, Gama-Rodrigues AC, Marques JRB (2016) Soil carbon stocks and origin under different cacao agroforestry systems in Southern Bahia, Brazil. Agric Ecosyst Environ 221:99–108. https://doi.org/10.1016/j.agee.2016.01.022

Nimo E, Dawoe E, Afele JT (2021) A comparative study of carbon storage in two shade-types of cocoa and a teak plantation in the moist semi-deciduous forest zone of Ghana. PELITA Perkeb 37:50–61. https://doi.org/10.22302/iccri.jur.pelitaperkebunan.v37i1.448

Obeng EA, Aguilar FX (2015) Marginal effects on biodiversity, carbon sequestration and nutrient cycling of transitions from tropical forests to cacao farming systems. Agrofor Syst 89:19–35. https://doi.org/10.1007/s10457-014-9739-9

Otekunrin OA (2025) Mapping cocoa research (*Theobroma cacao* L.) in Africa: production, trade outlook, and scientometric insights. Discov Agric 3:1–24. https://doi.org/10.1007/s44279-025-00298-1

Padovan MP, Cortez VJ, Navarrete LF et al (2015) Root distribution and water use in coffee shaded with *Tabebuia rosea* Bertol. and *Simarouba glauca* DC. compared to full sun coffee in sub-optimal environmental conditions. Agrofor Syst 89:857–868. https://doi.org/10.1007/s10457-015-9820-z

Petersson H, Holm S, Ståhl G et al (2012) Individual tree biomass equations or biomass expansion factors for assessment of carbon stock changes in living biomass – a comparative study. For Ecol Manage 270:78–84. https://doi.org/10.1016/j.foreco.2012.01.004

Post WM, Kwon KC (2000) Soil carbon sequestration and land-use change: processes and potential. Glob Chang Biol 6:317–327. https://doi.org/10.1046/j.1365-2486.2000.00308.x

Pretzsch H (2009) Forest dynamics, growth and yield. Springer-Verlag, Berlin Heidelberg

Quesada CA, Phillips OL, Schwarz M et al (2012) Basin-wide variations in Amazon forest structure and function are mediated by both soils and climate. Biogeosciences 9:2203–2246. https://doi.org/10.5194/bg-9-2203-2012

Saj S, Jagoret P, Todem Ngogue H (2013) Carbon storage and density dynamics of associated trees in three contrasting *Theobroma cacao* agroforests of Central Cameroon. Agrofor Syst 87:1309–1320. https://doi.org/10.1007/s10457-013-9639-4

Schroth G, Jeusset A, Gomes AdaS et al (2016a) Climate friendliness of cocoa agroforests is compatible with productivity increase. Mitig Adapt Strateg Glob Change 21:67–80. https://doi.org/10.1007/s11027-014-9570-7

Schroth G, Läderach P, Martinez-Valle AI et al (2016b) Vulnerability to climate change of cocoa in West Africa: patterns, opportunities and limits to adaptation. Sci Total Environ 556:231–241. https://doi.org/10.1016/j.scitotenv.2016.03.024

Schroth G, Läderach P, Martinez-Valle AI, Bunn C (2017) From site-level to regional adaptation planning for tropical commodities: cocoa in West Africa. Mitig Adapt Strateg Glob Chang 22:903–927. https://doi.org/10.1007/s11027-016-9707-y

Schultz EB, Matney TG, Grebner DL (2008) A tree biomass and carbon estimation system. In: Proceedings of the 14th Biennial southern silvicultural research conference. USDA Forest service general technical report SRS-175, pp. 317–320. pp 317–324

Six J, Conant RT, Paul EA, Paustian K (2002) Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241:155–176. https://doi.org/10.1023/A:1016125726789

Slik JWF, Paoli G, Mcguire K et al (2013) Large trees drive forest aboveground biomass variation in moist lowland forests across the tropics. Glob Ecol Biogeogr 22:1261–1271. https://doi.org/10.1111/geb.12092

Smiley GL, Kroschel J (2008) Temporal change in carbon stocks of cocoa-gliricidia agroforests in Central Sulawesi, Indonesia. Agrofor Syst 73:219–231. https://doi.org/10.1007/s10457-008-9144-3

Solomon D, Fritzsche F, Lehmann J et al (2002) Soil Organic matter dynamics in the Subhumid agroecosystems of the Ethiopian Highlands : evidence from natural 13 C abundance and particle-size fractionation. Soil Sci Soc Am J 66:969–978

Somarriba E, Cerda R, Orozco L et al (2013) Carbon stocks and cocoa yields in agroforestry systems of Central America. Agric Ecosyst Environ 173:46–57. https://doi.org/10.1016/j.agee.2013.04.013

Steffan-Dewenter I, Kessler M, Barkmann J et al (2007) Tradeoffs between income, biodiversity, and ecosystem functioning during tropical rainforest conversion and agroforestry intensification. Proc Natl Acad Sci U S A 104:4973–4978. https://doi.org/10.1073/pnas.0608409104

Taylor PG, Cleveland CC, Soper F et al (2019) Greater stem growth, woody allocation, and aboveground biomass in Paleotropical forests than in Neotropical forests. Ecology 100:1–9. https://doi.org/10.1002/ecy.2589

Thomas G (1982) Exchangeable cations. In: Page AL (ed) Methods of soil analysis Part 2, chemical and microbiological methods, agronomy monograph No. 9 (2). ASA-SSSA, Madison, Wisconsin, pp 159–166

Toledo M, Poorter L, Peña-Claros M et al (2011) Climate is a stronger driver of tree and forest growth rates than soil and disturbance. J Ecol 99:254–264. https://doi.org/10.1111/j.1365-2745.2010.01741.x

Tscharntke T, Clough Y, Bhagwat SA et al (2011) Multifunctional shade-tree management in tropical agroforestry landscapes - A review. J Appl Ecol 48:619–629. https://doi.org/10.1111/j.1365-2664.2010.01939.x

van Straaten O, Corre MD, Wolf K et al (2015) Conversion of lowland tropical forests to tree cash crop plantations loses up to one-half of stored soil organic carbon. Proc Natl Acad Sci U S A 112:9956–9960. https://doi.org/10.1073/pnas.1504628112

Veldkamp E, Schmidt M, Markwitz C et al (2023) Multifunctionality of temperate alley-cropping agroforestry outperforms open cropland and grassland. Commun Earth Environ. https://doi.org/10.1038/s43247-023-00680-1

Wagner FH, Hérault B, Bonal D et al (2016) Climate seasonality limits leaf carbon assimilation and wood productivity in tropical forests. Biogeosciences 13:2537–2562. https://doi.org/10.5194/bg-13-2537-2016

Walkley A, Black IA (1934) An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci 37:29–38

Wu J, Liu W, Chen C (2016) Can intercropping with the world's three major beverage plants help improve the water use of rubber trees? J Appl Ecol 53:1787–1799. https://doi.org/10.1111/1365-2664.12730

Zanne AE, Lopez-Gonzalez, G. Coomes DA, Ilic J, et al (2009) Data from towards a worldwide wood economic spectrum

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