Discover Agriculture

Review

Agroforestry as an old approach to a new challenge of combating climate change: a critical analysis of the cocoa sector

James S. Kaba[1] · Ernest K. Agyei[1] · Mohan Krishna Chowdry Avilineni[2] · Fred A. Yamoah[3] · Ibrahim Issahaku[4] · Priscilla Ntiamoah[1] · Emmanuel Acquah[1] · Mustapha Mas-Ud[5]

Received: 19 December 2023 / Accepted: 7 November 2024
Published online: 14 November 2024

Abstract
Climate change is the greatest challenge to developing countries, especially where rain-fed agriculture is the main source of livelihood and revenue. Agroforestry provides an opportunity for farmers to adapt and reduce the carbon footprint. We conducted an exploratory review on the role of cocoa agroforestry for climate change mitigation and adaptation of smallholders by applying combinations of keywords that include climate change, agroforestry, stakeholders, Paris agreement, INDCs/NDCs, mitigation and adaptation. The paper combined data sources covering reports on past and on-going cocoa sustainability projects and policy interventions in Ghana as well as the output of exploratory review that utilized relevant key words to identify appropriate literature for investigation and analysis. We established that, there is low adoption of pro-environmental interventions introduced by both Government and NGOs in the cocoa sector. In addition, there is a shift in cocoa farming from expansion into forest areas to adoption of intensive cocoa monoculture. Despite the importance of shaded trees in cocoa production such as the benefits gained from agroforestry system, cocoa farmers have low appreciation of their environmental, soil, nutrients and other ecological benefits. We recommend that cocoa farmers should be involved in the formulation and implementation of pro-environmental interventions that affect their cocoa production practices. This will make farmers take ownership of the innovation instead of it being introduced to them. In addition, since our review of the literature established that the surge in yield is the impetus for cocoa monoculture adoption, there is the need to introduce cocoa varieties with higher yields under agroforestry system. Finally, there should be monetary valuation of shade trees used in cocoa agroforestry systems for payment to farmers to help improve agroforestry adoption. We argue that cocoa agroforestry though considered an old practice, remains one of the most appropriate land-use systems that is climate-smart with great potential to contribute to sustainable cocoa production.

Keywords Climate change · Adaptation · Mitigation · Agroforestry · Pro-environmental · Cocoa production

✉ James S. Kaba, jskaba@knust.edu.gh | [1]Faculty of Renewable Natural Resources, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. [2]Faculty of Science, Department of Food and Resource Economics, University of Copenhagen, Copenhagen, Denmark. [3]School of Business and Law, Buckinghamshire New University, High Wycombe, UK. [4]Anglican University College of Technology, Accra, Ghana. [5]Department of Agriculture Engineering, Faculty of Agriculture, Tamale Technical University, P. O. Box 3 ER, Tamale, Ghana.

1 Introduction

Climate change threatens the lives of many species, and it is exacerbated in developing nations where most of the people and economy depend on rainfed agriculture [1]. National and international efforts to tackle climate change led to the new agreement "Nationally Determined Contributions" (NDCs) by the "Parties to the United Nations Framework Convention on Climate Change" (UNFCCC) in 2015 [2]; a blueprint narrating mitigation and adaptation measures by each party with domestic or international aid. The approved long-term objective was to maintain the global temperature well below 2 °C, while also striving to limit it even further to under 1.5 °C [3].

According to Riyadh et al. [4] twenty-three countries have acknowledged the significance of agroforestry in achieving their NDCs mitigation targets, while twenty-nine countries have recognized it for adaptation purposes. Agroforestry is a system of land-use where woody perennials are deliberately planted or left with annual crops, and or livestock/pasture under the same management [5]. Agroforestry has been described as a new name for an old practice of land use, considering that even in Europe, it was a common practice until the Middle Ages to clear degraded forests, burn the slash, cultivate food crops for certain periods on the cleared land, and then plant or sow trees either before, during, or after the crop cultivation [6, 7].

Roy et al. [8]; Kaba et al. [9] and Lasco et al. [10] identified agroforestry as an effective approach to boost resilience against climate change and decrease the carbon footprint at the global and smallholder farmer level. For instance, agroforestry helps sequester carbon in soil and life-biomass, decreases emissions of greenhouse gases, and minimizes fossil fuel and energy use on farms [11, 12].

In addition, despite the competition between crops and trees, intercropping multipurpose trees with crops reduces the vulnerability of annual crops to climate extremes, mitigating the possibility of yield failure and increasing green cover [13]. Thus, making it an important climate smart approach in the Agricultural, Forestry and Other Land Use (AFOLU) sector. In contrast, traditional agriculture practices without trees, contribute significantly to the emission of greenhouse gases [14].

Therefore, this paper provides a perspective on how agroforestry could be used to combat the threat of climate change in the twenty-first century, especially in Africa where land degradation is a major problem.

In the rest of the paper, we examined the nexus between climate change impact and agroforestry mitigation and adaptation potential. A discussion on the potential of cocoa agroforestry as an approach to climate change mitigation and adaptation strategy for cocoa farmers. The critical analysis focused on the role of agroforestry in GHG mitigation with a link to the Nationally Determined Contributions (NDCs) using the cocoa sector in Ghana as an exemplar framework. The research findings and discussion as well as implication of the research findings are then presented.

2 Research approach

The paper utilized the review and analysis of data from non-governmental and government reports, published expert interviews and policy feedback literature to understand climate change and agroforestry interventions and policies on ecological sustainable cocoa production. Specifically, our data sources included reports on past and on-going cocoa sustainability projects in Ghana taken from websites of Ghana cocoa research institute, the national determined contribution status report of Ghana (from 2015 to 2021) and Non-Governmental Organizations (link to reports cited in references) such as Conservation Alliance, Forest Capital (2014–2024), CARE International, Cargill, International Fertilizer Development Center, SNV Project, Center of innovation and Technology Dissemination (CITED)-UENR, Ghana, and Nature Conservation and Research Centre. In addition, we supplemented our data with relevant online news data and specific reports on agroforestry, climate change, cocoa projects in Ghana such as the REDD + /enhancement of carbon-stocks ELCIR + project (2014–2018), Cocoa Rehabilitation and Intensification Programme (2014–2016), and Ghana Cocoa Platform (2013–2016). Sections of the 2013 technical report of the European Commission on the effect of European Union consumption on deforestation, the UNDP Green Commodities Programme (2013–2016) on sustainable ecological Policy for cocoa in Ghana, AfDB (Africa Development Bank) report on Government of Ghana cocoa rehabilitation project and the Ecobank Group (2015) Technical Report on cocoa production in West Africa were also used.

In search of the appropriate literature, we used keywords such as farmers, climate change, agroforestry, Paris agreement, INDCs/NDCs, UNFCCC, stakeholders/collaborations, mitigation, adaptation etc. Subsequently, we examined only the documents that focused on climate change and agroforestry to achieve sustainability in crops/cocoa production.

It also helped us outline key climate change policies within the agroforestry sector that could help influence farmers incorporate ecological sustainable farming technics in their cocoa production. In the next sections, we discussed in detail our findings based on the archival data review and analysis and its implications for theory and industry and policy.

3 The nexus between climate change impact and cocoa Agroforestry mitigation and adaptation potential

Climate change refers to significant long-lasting (at least 20–30 years) shift in global climate factors such as temperature, precipitation and wind patterns [15]. The change in climate is getting worse thus, there have been rise in temperature, change in rainfall patterns, and increase in carbon dioxide concentrations [16]. The most significant component causing these events is the increment in greenhouse gases (GHGs) concentration especially, carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) [17]. Over the past century, the usual global surface temperature has risen by 0.6 ± 0.12 °C, and it is projected to rise by 1.5–5.8 °C by the end of the twenty-first century [18].

Climate change poses risks including severe droughts, flooding and diseases, which can have extensive effects on agricultural systems leading to failure of crops, soil erosion, biodiversity loss, reduction in soil moisture, pest damages and economic losses [19]. The increasing rate of extreme events and unpredicted weather conditions are already making it difficult for farmers to plan planting and harvesting crops and this threatens the current production systems and heightening food insecurity [19].

However, agroforestry can help enhance crop resilience and reduce the adverse effect of climate change on crops and the life of farmers. Agroforestry has many advantages such as improving and conserving the fertility of soil and providing other ecological services (Fig. 1) that help improve the capacity of farmers at the smallholder, national and global level.

Carbon sequestration and micro-climate buffering all help to mitigate climate change and moderate the adversities of climate change [20]. For instance, Reppin et al. [21] assessed the carbon stock of agroforestry systems in Africa and found that it varied from 1.0 to 18.0 Mg C ha^{-1} and up to 105 Mg C ha^{-1} in the aboveground biomass, indicating that significant amount of carbon can be lost if the farmland trees are cleared or die and decompose.

In addition, under tree-based cocoa systems, the deep root systems facilitate the exploration of larger volume of soil for water and nutrients during droughts period, improves soil water infiltration and increases litter biomass on the soil surface. Likewise, under waterlogged conditions, tree-based agroforestry systems exhibit greater evapotranspiration

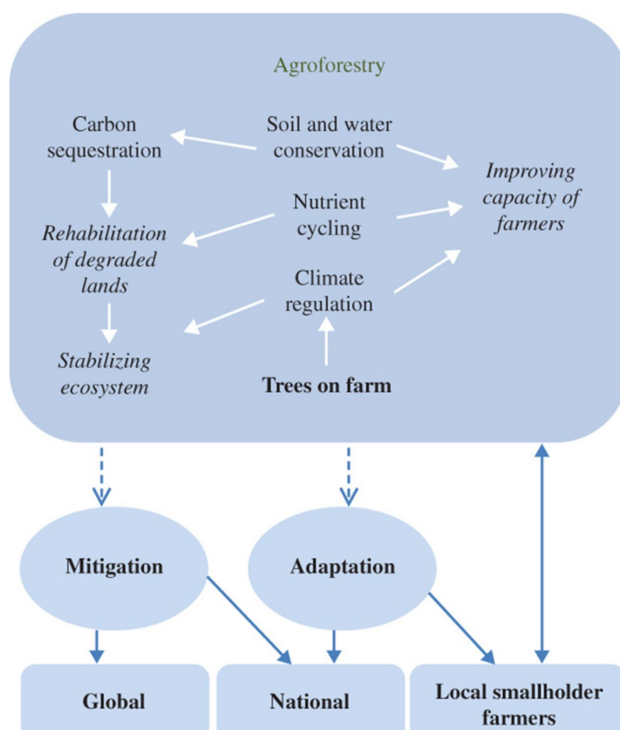

Fig. 1 Mitigation and adaptation of climate change in an agroforestry system (Adapted from Lasco [10])

rates than traditional sole cropping thus enabling rapid removal of excess water and maintaining well-aerated soil conditions [22].

However, intercropping cocoa with other trees in agroforestry system could create competition, which may be for light, water, or soil nutrients and this may reduce the growth and yield of cocoa trees [4, 9, 20]. In addition, black pod disease (*Phythphora palmivora*) of cocoa is reported to be favored by increased humidity due to increased shading [9]. It is important to highlight that, the removal of shade trees has also increased photosynthetic activity of cocoa trees, thereby increasing its productivity and yield [9, 23]. For example, Kaba et al. [9] found that farmers removed shade trees from their cocoa farms because, less shade improves yield, shade trees harvesting causes a lot of destruction to cocoa farms, farm activities such as weeding, spraying, fertilizer application is usually difficult to undertake when shade trees are present and shade trees occupy space meant for cocoa trees (reduces space for cocoa plants). In addition, other functions such as competition for applied nutrients, harbouring pests of cocoa and generally competition for all growth factors trigger de-shading. Therefore, proper tree species selection when farmers are integrating trees into cocoa at the beginning of cocoa farm establishment or selectively clearing and retaining some trees is essential.

4 Trajectory of Cocoa Agroforestry: analysis of Ghana's cocoa sector

West Africa accounts for over 70% of the world cocoa production, with Ghana being the second largest producer after Ivory Coast. Thick forests marked the early stages of cocoa production in West Africa and this condition was suitable for the inherent growth requirement of cocoa (Fig. 2). However, the production has faced many challenges due to the quick deforestation occurring at a rate of 2% per year [23, 24].

The archival analysis showed that since the introduction of cocoa in Ghana in the nineteenth century, the sector has been a major beneficiary of deforestation and land degradation [23, 24]. Despite the stagnating yield, Ghana's cocoa production has increased through the expansion of cocoa farms either through clearing forest or establishing cocoa farms on logged forest (about 1.6 million hectares under cocoa cultivation) motivated by a switch to full-sun/no shading system (25% of Ghana' cocoa area) compared to the initial retention or integration of woody perennials (Fig. 2) to form a cocoa agroforestry system [25].

For example, records of deforestation show that when cocoa was introduced into Ghana in 1900, approximately 34% of Ghana's land area (8.2 million ha) was covered by natural high rainforest [23]. However, from 1981 to 1985 only 21% of the 8.2 million hectares (ha) remained as protected reserves while the remaining 6.5 million hectares were deforested at the rate of 22,000 ha per annum (0.3%). By the year 2000, the situation had deteriorated as 67% of the original 8.2 million ha had been lost, at a deforestation rate of 115,400 ha per annum.

The status quo remains unchanged, as the Ghana Forestry Commission and the Ghana Cocoa Board reported a 10-year (2000–2010) deforestation rate of 1.4% annually in forest zones of Ghana where cocoa is widely cultivated [26].

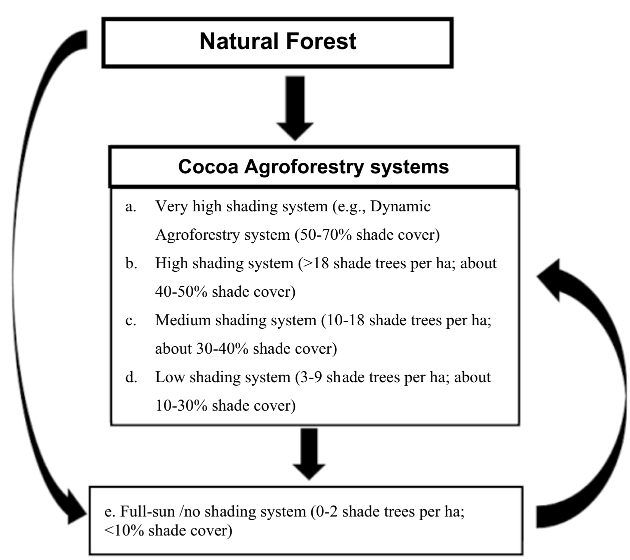

Fig. 2 Pathway to current cocoa production systems in Ghana (Agroforestry Systems indicating a gradient of declining shade levels: Authors concept based on shade trees recommendation)

The motivation driving farmers' adoption of unshaded cocoa system and the reduction of tree cover on cocoa farms in Ghana can be attributed to the general mentality about the poor yield caused by the presence or integration of woody perennials under an agroforestry system [9]. Even though cocoa yield in monocropping system could be higher than in agroforestry systems [27], it is important to point out that it varies, especially with the type of shade trees intercropped with the cocoa, location and density of shade trees. In most cases, cocoa agroforestry system though provides lower yield than monocropping system offer other benefits such as maintain the soil properties/fertility, increase biodiversity, provide extra income and food products from the intercropped crops and store larger amounts of carbon [27].

This expansionist approach of forest clearance has devastating consequences by exposing the cocoa to the thread of climate change due to higher temperatures and drought which cause flower and premature fruit drop, stunted growth and lower yield [28].

Considering the significant role the cocoa sector plays in Ghana's forest management, the acceptance of cocoa agroforest, either through the integration of trees with cocoa or the preservation of permanent trees in newly cultivated cocoa farms, could contribute to helping Ghana achieve its emission reduction goal (unconditionally) of 15% relative to a business-as-usual (BAU) scenario emission of 73.95 MtCO2e2 by 2030.

5 Research findings and discussion

Promoting REDD + ("Reducing Emissions from Deforestation and forest Degradation"; the " + " implies the role of conservation, sustainable management of forests and enhancement of forest carbon stocks) in the AFOLU sector, especially agroforestry in cocoa systems constitute a major policy to attain both mitigation and adaptation objectives. However, the majority of cocoa farmers in Ghana currently employ methods that raise concerns regarding their ability to reduce GHGs, as they continue to grow cocoa in monocultures under the full sun owing to the surge in yield within 20 years of establishment [9, 23]. For example, in Ghana, out of the 1.6 million hectares of land under cocoa cultivation about 400,000 hectares (less than 25%) are covered by shaded cocoa agroforestry [29].

These figures emphasize the worsening repercussions of farmers' decision to produce cocoa in way which may compromise the anticipated NDCs associated with the AFOLU sector.

Ironically, cocoa is extremely vulnerable to climate change, and recent research indicates that most cocoa growing regions of Africa, where over 60% of the world's cocoa is produced may no longer support the cultivation of cocoa by 2050 due to changing climate [30]. For instance, precipitation will reduce by 11% by 2050 and 19% in the year 2080, whilst daily temperatures will increase by 1.1ºC to 6.4 °C [23, 31]. The cumulative effect is the projected drop in cocoa yield by 28% in 2050 or even earlier [23, 29].

A current limitation in the cocoa industry is how major players in the cocoa sector can explore varied opportunities to peruse the low interest of cocoa farmers in adopting innovations which are considered pro-environmental (e.g., shaded cocoa system). Generally, farmers are less concerned of the environmental, climate, soil, nutrients and other ecological benefits of shade trees when integrating them into their cocoa farms [9]. In the case of Ghana, this opportunity is underscored in Ghana's National Agroforestry Policy; which has the overall objective to promote agroforestry practices for sustainable land use [32]. Therefore, partnership among farmers and other stakeholders (i.e., stakeholders-collaboration) in the cocoa sector (Both Governments and NGOs) holds great potential in promoting the adoption of the cocoa shaded system and contributing to the reduction of GHG. Previous studies by Yamoah et al. [25] raised concerns on the danger of having a majority of the climate smart cocoa initiatives solely led by Government institutions without the involvement of farmers and community-based NGOs in the cocoa sector.

Therefore, we developed a framework (Fig. 3) that assesses the current possible cocoa production systems and situating it with initiatives to provide a pathway to the adoption of cocoa agroforestry system and its subsequent contribution to climate change mitigation. This framework is essential in cocoa extension education especially taking into consideration the need for stakeholders' collaboration.

More importantly, engaging other stakeholders apart from cocoa farmers could help in raising the needed finance required to implement activities under the AFOLU sector [33].

Fortunately, some NGOs have already started some projects aimed at reducing GHS and enhancing carbon sinks in the cocoa sector. For instance, Fairtrade Africa, Max Havelaar France and the French Development Agency (AFD France) launched the Ghana Agroforestry for Impact (GAIM) Project aimed to help provide tools to farmers to fight against the adverse effects of climate change, their dependence on the sole commodity of cocoa and against ageing cocoa farms through dynamic agroforestry techniques [34].

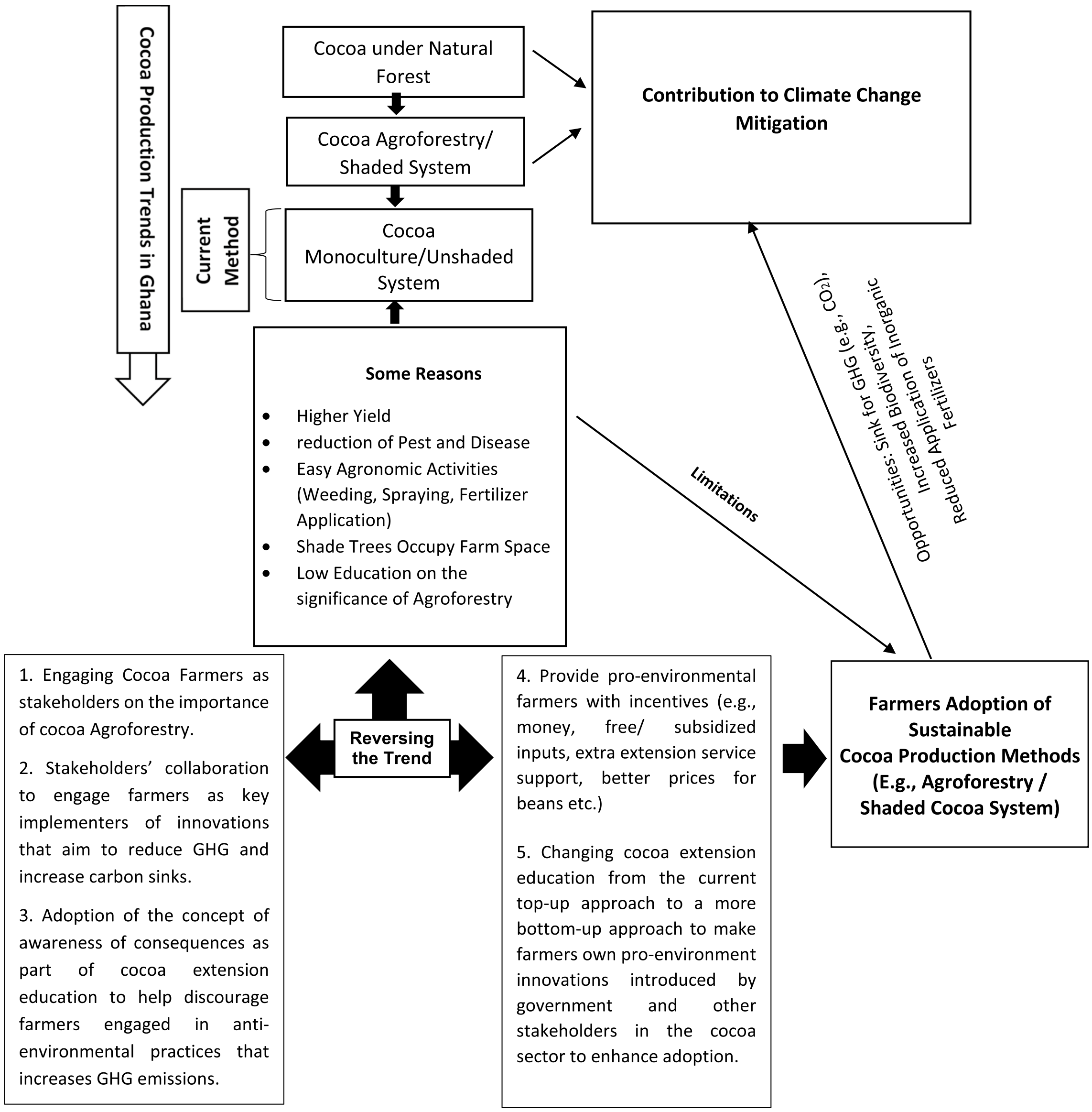

Fig. 3 Framework Towards Achieving Climate Change Mitigation through Cocoa Agroforestry System and Stakeholders' Collaboration

The importance of our framework (Fig. 3) highlights the findings of Kaba et al. [9] who reported that farmers were willing to integrate trees with their cocoa if they are well educated on the indirect benefits (e.g., climate mitigation) and provided with the needed incentives (money, inputs and extension support, better prices for beans). Therefore, cocoa extension needs to draw on the concept of awareness of consequences as part of its cocoa extension education as it is envisaged that if farmers are engaged to appreciate the importance of pro-environmental behavior it could influence their decision to practice shaded cocoa agroforestry system and other activities aimed at reducing GHS [35]. In addition, considering that most farmers are not oblivious of the positive impact of agroforestry but are reluctant to practice it [9], underlines the need to question the orthodox (top-down) method [36] of disseminating or promoting innovations such as agroforestry technique. Furthermore, considering the fact that there are varied reports on yield differences in cocoa agroforestry and monocropping systems (Table 1), it is important to point out that, cocoa agroforestry systems provide other benefits (Table 1) that makes it a more sustainable approach to cocoa production.

In conclusion, based on the above discussion our perspective is that cocoa agroforestry though considered an old practice, remains one of the most appropriate land-use systems that is climate-smart with great potential to contribute to sustainable cocoa production. However, there is the need to enhance collaboration and engagement with farmers and other stakeholder (e.g., the chocolate and confectionery industry and pro-environmental NGOs). In addition,

Table 1 Trade-off in the choice of land use system for cocoa production

Indicator	Trade-off in the choice of cocoa agroforestry system (AFS) and monocropping system (MCS)
Yield	i. Average yield for five cropping seasons was higher in the MCS (751 kg/ha) than the AFS (564 kg/ha) in Ghana, but after 5 years, yield was similar (av. 650 kg/ha) [35] ii. Cocoa AFS with *Khaya ivorensis* as shade trees increased yield to about 608 kg ha^{-1} compared to 438 ha^{-1} in MCS, with 38.8% higher yield observed in shaded plots compared to unshaded plots [37] iii. Cocoa yield was lower (0.6 Mg ha^{-1}) in AFS compared to 0.9 Mg ha^{-1} in MCS [38] iv. The average cocoa yield in simple agroforestry system (SAFS) was 2.3% less than cocoa monocultures but the most productive SAFS were associated with *Elaeis guineensis* and *Cordia alliodora*. The yield was even much lower (40% less than cacao monocrops) in the complex agroforestry systems (CAFS) where there were more than 3 shade trees per ha [27] v. Cocoa of 10–20 years MCS gave higher yield (av. 2000 kg ha^{-1}) compared to AFS (1500 kg ha^{-1}) [39, 40] vi. Under low input conditions (of fertilizer and pesticides) AFS increased yields (548 kg ha^{-1}) compared to MCS (Av. 400 kg ha^{-1}) [41] vii. Under high input fertilizer, higher cocoa yield was reported under MCS compared to AFS in a pioneering long-term study of the relation between shade and cocoa nutrition [42] viii. MCS require more fertilizer than shaded ones, and lack of fertilizers, especially P, will cause a decline in yield in less than 10 years [43]
Soil fertility and Biodiversity enhancement	i. Cocoa-Gliricidia AFS can fix 31.4 to 39 kg N ha^{-1} from the atmosphere as additional source of nitrogen [44] ii. In AFS there is increased uptake of nitrogen (43–80%), phosphorus (22–45%) and potassium (96–140%) by cocoa trees compared to MCS [45] iii. No significant differences were observed between AFS and MCS in terms of soil concentrations of total nitrogen, exchangeable potassium, calcium and magnesium [42] iv. In AFS, shade trees buffer high and low temperature extremes by as much as 5 °C and can produce up to 14 Mg ha^{-1} yr^{-1} of litterfall and pruning residues, containing up to 340 kg N ha^{-1} yr^{-1} [46] v. Shade trees in AFS could compete for growth resources (e.g., nutrients) with cocoa trees [47] vi. Cocoa in MCS requires high inputs (fertilization) and management to maintain productivity [56] vii. AFS plays major roles in conserving biodiversity by providing habitat and preserving genetic resources of sensitive species compared to MCS [48] viii. AFS provide habitat for functionally more diverse species communities because they are structurally more complex and diverse than MCS [49]
Carbon storage and system sustainability	i. About 14–52 Mg C ha^{-1} is stored in the aboveground woody biomass of shade trees in coffee and cocoa plantations. Cocoa trees themselves store 7.45 t C/ha while shade trees also stored an additional 12.3t, 29.43t, 38t and 50.85t of C in low shade, shaded, high shade and very high shade cocoa AFS respectively [50] ii. Cocoa AFS contributed to climate change mitigation by storing 2.5 times more carbon and to adaptation by lowering mean temperatures and buffering temperature extremes than MCS [38] iii. In AFS shade trees reduce environmental stress and increase the life span of the cocoa trees for 60–100 years. However, under MCS, there is initial increase in yield due to overbearing of fruits reducing the productivity of the trees to less than 25 years [51] iv. Unlike MCS, cocoa AFS usually leads to higher incident of pest and disease, and destruction of farms especially when branches fall or timber species are harvested [9] v. Incidence of cocoa pod borer (*Conopomorpha cramerella*) was lower in the AFS, especially the high-diversity system, while the incidence of black pod disease (*Phytophthora spp*.) did not differ between AFS and MCS [52] vi. AFS may provide internal control mechanisms for cocoa pests (pod borer, mirids) through the increased presence of antagonists and reduced stress of cacao trees but pathogens like Phytophthora that benefit from humidity can show a higher prevalence in AFS than MCS [53] vii. Cocoa tree development in AFS can be slower compared to MCS [49]
Living income and Livelihood	i. AFS provide diverse products like fuel wood, timber, food, medicines and animal fodder compared to single product or service function provided by cocoa MCS [54] ii. Reduced cacao tree development and yield in the high-diversity AFS were compensated by additional harvests of cassava and banana compared to MCS [52] iii. Low input, high-diversity AFS have the potential to increase nutrition, food security and income of smallholders and represent a feasible option to support farmers during the first years of establishment, when cacao harvests are lacking compared to MCS [55]

incorporating the concept of awareness of consequences into cocoa extension education could help farmers reduce their adoption of environmentally unsustainable practices that increase GHG emissions. Finally, the top-down strategy for cocoa extension education must be changed to a more bottom-up approach so that farmers can take ownership for the decisions towards adoption of pro-environment innovations.

Author contributions James S. Kaba; Fred Yamoah; Mohan Krishna Chowdry Avilineni; Ernest K. Agyei conceived the ideas and designed methodology; James S. Kaba; Fred Yamoah; Mohan Krishna Chowdry Avilineni; Ernest K. Agyei; Ibrahim Issahaku; Priscilla Ntiamoah, Mustapha Mas-Ud and Emmanuel Acquah reviewed the literature, analyzed the content. James S. Kaba; Fred Yamoah; Mohan Krishna Chowdry Avilineni; Ernest K. Agyei wrote the first draft of the paper Ibrahim Issahaku; Priscilla Ntiamoah, Mustapha Mas-Ud and Emmanuel Acquah reviewed and edited the first draft of the paper. All authors contributed critically to the drafts and gave final approval for publication.

Funding No funds, grants, or other support was received.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

1. Raihan A, Muhtasim DA, Pavel MI, Faruk O, Rahman M. An econometric analysis of the potential emission reduction components in Indonesia. Clean Prod Lett. 2022;3:100008.
2. Matemilola S, Fadeyi O, Sijuade T. Paris agreement. Encyclopedia of sustainable management. Cham: Springer; 2020. p. 1–5.
3. Zheng J, Duan H, Zhou S, Wang S, Gao J, Jiang K, Gao S. Limiting global warming to below 1.5 C from 2 C: an energy-system-based multi-model analysis for China. Energy Econ. 2021;100:105355.
4. Riyadh ZA, Rahman MA, Saha SR, Ahamed T, Current D. Adaptation of agroforestry as a climate smart agriculture technology in Bangladesh. Int J Agric Res, Innov Technol. 2021;11(1):49–59.
5. Santoro A. Traditional oases in Northern Africa as multifunctional agroforestry systems: a systematic literature review of the provided Ecosystem Services and of the main vulnerabilities. Agrofor Syst. 2022;97:1–16.
6. King KFS. The history of agroforestry. Agroforestry: a decade of development, 1987. 111.
7. Wood PJ, Burley J. A tree for all reasons: introduction and evaluation of multipurpose trees for agroforestry. Nairobi: International Centre for Research in Agroforestry (ICRAF); 1991.
8. Roy T, Kalambukattu JG, Biswas SS, Kumar S. Agro-climatic variability in climate change scenario: adaptive approach and sustainability. In: Ecological footprints of climate change: adaptive approaches and sustainability. Cham: Springer International Publishing; 2023. p. 313–48.
9. Kaba JS, Otu-Nyanteh A, Abunyewa AA. The role of shade trees in influencing farmers' adoption of cocoa agroforestry systems: insight from semi-deciduous rain forest agroecological zone of Ghana. NJAS-Wagening J Life Sci. 2020;92:100332. https://doi.org/10.1016/j.njas.2020.100332.
10. Lasco RD, Delfino RJP, Espaldon MLO. Agroforestry systems: helping smallholders adapt to climate risks while mitigating climate change. Wiley Interdiscip Rev: Clim Change. 2014;5(6):825–33.
11. Dinesh GK, Sinduja M, Priyanka B, Sathya V, Karthika S, Meena RS, Prasad S. Enhancing soil organic carbon sequestration in agriculture: plans and policies. In: Plans and policies for soil organic carbon management in agriculture. Singapore: Springer Nature Singapore; 2022. p. 95–121.
12. Abdulraheem KA, Adeniran JA, Aremu AS. Carbon and precursor gases emission from forest and non-forest land sources in West Africa. Int J Environ Sci Technol. 2022;19(12):12003–18.
13. Dhyani SK, Nayak D, Rizvi J. Historical development of Agroforestry and overview of global agroforestry systems. Training Lecture Notes, 2019. 16.
14. Nunes LJ, Meireles CI, Pinto Gomes CJ, Almeida Ribeiro NM. Forest contribution to climate change mitigation: management oriented to carbon capture and storage. Climate. 2020;8(2):21.
15. Fakana ST. Causes of climate change. Glob J Sci Front Res: H Environ Earth Sci. 2020;20(2):7–12.

16. Kinney PL. Indoor air quality in the context of climate change. In: Handbook of indoor air quality. Singapore: Springer Nature Singapore; 2022. p. 2145–62.
17. Wuebbles DJ. Climate science special report: 4th US National Climate Assessment, Volume I. In: World scientific encyclopedia of climate change: case studies of climate risk, action, and opportunity, vol. 2. Singapore: World Scientific; 2021.
18. Masson-Delmotte V, Zhai P, Pörtner HO, Roberts D, Skea J, Shukla PR. Global warming of 1.5 C: IPCC special report on impacts of global warming of 1.5 C above pre-industrial levels in context of strengthening response to climate change, sustainable development, and efforts to eradicate poverty. Cambridge: Cambridge University Press; 2022.
19. Nhemachena C, Nhamo L, Matchaya G, Nhemachena CR, Muchara B, Karuaihe ST, Mpandeli S. Climate change impacts on water and agriculture sectors in Southern Africa: threats and opportunities for sustainable development. Water. 2020;12(10):2673.
20. Awazi NP. Agroforestry for climate change adaptation, resilience enhancement and vulnerability attenuation in smallholder farming systems in Cameroon. J Atmos Sci Res. 2022. https://doi.org/10.30564/jasr.v5i1.4303.
21. Reppin S, Kuyah S, de Neergaard A, Oelofse M, Rosenstock TS. Contribution of agroforestry to climate change mitigation and livelihoods in Western Kenya. Agrofor Syst. 2020;94:203–20.
22. Gifawesen ST, Tola FK, Duguma MS. Review on role of home garden agroforestry practices to improve livelihood of small-scale farmers and climate change adaptation and mitigation. J Plant Sci. 2020;8(5):134–45.
23. UNDP. Environmental Baseline Report on Cocoa in Ghana. 2011. PP 144.
24. Asubonteng K, Pfeffer K, Ros-Tonen M, Verbesselt J, Baud I. Effects of tree crop farming on land-cover transitions in a mosaic landscape in the eastern region of Ghana. Environ Manage. 2018;62:529–47. https://doi.org/10.1007/s00267-018-10603.
25. Yamoah FA, Kaba JS, Amankwah-Amoah J, Acquaye A. Stakeholder collaboration in climate-smart agricultural production innovations: insights from the cocoa industry in Ghana. Environ Manage. 2020;66:600–13. https://doi.org/10.1007/s00267-020-01327-z1-14.
26. GoG. Emission reductions program idea note. Ghana's emission reductions program for the cocoa forest mosaic landscape. Accra: Forest Carbon Partnership Facility Carbon Fund. 2014. Pp 1–3. https://www.forestcarbonpartnership.org/system/files/documents/Ghana%20Summary.pdf. Accessed 1 Nov 2020.
27. Mattalia G, Wezel A, Costet P, Jagoret P, Deheuvels O, Migliorini P, David C. Contribution of cacao agroforestry versus mono-cropping systems for enhanced sustainability. A review with a focus on yield. Agrofor Syst. 2022;96(7):1077–89. https://doi.org/10.1007/s10457-022-00765-4.
28. CRIG, W. Report on Land Tenure and Cocoa Production in Ghana. USAID. GO V pp49. 2017.
29. Somarriba E, López Sampson A. Coffee and cocoa agroforestry systems: pathways to deforestation, reforestation, and tree cover change. 2018. https://doi.org/10.13140/RG.2.2.29700.78724
30. Läderach P, Martinez-Valle A, Schroth G, Castro N. Predicting the future climatic suitability for cocoa farming of the world's leading producer countries Ghana and Côte d'Ivoire. Clim Change. 2013;119(3–4):841–54. https://doi.org/10.1007/s10584-013-0774-8.
31. Asante FA, Amuakwa-Mensah F. Climate change and variability in Ghana: stocktaking. Climate. 2014;3(1):78–101.
32. MOFA, AFU. The national agroforestry policy. Accra: Ministry of Food and Agriculture Accra; 1986.
33. Ghana NDCs report. Ghana's intended nationally determined contribution (INDC) and accompanying explanatory note. 2015. https://www.fao.org/faolex/results/details/en/c/LEX-F%20AOC187060/. Accessed 20 Oct 2020.
34. Joy news Agribusiness Report. Fairtrade Africa and partners launch Ghana Agroforestry for Impact Project. 2024. https://www.myjoyonline.com/fairtrade-africa-and-partners-launch-ghana-agroforestry-for-impact-project/). Accessed 25 May 2024.
35. Yamoah FA, Kaba JS, Botchie D, Amankwah-Amoah J. Working towards sustainable innovation for green waste benefits: the role of awareness of consequences in the adoption of shaded cocoa agroforestry in Ghana. Sustainability. 2021;13(3):1453.
36. Wartenberg AC, Blaser WJ, Janudianto KN, Roshetko JM, van Noordwijk M, Six J. Farmer perceptions of plant–soil interactions can affect adoption of sustainable management practices in cocoa agroforests. Ecol Soc. 2018. https://doi.org/10.5751/ES-09921-230118.
37. Asitoakor BK, Vaast P, Ræbild A, Ravn HP, Eziah VY, Owusu K, Asare R. Selected shade tree species improved cocoa yields in low-input agroforestry systems in Ghana. Agric Syst. 2022;202:103476. https://doi.org/10.1016/j.agsy.2022.103476.
38. Niether W, Jacobi J, Blaser WJ, Andres C, Armengot L. Cocoa agroforestry systems versus monocultures: a multi-dimensional meta-analysis. Environ Res Lett. 2020;15(10):104085.
39. Ngala TJ. Effect of shade trees on cocoa yield in small-holder cocoa (Theobroma cacao) agroforests in Talba, centre Cameroon. Dschang: University of dschang; 2015.
40. Quainoo-Mensah F, Afele JT, Gorleku DO. Cocoa agroforestry systems and yield dynamics within the Offinso Municipality of Ghana. Pelita Perkebunan (Coffee Cocoa Res J). 2023;39(2):129–40.
41. Asitoakor BK, Ræbild A, Vaast P, Ravn HP, Owusu K, Mensah EO, Asare R. Shade tree species matter: sustainable cocoa-agroforestry management. In: Agroforestry as climate change adaptation: the case of cocoa farming in Ghana. Cham: Springer International Publishing; 2023. p. 59–92.
42. Ahenkorah Y, Halm BJ, Appiah MR, Akrofi GS, Yirenkyi JEK. Twenty years' results from a shade and fertilizer trial on Amazon cocoa (Theobroma cacao) in Ghana. Exp Agric. 1987;23(1):31–9.
43. Ahenkorah Y, Akrofi GS, Adri AK. The end of the first cocoa shade and manorial experiment at the Cocoa Research Institute of Ghana. J Hortic Sci. 1974;49(1):43–51.
44. Kaba JS, Zerbe S, Agnolucci M, Scandellari F, Abunyewa AA, Giovannetti M, Tagliavini M. Atmospheric nitrogen fixation by gliricidia trees (Gliricidia sepium (Jacq.) Kunth ex Walp.) intercropped with cocoa (Theobroma cacao L.). Plant Soil. 2019;435:323–36.
45. Isaac ME, Timmer VR, Quashie-Sam SJ. Shade tree effects in an 8-year-old cocoa agroforestry system: biomass and nutrient diagnosis of Theobroma cacao by vector analysis. Nutr Cycl Agroecosyst. 2007;78:155–65.
46. Beer J, Muschler R, Kass D, Somarriba E. Shade management in coffee and cacao plantations. Agrofor Syst. 1998;38:139–64.
47. Blaser WJ, Oppong J, Hart SP, Landolt J, Yeboah E, Six J. Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. Nat Sustain. 2018;1(5):234–9. https://doi.org/10.1038/s41893-018-0062-8.
48. Josre S. Agroforestry for ecosystem services and environmental benefits. Agrofor Syst. 2009;76:1–10.
49. Schneider M, Andres C, Trujillo G, Alcon F, Amurrio P, Perez E, Milz J. Cocoa and total system yields of organic and conventional agroforestry vs. monoculture systems in a long-term field trial in Bolivia. Exp Agric. 2017;53(3):351–74.

50. Kürsten E, Burschel P. CO2-mitigation by agroforestry. Water Air Soil Pollut. 1993;70:533–44.
51. Jacobi J, Schneider M, Bottazzi P, Pillco M, Calizaya P, Rist S. Agroecosystem resilience and farmers' perceptions of climate change impacts on cocoa farms in Alto Beni Bolivia. Renew Agric Food Syst. 2015;30(2):170–83.
52. Riedel J, Kägi N, Armengot L, Schneider M. Effects of rehabilitation pruning and agroforestry on cacao tree development and yield in an older full-sun plantation. Exp Agric. 2019;55(6):849–65. https://doi.org/10.1017/S0014479718000431.
53. Abdulai I, Vaast P, Hoffmann MP, Asare R, Jassogne L, Van Asten PJ, Graefe S. Cocoa agroforestry is less resilient to suboptimal and extreme climate than cocoa in full sun: reply to Norgrove 2017. Glob Change Biol. 2018. https://doi.org/10.1111/gcb.14044.
54. Belsky JM, Siebert SF. Cultivating cacao implications of sun-grown cacao on local food security and environmental sustainability. Agric Hum Values. 2003;20:277–85.
55. Leakey RRB, Tchoundjeu Z. Diversification of tree crops: domestication of companion crops for poverty reduction and environmental services. Exp Agric. 2001;37(3):279–96.
56. Waarts YR, Janssen V, Ingram VJ, Slingerland MA, van Rijn FC, Beekman G, ... van Vugt SM. A living income for smallholder commodity farmers and protected forests and biodiversity: how can the private and public sectors contribute? White Paper on sustainable commodity production (No. 2019-122). Wageningen Economic Research; 2019.