GRK 2654
Sustainable Food Systems

RTG 2654 Sustainable Food Systems

University of Goettingen

SustainableFood Discussion Papers

No. 24

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March 2025

RTG 2654 Sustainable Food Systems · Heinrich Düker Weg 12 · 37073 Göttingen · Germany
www.uni-goettingen.de/sustainablefood

ISSN (2750-1671)

Suggested Citation

Wätzold, M. Y. L., K. Krumbiegel, M. Wollni (2025). Agroforestry as a Climate Change Adaptation Strategy: Evidence from Ghana’s Cocoa Sector. SustainableFood Discussion Paper 24, University of Goettingen.

Imprint

SustainableFood Discussion Paper Series (ISSN 2750-1671)

Publisher and distributor:
RTG 2654 Sustainable Food Systems (SustainableFood) – Georg-August University of Göttingen
Heinrich Düker Weg 12, 37073 Göttingen, Germany

Agroforestry as a Climate Change Adaptation Strategy: Evidence from Ghana's Cocoa Sector

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Abstract: Climate change is intensifying extreme weather events such as droughts and extreme temperatures, threatening agricultural systems. In sub-Saharan Africa, where most farmers rely on rain-fed agriculture, the impacts are particularly severe. Agroforestry practices have the potential to provide a viable climate change adaptation strategy for many farmers. The ecological and economic benefits of agroforestry systems have been well studied, yet the extent to which agroforestry can enhance resilience towards adverse weather events at the household level, such as drought, remains largely unknown. Using a two-wave panel data set of 365 cocoa producing households and publicly available satellite climate data, we investigate whether the effect of drought differs between agroforestry adopters and non-adopters. We find that on average, agroforestry adopters are less severely affected by reduced rainfall. However, when disaggregating between regions that differ in climatic suitability, we find that this effect holds only in regions that are climatically suitable for cocoa production. In contrast, we do not find any significant effects in less suitable regions, where farmers are more prone to drought stress. Our findings suggest that agroforestry can serve as a climate adaptation strategy, though future research is needed to better understand under what conditions its benefits can be realised best.

Keywords: Agroforestry, Cocoa, Climate-smart agriculture, Climate change adaptation, Ghana

JEL: O13, Q01, Q54, Q56, Q57

Acknowledgements: This research was financially supported by the German Research Foundation (DFG) through the grant number RTG 2654 Sustainable Food Systems. We thank all those that made the implementation of the data collection in Ghana possible, particularly Dr. Alex Kombat and his family for their generous support, our research assistant Michael Boateng and enumerators who provided exceptional field assistance, and all the farmers who devoted their time to answering our questions. We also appreciate the valuable feedback on earlier versions of this paper from Magdalena Pallauf, as well as the assistance of Viviane Eckert and José Blotta in generating the rainfall variables and creating the maps.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) underscores the severe and widespread loss and damage resulting from anthropogenic climate change. Increasingly frequent, intense, and prolonged extreme weather events—such as droughts, wildfires, heatwaves, cyclones, and floods—are exceeding the capacity of agricultural systems to cope (IPCC 2023). Moreover, increases in temperature are creating favourable conditions for pests and disease outbreaks, further exacerbating crop stress (Skendžić et al. 2021).

In tropical regions, particularly sub-Saharan Africa, where agriculture provides livelihoods for the majority of the population, these impacts can be devastating. Tropical areas already experience high temperatures, so even small increases in temperature can push conditions beyond the optimal thresholds for many crops. Additionally, smallholder farmers in this region, who predominantly rely on rain-fed production systems, often lack the resources and adaptive mechanisms needed to cope with climate change (Pachauri et al. 2014).

Moreover, agricultural intensification and landscape homogenization lead to biodiversity loss (Meyfroidt et al. 2014). Biodiversity is important for sustaining long-term agricultural productivity and essential for the health of agro-ecosystems to improve their resilience towards climate disturbances (Tscharntke et al. 2024). Given these current challenges, there is an urgent need to identify feasible land-use practices that address these environmental and climate-related issues for achieving sustainable and climate-resilient farming systems.

Agroforestry, which is the intentional integration or retention of trees in cropping systems (Nair 1993), offers a promising approach. By providing shade through their canopy cover, these so-called shade trees contribute to stabilizing microclimates at the plot level, thereby mitigating the impacts of extreme weather events (Blaser et al. 2018; Niether et al. 2018). Compared to other climate change adaptation practices, agroforestry is particularly beneficial as it also contributes to climate change mitigation by storing and sequestering carbon, thereby reducing greenhouse gas emissions (Nimo et al. 2021; Somarriba et al. 2013). Additionally, shade trees can serve as habitat corridors between forest fragments (Asare et al. 2014) – thereby conserving biodiversity (Barrios et al. 2018), regulating pest control (Guenat et al. 2019) and disrupting landscape homogenization (Asare et al. 2014; Deikumah et al. 2017). Given the numerous ecosystem services provided by shade trees within agroforestry systems, they have the potential to enhance crop yields and thereby improve livelihoods (Asare et al. 2019; Jezeer et al. 2017). Despite these well studied benefits that agroforestry systems can offer, the extent to which agroforestry adoption enhances resilience to adverse weather events, such as drought, at the household level remains poorly understood. Yet, planting shade trees is widely recommended as a climate change adaptation strategy (Asare and David 2011; Bunn et al. 2019). Therefore, this study examines whether the effect of reduced rainfall on crop yields differs between agroforestry adopters and non-adopters.

Recognizing that climate change effects are expected to vary across regions (Läderach et al. 2013), we additionally analyze the effects in two regions that differ in climatic suitability for cocoa production in order to explore potential regional differences.

To address our research question, we conduct a case study in the cocoa sector of Ghana, the world's second-largest cocoa producer (FAO 2023). Cocoa farmers in Ghana face significant challenges, including declining cocoa yields which are increasingly attributed to climate change (Läderach et al. 2013). At the same time, global demand for cocoa continues to rise, with production increases over the past decades largely driven by the expansion of cocoa plantations into natural forests (Kalischek et al. 2023). In response to these challenges, the European Union implemented a more restrictive regulatory framework at the end of 2024, aimed at ensuring the import of deforestation-free cash crops such as soy, rubber, coffee, and cocoa (European Commission 2023). Given these developments, our study is particularly timely, as it seeks to identify opportunities for cocoa farmers to intensify production while preserving biodiversity in the face of climate change.

For our study, we rely on a two wave panel data set from 2019 and 2022 of 365 smallholder cocoa farming households from five major cocoa producing regions in Ghana. We additionally use publicly available data of local rainfall that we merge with the households' geographical location. Using the correlated random effects model approach, we show that on average, agroforestry adopters are less severely affected by reduced rainfall than non-adopters. However, when disaggregating between regions that differ in climatic suitability, we find that the effects hold only in regions that are climatically suitable for cocoa production. In contrast, we do not find any significant effects in climatically less suitable regions, where farmers are more prone to drought stress.

Our contributions to the literature are threefold. Firstly, literature focusing on climate change adaptation and combining climate and household panel data has mainly focused on staple crops in Eastern Africa. Evidence on the effectiveness of climate change adaptation measures for cash crops is limited, despite their importance in global value chains where demand continues to rise (European Commission 2024). Secondly, studies that explore the relationship between agroforestry, crop yields, and water availability are rooted in crop science and rely on small samples of experimental plots (Abdulai et al. 2018b; Niether et al. 2017). To the best of our knowledge, this is the first study to incorporate household-level and socioeconomic factors into the analysis, therefore providing household-level evidence. Thirdly, our household sample represents a large geographic area covering five major cocoa producing regions in Ghana that differ in climatic suitability. This allows us to capture regional heterogeneity in the effects of agroforestry and the climate, thereby enhancing the external validity of our findings for other cocoa-producing countries in West Africa.

The remainder of the paper is organized as follows: In section 2, we discuss the role of cocoa agroforestry in mitigating climate change effects and present the study context. In section 3, we present our sampling strategy and discuss our main variables and our empirical strategy. Section 4 presents an overview of selected descriptive statistics on yield, agroforestry-related practices and rainfall, and respondents' perceptions of climate changes, as well as our regression results. Section 5 discusses the findings and concludes.

2. Background and literature review

Shade trees in cocoa cultivation

Historically, cocoa farming developed through converting primary forest to cocoa plantations. In agroforestry systems, large shade trees were left standing and cocoa was planted into the thinned forest areas (Niether et al. 2017). In addition to the deliberate retention of trees, cocoa agroforestry systems today are mixed-tree plantations where cocoa trees are planted together with fruit, timber, firewood, and leguminous trees (hereafter referred to as shade trees) (Niether et al. 2020). The management of shade trees plays an important role for the long-term sustainability of cocoa plantations. When establishing a cocoa tree plantation, shade is essential for covering the cacao seedlings and protecting them from the sun. When cacao trees mature, farmers have the choice to remove shade trees which increases short-term yield. However, these so-called "short-term boom-and-bust cycle" monocultures lead to dwindling yields and increasing pressure from pests and diseases in the unshaded sun (Tscharntke et al. 2011). Short-term boom-and-bust cycles have been common in cocoa production throughout history and have had great environmental drawbacks. Degraded cocoa plantations are abandoned and new cocoa land is established, usually at the expense of primary forest land (Kalischek et al. 2023). Rather than felling shade trees after cocoa trees mature, retaining some level of shade is considered a more sustainable management practice (Asare et al. 2019). While yields may take some time to develop, shade trees can extend the productive life-cycle of the plantation (Tscharntke et al. 2011; Wessel and Quist-Wessel 2015).

The relationship between shade trees, cocoa yields and the climate is complex, as it is shaped by both the shade trees' ecological benefits and the potential competition with cocoa trees for resources. One key benefit of shade trees is their potential to stabilize the plot's microclimate and thereby buffer against adverse climate shocks (Tscharntke et al. 2011). For instance, Blaser et al. (2018) and Niether et al. (2018) find that shade trees lower air temperatures during the dry season, which in turn reduces evaporative demand and therefore can mitigate drought-related stress on cocoa trees.

Changes in rainfall patterns and associated temperature fluctuations can create favorable conditions for pests (e.g., capsids, stem borers, mealybugs) and diseases (e.g., black pod, swollen shoot virus, pink disease) that harm cocoa productivity (Dohmen et al. 2018; Niether et al. 2018). One of the biggest concerns for farmers is that shade trees increase pest and disease pressures in their farms (Ruf 2011). Nonetheless, a number of studies support contrary findings showing that shade trees can naturally suppress the risk of climate change-associated pest and disease outbreaks (Jaimes-Suárez et al. 2022). For example, diverse agroforestry systems support a rich diversity of animals, which in turn enhances biological control (e.g. through black ants) (Tscharntke et al. 2011). Additionally, the combination of leaf litter from cocoa and shade trees influences the structure of the decomposer community, as well as the rate of litter decomposition (Costa et al. 2017). Increased litter from shade trees fosters a diverse community of decomposer organisms and other species, which further improves pest control. Additionally, shade trees can reduce the spread of cocoa swollen shoot virus by restricting the movement of mealybug vectors responsible for spreading the disease across the plantation floor (Andres et al. 2018).

Despite these multiple benefits, excessive shade trees may compete with cocoa trees for water particularly during periods of reduced rainfall. For instance, Blaser et al. (2018) find that shade tree cover decreases soil moisture and has no effect on air humidity during the dry season and Niether et al. (2018) find that shade trees reduce rain throughfall. Similarly, Abdulai et al. (2018b) report that after a drought event, soil water content was higher in full-sun cocoa plantations than in agroforestry systems.

Climate change projections and agroforestry in Ghana

Despite Ghana’s significant contribution to global cocoa production, with 30% of its population dependent on cocoa for part or all of their livelihoods (Antwi et al. 2022), yields remain below global average (FAO 2023). Contributing factors include aging cocoa tree plantations, limited access to and use of agro-chemical inputs and modern technologies, degraded soils and aging farmers (Bymolt et al. 2018). Furthermore, cocoa farmers in Ghana face challenges posed by climate change. Model projections estimate an average temperature increase of 2 degrees Celsius by 2050. This rise in temperature will enhance evapotranspiration, leading to a drier climate and increasing the risk of drought, thereby reducing overall climatic suitability for cocoa production (Läderach et al. 2013). Moreover, the authors project that the impacts will vary across regions (see Figure 1). While some areas that are currently cooler and wetter, will remain relatively unaffected, others, particularly those bordering the savannas in the north, will become marginally suitable for cocoa cultivation.

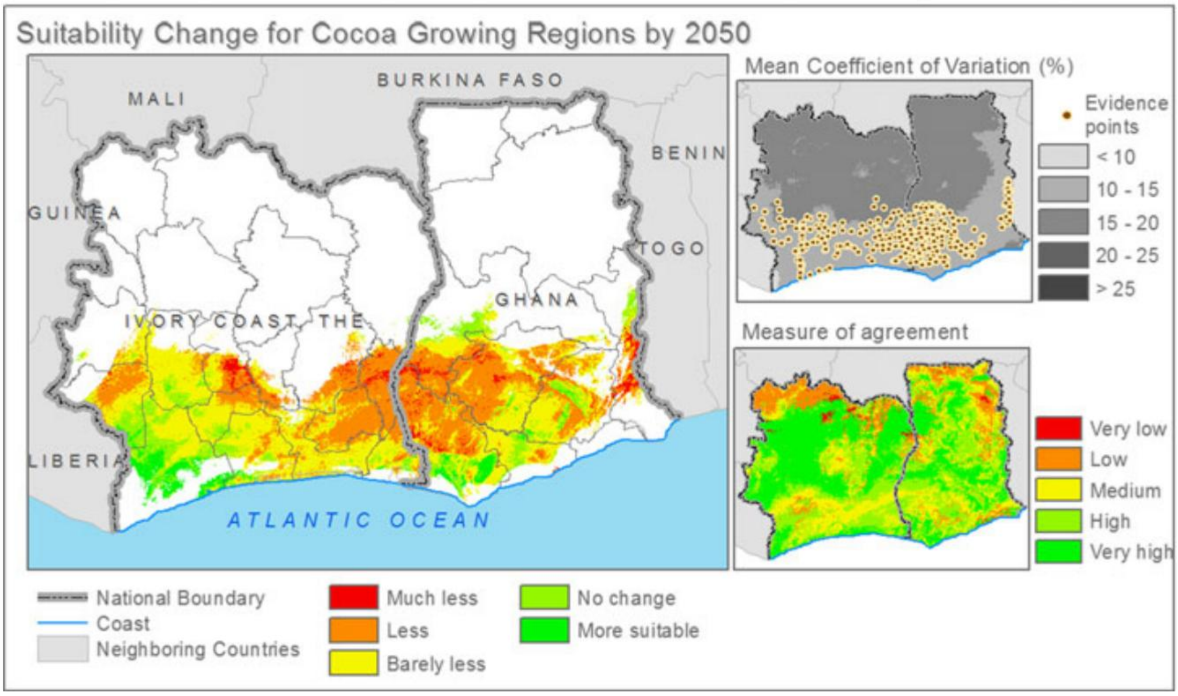

Figure 1: Suitability change for cocoa growing regions by 2050 (taken from Läderach et al. (2013)).

Schroth et al. (2016) recommend the systematic implementation of climate change adaptation strategies, such as shade tree planting on cocoa farms, to reduce their vulnerability to climate change. In Ghana, policy interventions have historically played a significant role in shaping farmers' incentives to retain and plant shade trees. When primary forests were cleared to cultivate cocoa, farmers kept large shade trees on their cocoa plots, hence preserving numerous economically and environmentally valuable species within the landscape (Antwi et al. 2022). However, in the late 1950s, the government intervened in the timber market by claiming tenure rights to naturally occurring shade trees on cocoa plots. This intervention spurred increased shade tree harvesting for timber by the government, a trend that intensified in the 1980s when Ghana’s Cocoa Marketing Board (Cocobod) revised its policy, encouraging farmers to remove shade trees to boost cocoa productivity. While this new policy led to short-term yield increases, it also made cocoa trees more vulnerable to diseases and significantly reduced their productive lifespan (Antwi et al. 2022).

State ownership of naturally occurring shade trees is considered a strong disincentive for farmers to maintain and plant shade trees, as they do not financially benefit if the tree is harvested by government authorities. Since 1992, a tree tenure reform allows farmers to hold legal ownership over trees they plant themselves, provided they are registered with the national tree registry. Any shade trees that farmers fail to register is owned by the state. However, the tree tenure reform is considered to be largely ineffective, as the high transaction and registration costs have discouraged farmers from registering their trees (Antwi et al. 2022).

In recent years, the Ghanaian government as well as various stakeholders of the cocoa industry have increasingly recognized the beneficial ecosystem services provided by agroforestry systems. Government extension services, as well as various non-governmental organizations, voluntary certification bodies (e.g. The Rainforest Alliance) and cocoa buying companies have set up programs to promote the planting of shade trees (Schulte 2020). Such programs include training on establishing agroforestry systems, the free distribution of shade tree seedlings, as well as setting minimum requirements for shade tree levels in the case of voluntary certifications (Schulte 2020). However, the adoption of shade tree planting remains low. In addition to the challenges posed by the tree tenure system, many cocoa farmers are concerned that shade trees may compete with cocoa trees for resources or create microclimates conducive to pests and diseases (Armengot et al. 2016).

3. Materials and methods

3.1 Sampling and data collection

For our analyses we use two waves of household data collected between November and December in 2019 and 2022 in Ghana. Our sampling relies on a multi-stage sampling strategy where communities were randomly selected based on existing population census data. To ensure that regions with higher production levels were proportionately represented, the number of communities in each region was identified based on their 2019 production volumes (Cocobod 2024). Within each community, we then randomly selected 12 cocoa farming households based on existing lists that had been provided by extension officers. In 2019, a total of 527 cocoa farming households coming from 46 communities and 24 districts within Ashanti, Brong Ahafo, Eastern, Central and Western North region were interviewed. This large geographic area covers regions that are projected to significantly decrease in climatic suitability for cocoa production (hereafter called *less suitable region*) and regions whose suitability will barely reduce in climatic suitability (hereafter called *suitable region*) (Läderach et al. 2013) (see Figure 1). Within our sample 18 communities (157 households) are located in the less suitable region and 25 communities (208 households) are located in the more suitable region.

In 2022, we revisited all communities and were able to re-interview 365 households, leading to an attrition rate of 31%. The primary reasons for attrition included the death of the farmer, relocation, or inability to locate the household. Overall our analysis is based on a balanced panel of 365 households.

To check if attrition is non-random we employ a balance test to ascertain if the means of our variables differ between non-attritors (re-interviewed farmers) and attritors (farmers we could not trace back) with the use of a t-test (Bulte et al. 2014). Table A1 in the appendix shows that attrition is primarily influenced by location characteristics and therefore is not random. Non-attritors live significantly closer to an input shop, which may explain why a significantly higher proportion of non-attritors use pesticides compared to attritors. Additionally, a significantly smaller proportion of attritor households live in villages connected to an electricity grid. To address these differences across groups, we create inverse probability weights which we include in the estimations as robustness checks, thereby giving more weight to households that are underrepresented due to attrition and ensuring that our estimates remain unbiased and representative of the overall sample (Wooldridge 2002). Following Wooldridge (2002), we run a probit regression to determine the probability of being re-interviewed over all control variables used. The inverse of the estimated probability is the adjusted weight which we add to the estimations (see Table A2 in the appendix).

3.2 Variables

Treatment variable: Reduced rainfall

Given the importance of rain during the dry season (Schroth et al. 2016), we use an indicator of reduced rainfall during the dry season as our climate variable. Although rainfall is lower during the dry season, some rainfall is necessary to ensure uniform flowering which occurs during this period (Zuidema et al. 2005).

To derive the reduced rainfall for each household, we use the household's geographical location and merge the survey data with data on local rainfall conditions during the years of data collection. Rainfall data is derived from the Climate Hazards Center InfraRed Precipitation with Station dataset (CHIRPS) which provides publicly available data on monthly rainfall at 0.05 degrees of spatial resolution (Funk et al. 2015). We use the rainfall data to construct a continuous variable used to measure reduced rainfall during the dry season (January and Feburary). Following Maggio et al. (2022), we calculate reduced rainfall by constructing a variable that measures the local negative rainfall deviation from the last 30 years (1989-2018), which we consider to be the long-term average. This is calculated as the difference between the average rainfall in millimeter per square meters per month during the dry season in year *t* of the survey, with t = 2019, 2022, and the long-term average rainfall per month during the dry season at location of each household.

$$RedRain = Rainfall_t - \overline{Rainfall} \; \{0 \; if RainDev \geq 0; \; |RainDev| \; if < 0\}$$

$t = 2019, 2021$

For ease of interpretation, we set the positive values of rainfall deviations to zero and take the absolute values of the negative rainfall deviation. This means that higher values of the coefficient correspond to lower levels of rainfall.

Treatment variable: Agroforestry adoption

Defining households as agroforestry or non-agroforestry adopters can be challenging, as various institutions have differing criteria for when a cocoa farming system qualifies as an agroforestry system.

Several institutions and NGOs (e.g. (Initiative for Sustainable Cocoa 2020; Rainforest Alliance 2023) set minimum shade cover levels, typically ranging from 30% to 40%. However, these percentages are difficult to measure using self-reported household data, as farmers are likely to struggle with estimating shade cover in percentage terms.

The Initiative for Sustainable Cocoa defines a cocoa farm as an agroforestry system if it has more than 16 shade trees per hectare and at least three different species on the plot (Initiative for Sustainable Cocoa 2020). On the other hand, the local extension department of the Ghana Cocoa Board (Cocobod) classifies a farm as agroforestry if it has at least 18 shade trees per hectare, regardless of species diversity (Ghana Cocoa Board 2018). For our analysis, we rely on ISCO's definition, as it incorporates shade tree diversity, which is important for biodiversity. Additionally, we acknowledge the challenges associated with setting a threshold based on a specific number of shade trees and tree species to determine who qualifies as an agroforestry adopter, as adoption is a continuous process rather than a binary one (Müting and Mußhoff 2025). To address this, as a robustness check we will also explore the shade tree density (i.e. the number of shade trees per hectare) as an additional measure to assess agroforestry adoption.

To collect the necessary data to construct our agroforestry-related variables, in the second survey wave in 2022, we asked farmers to provide details about the number and type of mature shade trees on each of their cocoa plots. We also inquired about the size of each productive cocoa plot, allowing farmers to provide the measurement in their preferred units (acres, hectares, or traditional poles), which we later converted to hectares. To calculate shade trees per hectare, we divided the number of shade trees on all productive cocoa plots by the total size of the productive cocoa plots in hectares.

We consider the reported number of shade trees to be time invariant over the three-year time period between our data collection in 2019 and 2022. Because we use the number of shade trees reported in 2022, it is unlikely that there were significantly fewer shade trees in 2019. Agroforestry systems develop gradually, as trees take time to grow, making a rapid increase in shade tree numbers in such a short period of time unlikely. Additionally, in established cocoa plantations, introducing more shade trees usually requires farmers to remove cocoa trees. However, farmers are generally reluctant to cut down cocoa trees due to concerns about yield loss, unless the trees are diseased, very old, or dying. Moreover, while it is possible that more shade trees existed in 2019 and were later removed, this scenario is unlikely in our study context. As discussed in Chapter 2, shade trees that were not planted by the farmer are owned by the state and cannot be legally harvested without a permit period.

Outcome variable: Cocoa yield per hectare

The primary outcome variable is cocoa yield, measured in kilograms per hectare (kg/ha) of dried cocoa beans harvested during the light season[1] preceding the survey. The light harvest season provides an additional source of income before the main harvest season begins in September. Even though yields are on average lower than in the main season, it helps farmers maintain a more stable cash flow throughout the year. This is crucial for meeting immediate financial needs, such as purchasing agricultural inputs and covering household expenses. To accurately capture cocoa yields, we asked farmers to report the number of cocoa bags they harvested during this period on all their cocoa plots. The size of the bags is standardized, and farmers typically record the number of bags sold in their "passbook"[2], provided by extension officers. To calculate the cocoa yield, we multiplied the number of harvested bags by 64 (the weight in kilograms of a standard cocoa bag) and then divided this figure by the total size of all plots.

3.3 Estimation strategy

We use the correlated random (CRE) effects model for our estimations. The CRE model is suitable for our data because it can estimate the effects of both time-varying and time-invariant variables in panel structured data. Furthermore, the CRE model controls for some of the endogeneity that arises when observable variables are correlated with unobservable time-invariant variables such as skill or ability by including the panel means of time-varying variables as additional controls (Wooldridge 2019). In our case, this is particularly relevant for the variable representing the agroforestry adoption, as agroforestry adoption may be correlated with unobservable farmer traits such as motivation or skill[3].

We first determine the total effect of reduced rainfall on the entire sample using the following equation:

$$Y_{i,t} = RedRain_{i,t}\beta_1 + Agroforestry_{i,t}\beta_2 + X_{i,t}\beta_3 + P_{i,t}\beta_4 + a_i + \varepsilon_{i,t}$$

eq. (1)

where $Y_{i,t}$ is the cocoa yield (kg/ha) of the household i in year t = 2019 and 2022 and $RedRain_{i,t}$ refers to reduced rainfall. $X_{i,t}$ relates to a vector of time-varying covariates hypothesized to affect cocoa productivity. These variables include a set of standard characteristics at the household, plot and community levels. At the household level, we control for the household head's level of education, age

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[1] Cocoa production follows a dual-season cycle: a light season from April to July and a main season from September to December (Bymolt et al. 2018).

[2] The farmer passbook is a record-keeping tool issued by Cocobod that tracks cocoa production, sales, and financial transactions, helping farmers manage their activities and access government support and services.

[3] The CRE model, by including the means of time varying variables as additional controls, is able to account for some endogeneity, however, to fully account for endogeneity would require a randomized control trial or instrumental variable approach.

and sex and the ratio between adults and dependents. To account for the production factors, such as labour and land availability, we further include whether the household hires external labour and manages non-cocoa plots. At the plot level, we control for pest or disease shocks within the past 12 months. Moreover, we control for the share of cocoa trees under 5 years and above 25 years of age to account for lower productivity levels, and for the share of fertile soil reported by the farmer. We include information about the application of other farming practices such as weeding, pruning and sanitary harvesting as well as the use of agrochemicals. At the community level, we control for the availability of electricity and the distance to nearest agricultural input shop. To take into consideration the overall level of local development, we include an urbanization index as a control variable. This data is provided through the GHS Settlement Model Grid, which classifies the country territory along an urban-rural continuum, considering population size as well as density (Schiavina et al. 2023). The data is available for 2015 and 2020 which we include into our analysis[4]. Lastly, we control for regional characteristics by including regional dummy variables. The model also includes household fixed effects a_i and an error term, $\varepsilon_{i,t}$.

Additionally, to estimate the heterogenous effects of reduced rainfall on cocoa yields based on agroforestry adoption, we extend equation 1 to the following equation:

$$\begin{aligned} Y_{i,t} = {} & Agroforestry_{i,t}\beta_1 + RedRain_{i,t}\beta_2 + (RedRain * Agroforestry_{i,t})\beta_3 \\ & + X_{i,t}\beta_3 + P_{i,t}\beta_4 + a_i + \varepsilon_{i,t} \end{aligned}$$

eq. (2)

where we add the interaction variable $RedRain * Agroforestry_{i,t}$ that allows us to assess whether the impact of reduced rainfall varies depending on agroforestry adoption status.

Finally, we want to estimate whether the heterogeneous effects of reduced rainfall on cocoa yields based on agroforestry adoption differ between households in regions of different climatic suitability. To do so, we re-estimate equations 1 and 2 separately for households in suitable and less suitable regions, respectively (Chapter 3.1).

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[4] Higher numbers represent more urban areas.

4. Results

We present descriptive statistics on cocoa production, agroforestry practices and rainfall (Table 1), as well as respondents' perceptions of changes in climate (Figure 3 and 4) before discussing the regression results. Table A3 in the appendix shows the descriptive statistics for all variables used in the analysis for 2019 and 2022.

4.1 Descriptive statistics

Cocoa production, agroforestry practices and rainfall

Cocoa yields harvested during the light season differ significantly between the two regions in both study years (Table 1). While in the less suitable region total cocoa yields declined on average from 82.50 kg/ha in 2019 to 75.50 kg/ha in 2022, in the suitable region, they rose from 94.99 kg/ha to 107.38 kg/ha. Regional differences in cocoa yields align with findings by Abdulai et al. (2020) and Kalischek et al. (2023), reflecting variations in climatic suitability.

Regarding agroforestry practices, the shade trees density is slightly higher in the suitable region (16.86 trees/ha) compared to the less suitable region (15.02 trees/ha), but this difference is not statistically significant. The proportion of agroforestry adopters is also similar, at 29% overall, with no significant difference between the two regions. These numbers align with findings in the literature which show that shade tree levels in Ghana are generally low (Schulte 2020).

We further examine the five shade tree species most commonly reported by our respondents: ofram (*Terminalia superba*), avocado (*Persea americana*), orange (*Citrus sinensis*), emery (*Terminalia ivorensis)* and odum (*Milicia excelsa*). Among these, ofram and emery trees are classified as 'desirable shade trees' by the local extension research institute and their distribution is subsidized by the government (Ghana Cocoa Board 2018). Shade trees such as avocado and orange trees are primarily valued for their economic benefits as sales from their harvest can contribute as an additional income stream (Abdulai et al. 2018a). Our results show that farmers seem to prefer a mix of timber and fruit trees on their plots, with ofram and avocado trees being the most widely planted. While the average number of shade tree species per plot is similar across regions (5.53 species on average), statistically significant differences exist in the type of species planted. Specifically, ofram and avocado trees are significantly more common in the less suitable region, while emery trees are more prevalent in the suitable region.

Rainfall patterns differ substantially between regions with overall more rain in the suitable region. The historical average rainfall during the months of January and February is significantly higher in the suitable region (80.89 mm) than in the less suitable region (68.98 mm). This pattern persists for dry-season rainfall for both 2019 and 2022, with significantly more rainfall in the suitable region. Dry season rainfall decreased from 2019 to 2022 in both regions. In 2022, average dry season rainfall was 52 mm in the suitable region and 34 mm in the less suitable region on average. This indicates severely low rainfalls in both regions, as previous research has shown that cocoa trees with less than 50 mm of rain during the two driest months produce less than 60% of their potential under optimal water supply (Zuidema et al. 2005).

Table 1: Descriptive statistics of cocoa yield, agroforestry and rainfall variables

	All regions		Less suitable region		Suitable region		Mean difference between regions
	mean	sd	mean	sd	mean	sd	
Cocoa yields							
Cocoa yields (kg/ha) in 2019	89.62	66.88	82.50	58.90	94.99	72.00	12.48^{*}
Cocoa yields (kg/ha) in 2022	93.47	90.75	75.05	74.78	107.38	99.08	32.33^{***}
Agroforestry practices							
Shade trees density	16.07	13.26	15.02	12.90	16.86	13.50	1.84
Agroforestry (1/0)	0.29	0.46	0.29	0.45	0.30	0.46	0.01
No. of shade tree species	5.53	2.82	5.46	2.65	5.58	2.95	0.12
No. of ofram trees	1.29	1.18	1.53	1.14	1.11	1.19	-0.42^{***}
Ofram tree (1/0)	0.71	0.45	0.85	0.36	0.61	0.49	-0.24^{***}
No. of avocado trees	1.03	0.89	1.23	0.91	0.88	0.85	-0.35^{***}
Avocado tree (1/0)	0.71	0.45	0.81	0.39	0.63	0.48	-0.17^{***}
No. of orange trees	0.87	0.83	0.91	0.81	0.85	0.85	-0.06
Orange tree (1/0)	0.64	0.48	0.67	0.47	0.61	0.49	-0.06
No. of emery trees	0.70	1.09	0.53	0.78	0.83	1.25	0.30^{***}
Emery tree (1/0)	0.41	0.49	0.37	0.48	0.43	0.50	0.06
No. of odum trees	0.39	0.69	0.41	0.66	0.37	0.72	-0.04
Odum (1/0)	0.30	0.46	0.32	0.47	0.27	0.45	-0.05
Rainfall data							
Historical average (mm) during dry season	75.77	12.18	68.98	15.08	80.89	5.28	11.92^{***}
Average rainfall (mm) during dry season (2019)	80.60	20.21	67.09	17.28	90.80	15.81	23.70^{***}
Average rainfall (mm) during dry season (2022)	43.83	13.23	33.69	11.23	51.48	8.71	17.79^{***}
Observations			157		208		365

Note: sd = standard deviations. * p < 0.1, ** p < 0.05, *** p < 0.01.

Figure 2 illustrates the geographic distribution of surveyed households for both years. The triangular shapes represent households living in the less suitable region, while the circles represent those living in the suitable regions. The colour of the shapes represents the intensity of reduced rainfall (our treatment variable), while the background colour represents dry season rainfall in 2019 and 2022. Figure 1 shows that the year 2022 received less rainfall overall than 2019 and reduced rainfall was higher in 2022 than in 2019 for all households. In addition, households living more to the west experienced less reduced rainfall than those living to the east.

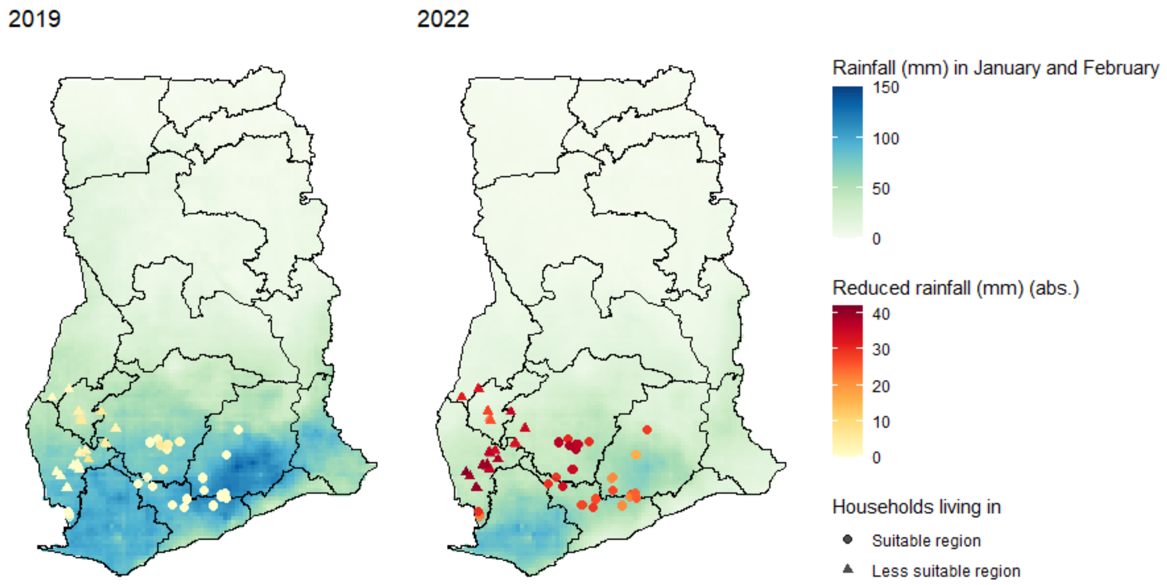

Figure 2: Map of sampled villages in Ghana with total rainfall for January and February in 2019 (left) and 2022 (right).[5] Triangular shapes represent households living in less suitable regions and circles represent households living in suitable regions.

Farmer perceptions about climate change

Läderach et al. (2013) predict that there will be a shift in the timing of the rainy and dry seasons across Ghana. We therefore assess farmers' perceptions of changing climate patterns over the entire year in 2019. We asked our respondents: “How has the arrival of the rains changed since you started working in cocoa?” Figure 3 illustrates that the majority of farmers perceive the season to be shifting. Only a small share of farmers (13%) report to observe no change, while most farmers report a later onset of the rainy season in comparison to previously observed patterns.

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[5] Ghana recently divided the Brong Ahafo region into the Bono and Ahafo regions; these were considered as one region at the time of the sampling.

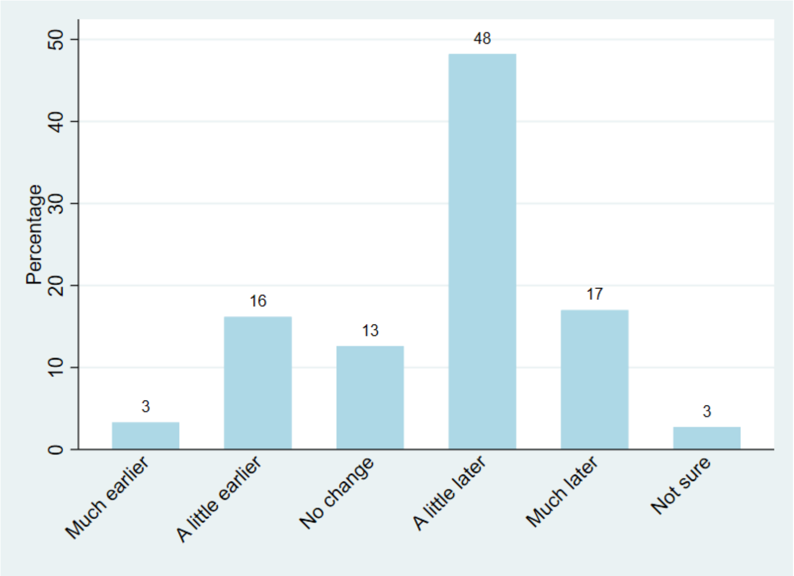

Figure 3: Responses by respondents to the question: "How has the arrival of the rains changed since you started working in cocoa?" in 2019.

Additionally, we asked farmers whether they have noticed changes in the duration of the rainy season since they started working in cocoa. While a shorter rainy season can lead to drought, prolonged rainfall may negatively impact cocoa production by increasing humidity levels, which foster mold and fungal diseases. Figure 4 shows that most farmers report either a shorter or longer duration of the rainy season.

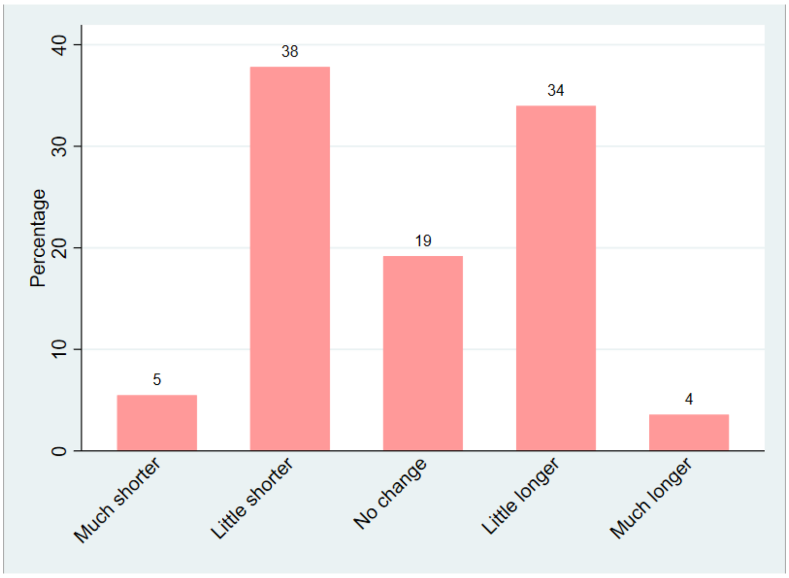

Figure 4: Responses by respondents to the question: "How has the duration of the rainy season changed since you started working in cocoa?" in 2019.

Farmers' perceptions in Figures 3 and 4 suggest that they are already experiencing noticeable shifts in rainfall patterns. The variation in responses align with the climate projections of Läderach et al. (2013), who predict that climate change will have heterogeneous impacts across different areas in Ghana, potentially offsetting each other in overall averages.

4.2 Regression results

The role of agroforestry for climate change adaptation

In this section, we present the regression results of our CRE model estimations. Table 2 reports the results for the total sample across the five study regions, with column 1 displaying the estimates without the interaction between reduced rainfall and agroforestry adoption and column 2 incorporating the interaction term. The results in column (1) show that, on average, agroforestry adopters achieve significantly higher cocoa yields, producing nearly 18 kg/ha more than non-adopters. Furthermore, each additional millimeter of reduced rainfall, relative to the long-term historical average, leads to a significant average yield decline of 2.65 kg/ha, all else equal.

Including the interaction term allows us to assess whether the effect of reduced rainfall differs between agroforestry adopters and non-adopters. Column 2 shows that the coefficient for reduced rainfall remains negative and significant, while the interaction term between reduced rainfall and agroforestry adoption is positive and significant. This implies that one additional millimeter of reduced rainfall has a negative effect on yields by 2.9kg/ha for non-agroforestry adopters. The positive and significant β_3 of the interaction term shows that for agroforestry adopters, the negative effect of reduced rainfall is less; one additional millimeter of reduced rainfall has a negative effect on yields by 2.01kg/ha (-2.89+1*0.88).

Table 2: Effects of reduced rainfall and the interaction with agroforestry adoption (total sample, all regions)

	(1) Cocoa Yield (kg/ha)	P-value	(2) Cocoa Yield (kg/ha)	P-value
Agroforestry (1/0)	17.81 (6.89)	0.01	28.93 (30.46)	0.34
Reduced rainfall (mm)	-2.65 (0.88)	0.00	-2.9 (0.88)	0.00
Agroforestry (1/0)* Reduced rainfall (mm) (abs.)			0.88 (0.35)	0.01
Time-variant control variables	Yes		Yes	
Time-invariant control variables	Yes		Yes	
Means of time-varying variables	Yes		Yes	
Observations	314	314	413	413

Robust standard errors are in parentheses, Full regression output with all control variables is in the appendix in Table A4.

To evaluate whether these effects differ between regions with lower climatic suitability—where conditions are expected to worsen—and regions with higher suitability, which are projected to experience only a slight decline, we re-estimate our models separately for the two subsamples. The results in Table 3 (columns 1 and 3) indicate that in the suitable region, the findings remain consistent: the positive and significant coefficient of the interaction term suggests that agroforestry adoption mitigates the negative effects of reduced rainfall on cocoa yields. However, in the less suitable region (column 2), the interaction term is statistically insignificant. This means that we cannot draw definitive conclusions that our overall findings for the total sample are consistent in the less suitable, drier region.

Table 3: Effects of reduced rainfall and the interaction with agroforestry adoption for less suitable and suitable regions

	(Less suitable region)				**(Suitable region)**			
	(1) Cocoa Yield (kg/ha)	P-value	(2) Cocoa Yield (kg/ha)	P-value	(3) Cocoa Yield (kg/ha)	P-value	(4) Cocoa Yield (kg/ha)	P-value
Agroforestry (1/0)	21.3 (10)	0.03	9.5 (91.08)	0.92	16.19 (9.93)	0.10	48.72 (40.94)	0.23
Reduced rainfall (mm)	-1.85 (1.16)	0.11	-2.01 (1.17)	0.09	-3.72 (1.51)	0.01	-3.82 (1.5)	0.01
Agroforestry (0/1)* Reduced rainfall (mm) (abs.)			0.4 (0.43)	0.36			1.37 (0.55)	0.01
Time-variant control variables	Yes		Yes		Yes		Yes	
Time-invariant control variables	Yes		Yes		Yes		Yes	
Means of time-varying variables	Yes		Yes		Yes		Yes	
Observations	314		314		413		413	

Robust standard errors are in parentheses, Full regression output with all control variables is in the appendix in Table A5.

To test the robustness of our results, we replace the binary agroforestry adoption variable with a continuous measure of shade trees density and re-run all estimations for the total sample and the two subsamples within the less suitable and suitable region. The estimates align with the previous findings (Table 4). In the overall sample and the suitable region subsample, the coefficient for reduced rainfall remains negative and statistically significant, while the interaction term is positive and significant. This suggests that the negative impact of reduced rainfall on cocoa yields decreases as shade tree density increases—households with fewer shade trees experience greater yield losses, whereas those with more shade trees are less affected. However, in the less suitable region, the coefficient for shade tree density is statistically insignificant, meaning we do not find statistical evidence that the negative effects of reduced rainfall decrease with increasing shade tree density in areas more prone to drought stress.

Table 4: Effects of reduced rainfall and the interaction with shade trees density for less suitable and suitable regions

	(All regions)		**(Less suitable region)**		**(Suitable region)**	
	(1) Cocoa Yield (kg/ha)	P-value	(2) Cocoa Yield (kg/ha)	P-value	(3) Cocoa Yield (kg/ha)	P-value
Shade trees density	0.8 (1.01)	0.43	-0.98 (3.29)	0.77	0.2 (1.29)	0.88
Reduced rainfall (mm)	-2.97 (0.88)	0.00	-2.06 (1.17)	0.08	-4.01 (1.52)	0.00
Shade trees/ha*Reduced rainfall (mm)	0.03 (0.01)	0.01	0.02 (0.02)	0.24	0.05 (0.02)	0.00
Time-variant control variables	Yes		Yes		Yes	
Time-invariant control variables	Yes		Yes		Yes	
Means of time-varying variables	Yes		Yes		Yes	
Observations	727		314		413	

Robust standard errors are in parentheses, Full regression output with all control variables is in the appendix in Table A6.

As a final robustness check, we include inverse probability weights into our model to account for sample attrition observed in our sample [6]. As can be seen in tables A7, A8 and A9 in the appendix, after including the weights, the results remain consistent in both magnitude and significance.

5. Discussion and conclusion

The assumption that agroforestry can buffer crops from the worst effects of climate change is a major reason for its promotion in climate-vulnerable agricultural sectors (Schroth et al. 2017). For cocoa production, it is most important for shade trees to buffer climate extremes during the dry season, when cocoa is most vulnerable to drought stress (Zuidema et al. 2005).

Against this background, this study explores the heterogeneous effects of reduced dry-season rainfall on cocoa yields based on agroforestry adoption and shade tree density across different regions with varying climatic suitability in Ghana. On average, we find that reduced rainfall has a more negative

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[6] It is not possible to include inverse probability weights in the Stata command used to estimate the CRE models. We therefore use a fixed-effects (FE) model to include the weights. Results for time-variant coefficients (such as our treatment variables of interest) are the same for FE and CRE model estimations (Echeverri 2024).

effect on cocoa yield for agroforestry non-adopters and households with fewer shade trees than for agroforestry adopters and households with more shade trees. Additionally, we test whether these results differ between regions where climate change is projected to substantially reduce climatic suitability and those where the decline is expected to be minimal. We find that the same effects hold for households living in suitable climatic regions that are generally wetter. However, we do not find significant effects for households in drier and less suitable regions, cautioning against assuming that agroforestry benefits extend to areas more prone to drought stress.

There are two possible explanations for our findings. First, while both regions experienced a systematic decline in dry-season rainfall—to below suboptimal levels for cocoa production in 2022—the less suitable region experienced even lower rainfall. In wetter regions, where water availability is less constrained, agroforestry can help buffer against reduced rainfall by stabilizing subcanopy temperature, thereby reducing evaporative demand (Blaser et al. 2018; Niether et al. 2018).

However, in drier, more water-stressed regions, the benefits of shade trees may be outweighed by increased competition for already scarce water resources. For instance, (Blaser et al. 2018) find that higher shade tree cover in cocoa plots is associated with reduced soil moisture during the dry season. Niether et al. (2018) report that shade trees drastically reduce rainfall throughfall as their canopy covers the cocoa trees and ground. Furthermore, Abdulai et al. (2018b) observe higher cocoa tree mortality in agroforestry systems compared to full sun systems after a drought.

Second, the composition of shade tree species may play a key role in explaining the differing effects across regions (Kohl et al. 2024). Our descriptive statistics (Table 1) show that the type of shade tree species reported by the farmers vary between regions. For instance, avocado trees are more prevalent in the less suitable region. Avocado trees contribute to income diversification, which is particularly important when climate change threatens income from cocoa production. However, avocado trees have relatively shallow root systems (Atucha et al. 2013), similar to cocoa trees and are highly water-demanding (Caro et al. 2021). Consequently, they may compete with cocoa for water resources during the dry season, potentially offsetting the microclimatic temperature-reducing benefits that agroforestry can provide. Additionally, tree structure and canopy height may also play a role. The emery tree, which is more common in the suitable region, has a lower stem height which helps maintain higher relative humidity compared to taller species like ofram trees (Blaser-Hart et al. 2021), which are more prevalent in the less suitable region.

While our results suggest that shade trees mitigate climate change effects in wetter, more suitable region of Ghana, their role in the drier climate remains uncertain. Existing research is already investigating the effects of specific tree species and their characteristics on microclimatic parameters (Abdulai et al. 2025; Blaser-Hart et al. 2021; Kohl et al. 2024), but we need further studies that can determine whether these effects hold across different climatic regions and how specific tree species influence yields under varying climatic conditions. Additionally, future research could focus on identifying shade tree species that support income diversification—serving as an additional climate adaptation strategy—without competing excessively for resources with cocoa. Moreover, future research could explore whether an optimal threshold for shade tree density exists, beyond which competition under drought conditions becomes detrimental and if these thresholds differ in different climatic conditions. Finally, future research could examine whether agroforestry can mitigate the effects of other extreme rainfall events, such as heavy rainstorms or floods, by reducing soil erosion and canopy damage.

While our results may be applicable for cocoa production in other West African countries, they should not be generalized for other geographical areas as these may be exposed to other climatic conditions. As our study demonstrates, it is crucial to consider the heterogeneity of climate change effects, as evaluating average impacts may obscure local realities. Furthermore, we particularly refrain from generalizing the results to other agroforestry cropping systems as the physiological interactions between shade trees and crops may vary. Nevertheless, this study shows that a context-specific approach to agroforestry as a climate change adaptation strategy is essential, rather than assuming a one-size-fits-all strategy. Further, our study provides a valuable benchmark that can be replicated in other settings to explore the context-specific effects of agroforestry under varying climatic and agricultural conditions.

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Appendix

Table A1: Balance Test: Differences in means between non-attritors and attritors.

	Non-attritors		Attritors		Mean difference
	mean	sd	mean	sd	
Yield light season (kg/ha)	89.62	66.88	84.27	70.94	5.35
Age HH head	52.39	12.39	51.37	13.77	1.02
Female HH head	0.27	0.44	0.28	0.45	0.01
Yrs of educ. HH head	7.30	4.17	7.41	4.23	0.11
HH dependency ratio	0.89	0.87	0.77	0.80	0.12
HH hired labour	0.76	0.43	0.66	0.48	0.10**
Manages non-cocoa plots	0.27	0.45	0.23	0.43	0.04
Cocoa land cultivated (ha)	3.74	3.76	3.84	4.56	0.10
HH experienced pest attack	0.52	0.50	0.51	0.50	-0.01
Share of rich soil	0.76	0.41	0.75	0.43	0.02
Share cocoa trees < 5 years	0.10	0.29	0.14	0.34	0.04
Share cocoa trees > 25 years	0.08	0.27	0.10	0.29	0.01
No. Manual Weeding	2.67	1.19	2.80	1.13	0.12
Pruning (1/0)	0.84	0.37	0.86	0.35	0.02
Sanitary harvest (1/0)	0.76	0.43	0.80	0.40	0.04
Use of pesticide (1/0)	0.79	0.41	0.72	0.45	0.08*
Use of synthetic fertilizer (1/0)	0.27	0.45	0.26	0.44	0.01
Village has electricity (1/0)	0.87	0.34	0.81	0.39	0.06*
HH to input shop (km)	8.08	9.06	10.22	11.34	2.14**
Level of urbanization	2.48	1.72	2.44	1.92	0.04
Western region	0.27	0.45	0.28	0.45	0.01
Brong Ahafo region	0.12	0.32	0.10	0.31	0.01
Eastern region	0.19	0.39	0.17	0.38	0.01
Central region	0.15	0.36	0.10	0.30	0.05*
Ashanti region	0.27	0.45	0.27	0.45	0.00
Observations	365		162		527

Note: sd = standard deviations. * p < 0.1, ** p < 0.05, *** p < 0.01.

Table A2: Attrition Probit regression estimating the probability of being re-interviewed in 2022

	(1) Re-interviewed in 2022
Yield light season (kg/ha)	0
	(0)
Age HH head	0
	(.01)
Female HH head	-.09
	(.15)
Yrs of educ. HH head	-.01
	(.02)
HH dependency ratio	.11
	(.07)
HH hired labour	.27*
	(.14)
Manages non-cocoa plots	.1
	(.16)
Cocoa land cultivated (ha)	-.01
	(.02)
HH experienced pest attack	0
	(.12)
Community has electricity	.24
	(.18)
HH to input shop (km)	-.01*
	(.01)
Population density	-.07*
	(.04)
Western region	5.67
	(120.5)
Brong Ahafo region	5.67
	(120.5)
Eastern region	5.66
	(120.5)
Central region	5.92
	(120.5)
Ashanti region	5.76
	(120.5)
Constant	-5.41
	(120.5)
Observations	527
Pseudo R^2	.07

*Standard errors are in parentheses, *** p<.01, ** p<.05, * p<.1*

Table A3: Descriptive statistics of additional variables used in the analysis

	2019		2022		Mean difference
	mean	sd	mean	sd	
Yield light season (kg/ha)	89.62	66.88	103.95	140.76	14.33*
HH characteristics					
Age HH head	52.39	12.39	56.88	13.72	4.49***
Female HH head	0.27	0.44	0.22	0.42	0.04
Yrs of educ. HH head	9.06	5.05	9.02	4.17	0.04
HH dependency ratio	0.92	1.04	1.04	1.19	0.12
HH hired labour	0.76	0.43	0.88	0.33	0.12***
Manages non-cocoa plots	0.27	0.45	0.53	0.50	0.26***
Cocoa land cultivated (ha)	3.74	3.76	3.48	3.23	0.27
Plot characteristics					
HH experienced pest attack	0.52	0.50	0.54	0.50	0.02
Share of rich soil	0.76	0.41	0.79	0.37	0.02
Share cocoa trees < 5 years	0.10	0.29	0.03	0.15	0.07***
Share cocoa trees > 25 years	0.08	0.27	0.25	0.38	0.17***
No. of times manual weeding	2.67	1.19	3.01	2.75	0.34**
Pruning (1/0)	0.84	0.37	0.79	0.41	0.05*
Sanitary harvest (1/0)	0.76	0.43	0.94	0.24	0.18***
Use of pesticide (1/0)	0.79	0.41	0.89	0.31	0.10***
Use of synthetic fertilizer (1/0)	0.27	0.45	0.51	0.50	0.24***
Infrastructure characteristics					
Community has electricity	0.87	0.34	0.90	0.30	0.04
HH to input shop (km)	8.08	9.06	8.53	9.37	0.45
Population density	2.49	1.71	2.47	1.69	0.02
Regions					
Western region	0.27	0.45	0.27	0.45	0.00
Brong Ahafo region	0.12	0.32	0.12	0.32	0.00
Eastern region	0.19	0.39	0.19	0.39	0.00
Central region	0.15	0.36	0.15	0.36	0.00
Ashanti region	0.27	0.45	0.27	0.45	0.00
Observations	365		365		730

Note: sd = standard deviations. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Full regression output of all CRE estimations

Table A4: Effects of reduced rainfall and the interaction with agroforestry adoption (total sample, all regions)

	(1) Cocoa Yield (kg/ha)	(2) Cocoa Yield (kg/ha)
Agroforestry (1/0)	17.81***	28.93
	(6.89)	(30.46)
Reduced rainfall (mm) (abs.)	-2.65***	-2.9***
	(.88)	(.88)
Agroforestry (1/0)*Reduced rainfall (mm) (abs.)		.88**
		(.35)
	(.48)	(.47)
Female HH head	11.9	13.38
	(14.75)	(14.65)
Yrs of educ. HH head	-1.03	-.95
	(1)	(1)
HH dependency ratio	-2.27	-2.21
	(3.39)	(3.36)
HH hired labour	-8.15	-6.66
	(9.98)	(9.92)
Manages non-cocoa plots	-2.72	-1.98
	(8.44)	(8.38)
Cocoa land cultivated (ha)	-3.85**	-3.13*
	(1.69)	(1.7)
HH experienced pest attack	7.04	8.06
	(7.4)	(7.35)
Share of rich soil	7.08	8.52
	(9.19)	(9.13)
Share cocoa trees < 5 years	-44.03***	-43.51***
	(15.74)	(15.62)
Share cocoa trees > 25 years	-8.43	-8.98
	(12.12)	(12.03)
At least 3x manual weeding	6.64	6.83
	(7.85)	(7.79)
Pruning	4.71	5.63
	(9.38)	(9.31)
Sanitary harvest	16.43	14.46
	(10.83)	(10.77)
Use of pesticide	2.42	.09
	(9.81)	(9.78)
Use of syn. fertilizer	24.36***	24.21***
	(7.88)	(7.82)
Community has electricity	8.98	7.68
	(14.64)	(14.53)
HH to input shop (km)	.39	.36
	(.43)	(.43)
Level of urbanization	39.25*	40.94*
	(22.32)	(22.16)
Western region	-30.78***	-30.28***
	(8.87)	(8.97)
Brong Ahafo region	-8.04	-6.79
	(12.5)	(12.53)
Eastern region	8.49	9.09
	(16.52)	(16.57)
Central region	-32.74**	-32.05**
	(14.21)	(14.26)

Year 2022	74.66***	74.13***
	(27.21)	(26.99)
Means of time-varying control variables	YES	YES
Constant	58.67	52.08
	(48.02)	(48.99)
Observations	730	730
Pseudo R^2	.z	.z

*Robust standard errors are in parentheses, *** p<.01, ** p<.05, * p<.1*

Table A5: Effects of reduced rainfall and the interaction with agroforestry adoption for less suitable and suitable regions

	Less suitable region		Suitable region	
	(1) Cocoa Yield (kg/ha)	(2) Cocoa Yield (kg/ha)	(3) Cocoa Yield (kg/ha)	(4) Cocoa Yield (kg/ha)
Agroforestry (1/0)	21.3**	9.5	16.19	48.72
	(10)	(91.08)	(9.93)	(40.94)
Reduced rainfall (mm) (abs.)	-1.85	-2.01*	-3.72**	-3.82**
	(1.16)	(1.17)	(1.51)	(1.49)
Agroforestry (1/0)* Reduced rainfall (mm) (abs.)		.4		1.37**
		(.43)		(.55)
Age HH head	.14	.11	-.29	-.12
	(.61)	(.62)	(.72)	(.71)
Female HH head	-1.34	-.1	23.06	24.7
	(21.05)	(21.1)	(20.91)	(20.63)
Yrs of educ. HH head	-.31	-.3	-1.5	-1.38
	(1.36)	(1.37)	(1.49)	(1.47)
HH dependency ratio	2.21	1.98	-5.42	-4.64
	(4.05)	(4.06)	(5.79)	(5.72)
HH hired labour	4.93	5.47	-21.65	-20.29
	(13.69)	(13.71)	(14.81)	(14.62)
Manages non-cocoa plots	-.66	-.71	-13.23	-11.33
	(11.8)	(11.81)	(12.23)	(12.08)
Cocoa land cultivated (ha)	-4.86**	-4.46**	-3.47	-2.34
	(2.21)	(2.25)	(2.62)	(2.62)
HH experienced pest attack	.02	.21	10.99	14.1
	(10.68)	(10.69)	(10.71)	(10.63)
Share of rich soil	9.44	9.37	.73	4.25
	(13.11)	(13.11)	(13.42)	(13.31)
Share cocoa trees < 5 years	-47.04**	-48.33**	-42.33*	-36.79
	(21.64)	(21.7)	(23.67)	(23.45)
Share cocoa trees > 25 years	-12.5	-13.42	-9.66	-8.48
	(18.5)	(18.54)	(16.56)	(16.33)
At least 3x manual weeding	15.38	15.13	5.37	6.71
	(10.95)	(10.96)	(11.53)	(11.38)
Pruning	18.38	19.03	4.01	4.54
	(13.05)	(13.08)	(14.26)	(14.06)

Sanitary harvest	-10.67	-12.34	25.56*	23.35*
	(19.14)	(19.24)	(14.06)	(13.89)
Use of pesticide	25*	23.74	-13.48	-16.98
	(14.57)	(14.65)	(13.91)	(13.79)
Use of syn. fertilizer	18.92*	19.43*	29.48***	27.7**
	(11.28)	(11.3)	(11.31)	(11.18)
Community has electricity	-5.68	-6.01	8.79	2.62
	(17.38)	(17.39)	(25.59)	(25.35)
HH to input shop (km)	-.73	-.78	1.3**	1.3**
	(.61)	(.61)	(.62)	(.61)
Level of urbanization	-.42	.29	71.77**	71.72**
	(28.32)	(28.35)	(35.66)	(35.16)
Western region	-39.63**	-39.35**	-69.5**	-67.65**
	(15.73)	(15.93)	(34.02)	(34.17)
Brong Ahafo region	-25.02	-24.58		
	(22.34)	(22.81)		
Eastern region			4.51	4.79
			(21.76)	(21.86)
Central region			-37.29**	-36.32*
			(18.59)	(18.68)
Means of time-varying control variables	YES	YES	YES	YES
Year 2022	50.33	51.78	111.27**	101.68**
	(38.23)	(38.28)	(43.46)	(43.03)
Constant	133.75	131.18	63.46	60.57
	(93.77)	(101.44)	(70.96)	(71.84)
Observations	314	314	416	416
Pseudo R^2	.z	.z	.z	.z

*Robust standard errors are in parentheses, *** p<.01, ** p<.05, * p<.1*

Table A6: Effects of reduced rainfall and the interaction with shade trees density for less suitable and suitable regions

	Less suitable region			Suitable region		
	(1) Cocoa Yield (kg/ha)	(2) Cocoa Yield (kg/ha)	(3) Cocoa Yield (kg/ha)	(4) Cocoa Yield (kg/ha)	(5) Cocoa Yield (kg/ha)	(6) Cocoa Yield (kg/ha)
Shade trees/ha	.52**	1.37	.01	-.98	.84**	.84
	(.24)	(1.05)	(.35)	(3.29)	(.35)	(1.34)
Reduced rainfall (mm) (abs.)	-2.65***	-3.01***	-1.85	-2.06*	-3.72**	-4.2***
	(.88)	(.88)	(1.16)	(1.17)	(1.51)	(1.5)
Shade trees/ha* Reduced rainfall (mm) (abs.)		.03**		.02		.05***
		(.01)		(.02)		(.02)
Age HH head	-.13	-.11	.14	.18	-.29	-.32
	(.48)	(.47)	(.61)	(.61)	(.72)	(.71)
Female HH head	11.9	13.22	-1.34	.16	23.06	24.82
	(14.75)	(14.65)	(21.05)	(21.06)	(20.91)	(20.6)
Yrs of educ. HH head	-1.03	-1	-.31	-.22	-1.5	-1.67
	(1)	(1)	(1.36)	(1.36)	(1.49)	(1.47)
HH dependency ratio	-2.27	-2.6	2.21	1.51	-5.42	-4.62
	(3.39)	(3.37)	(4.05)	(4.09)	(5.79)	(5.71)
HH hired labour	-8.15	-5.96	4.93	6.64	-21.65	-20.24

	(9.98)	(9.94)	(13.69)	(13.75)	(14.81)	(14.59)
Manages non-cocoa plots	-2.72	-1.82	-.66	-.87	-13.23	-10.73
	(8.44)	(8.38)	(11.8)	(11.78)	(12.23)	(12.08)
Cocoa land cultivated (ha)	-3.85**	-2.86*	-4.86**	-4.07*	-3.47	-2.04
	(1.69)	(1.72)	(2.21)	(2.3)	(2.62)	(2.64)
HH experienced pest attack	7.04	8.52	.02	.04	10.99	16.09
	(7.4)	(7.36)	(10.68)	(10.66)	(10.71)	(10.72)
Share of rich soil	7.08	7.02	9.44	8.46	.73	1.33
	(9.19)	(9.12)	(13.11)	(13.11)	(13.42)	(13.22)
Share cocoa trees < 5 years	-44.03***	-44.75***	-47.04**	-50.35**	-42.33*	-36.05
	(15.74)	(15.62)	(21.64)	(21.79)	(23.67)	(23.43)
Share cocoa trees > 25 years	-8.43	-6.83	-12.5	-13.56	-9.66	-4.07
	(12.12)	(12.05)	(18.5)	(18.5)	(16.56)	(16.44)
At least 3x manual weeding	6.64	8.55	15.38	16.27	5.37	9.17
	(7.85)	(7.83)	(10.95)	(10.96)	(11.53)	(11.44)
Pruning	4.71	5.83	18.38	18.8	4.01	6.97
	(9.38)	(9.32)	(13.05)	(13.03)	(14.26)	(14.08)
Sanitary harvest	16.43	15.5	-10.67	-12.36	25.56*	25.16*
	(10.83)	(10.75)	(19.14)	(19.17)	(14.06)	(13.84)
Use of pesticide	2.42	.05	25*	23.35	-13.48	-17.3
	(9.81)	(9.78)	(14.57)	(14.62)	(13.91)	(13.77)
Use of syn. fertilizer	24.36***	24.64***	18.92*	19.6*	29.48***	29.02***
	(7.88)	(7.83)	(11.28)	(11.28)	(11.31)	(11.14)
Community has electricity	8.98	8.13	-5.68	-5.58	8.79	.79
	(14.64)	(14.53)	(17.38)	(17.35)	(25.59)	(25.38)
HH to input shop (km)	.39	.33	-.73	-.83	1.3**	1.34**
	(.43)	(.43)	(.61)	(.62)	(.62)	(.61)
Level of urbanization	39.25*	42.61*	-.42	1.63	71.77**	75.78**
	(22.32)	(22.19)	(28.32)	(28.33)	(35.66)	(35.14)
Western region	-29.81***	-29.24***	-34.64**	-34.81**	-75.45**	-75.45**
	(8.88)	(8.91)	(16.03)	(16.1)	(33.84)	(33.93)
Brong Ahafo region	-7.51	-6.95	-23.79	-24.51		
	(12.53)	(12.56)	(22.81)	(23.02)		
Eastern region	9.23	8.36			2.77	2.77
	(16.57)	(16.61)			(21.6)	(21.68)
Central region	-31.81**	-31.32**			-34.87*	-34.86*
	(14.27)	(14.29)			(18.45)	(18.51)
Means of time-varying control variables	YES	YES	YES	YES	YES	YES
Year 2022	74.66***	69.17**	50.33	46.98	111.27**	99.8**
	(27.21)	(27.09)	(38.23)	(38.28)	(43.46)	(43.01)
Constant	49.31	37.44	132.4	152.19	44.51	50.22
	(48.51)	(51.6)	(95.34)	(112.76)	(71.21)	(73.78)
Observations	730	730	314	314	416	416
Pseudo R^2	.z	.z	.z	.z	.z	.z

*Robust standard errors are in parentheses, *** p<.01, ** p<.05, * p<.1*

Fixed effects model estimations with inverse probability weights

Table A7: Effects of reduced rainfall and the interaction with agroforestry adoption (total sample, all regions) including inverse probability weights Note: The model drops time-invariant coefficients (e.g. agroforestry (0/1) and regional dummies)

	(1) Cocoa Yield (kg/ha)	(2) Cocoa Yield (kg/ha)
Agroforestry (1/0)		
Reduced rainfall (mm) (abs.)	-2.67***	-2.92***
	(.91)	(.9)
Agroforestry (0/1)* Reduced rainfall (mm) (abs.)		.9**
		(.37)
Age HH head	-.11	-.08
	(.45)	(.44)
Female HH head	13.88	16.19
	(13.19)	(13.01)
Yrs of educ. HH head	-1.3	-1.18
	(.95)	(.93)
HH dependency ratio	-1.74	-1.76
	(3.59)	(3.52)
HH hired labour	-7.67	-6.31
	(10.4)	(10.14)
Manages non-cocoa plots	-4.25	-3.63
	(8.05)	(8)
Cocoa land cultivated (ha)	-3.34*	-2.64
	(1.91)	(1.9)
HH experienced pest attack	6.34	7.26
	(6.75)	(6.86)
Share of rich soil	5.92	7.25
	(7.81)	(7.74)
Share cocoa trees < 5 years	-40.02**	-39.66**
	(15.98)	(15.66)
Share cocoa trees > 25 years	-8.85	-9.14
	(10.86)	(11.1)
At least 3x manual weeding	7.51	7.91
	(7.19)	(7.14)
Pruning	4	4.71
	(8.3)	(8.38)
Sanitary harvest	15.51	13.81
	(11.14)	(11.14)
Use of pesticide	4.77	2.16
	(9.13)	(9.11)
Use of syn. fertilizer	23.48***	23.39***
	(8.5)	(8.37)
Community has electricity	9.66	8.66
	(12.03)	(11.93)
HH to input shop (km)	.42	.39
	(.42)	(.42)
Level of urbanization	31.22*	32.8*
	(17.33)	(17.74)
Western region		
Brong Ahafo region		
Eastern region		

Central region		
Ashanti region		
Year 2022	75.41**	74.6**
	(29.33)	(28.97)
Constant	5.71	-2.91
	(55.09)	(56.28)
Observations	730	730
R-squared	.13	.15

*Robust standard errors are in parentheses, *** p<.01, ** p<.05, * p<.1*

Table A8: Effects of reduced rainfall and the interaction with agroforestry adoption for less suitable and suitable regions including inverse probability weights

	Less suitable region		Suitable region	
	(1) Cocoa Yield (kg/ha)	(2) Cocoa Yield (kg/ha)	(3) Cocoa Yield (kg/ha)	(4) Cocoa Yield (kg/ha)
Agroforestry (1/0)				
Reduced rainfall (mm)	-1.97	-2.09	-3.94***	-4.07***
	(1.3)	(1.31)	(1.46)	(1.46)
Agroforestry (1/0)* Reduced rainfall (mm) (abs.)		.31		1.45**
		(.46)		(.57)
Age HH head	.11	.08	-.29	-.09
	(.61)	(.59)	(.63)	(.63)
Female HH head	3.55	4.77	21.09	24.14
	(25.51)	(25.12)	(15.11)	(15.05)
Yrs of educ. HH head	-.54	-.53	-1.58	-1.37
	(1.23)	(1.22)	(1.36)	(1.37)
HH dependency ratio	2.91	2.69	-5.28	-4.49
	(4.43)	(4.43)	(5.25)	(5.08)
HH hired labour	7.06	7.39	-24.3	-22.91
	(11.55)	(11.51)	(15.66)	(15)
Manages non-cocoa plots	-1.12	-1.34	-15.92	-13.52
	(11.38)	(11.38)	(11.54)	(11.3)
Cocoa land cultivated (ha)	-4.64**	-4.35**	-3.01	-1.8
	(1.83)	(1.93)	(2.66)	(2.55)
HH experienced pest attack	.74	.86	10.38	13.48
	(8.57)	(8.61)	(10.42)	(10.58)
Share of rich soil	10.28	10.08	-1.58	2.12
	(11.78)	(11.83)	(11.87)	(11.33)
Share cocoa trees < 5 years	-38.83**	-40.01**	-38.58	-32.27
	(18.86)	(19.04)	(28.15)	(27.26)
Share cocoa trees > 25 years	-16.51	-17.03	-8.82	-7.89
	(17.29)	(17.48)	(14.32)	(14.52)
At least 3x manual weeding	14.99	15.01	6.56	7.98

	(11.22)	(11.19)	(8.82)	(8.85)
Pruning	15.81	16.31	5.56	5.8
	(13.46)	(13.55)	(11.14)	(11.52)
Sanitary harvest	-11.29	-12.21	26.3*	23.89*
	(16.75)	(16.7)	(13.99)	(13.79)
Use of pesticide	27.57**	26.56**	-13.15	-16.98
	(13.16)	(13.1)	(12.66)	(12.91)
Use of syn. fertilizer	16.77	17.19	31.29***	29.37**
	(11.64)	(11.69)	(11.84)	(11.58)
Community has electricity	-5.46	-5.78	8.77	3.26
	(16.48)	(16.34)	(18.01)	(18.2)
HH to input shop (km)	-.61	-.64	1.32**	1.31**
	(.51)	(.53)	(.52)	(.53)
Level of urbanization	-4.58	-4.33	69.62**	70.04**
	(22.72)	(22.43)	(31.19)	(32.13)
Western region				
Brong Ahafo region				
Eastern region				
Central region				
Ashanti region				
Year 2022	55.22	56.18	117.07***	107.58**
	(44.56)	(44.59)	(41.83)	(41.67)
Constant	73.59	74.9	-42.08	-59.02
	(81.5)	(81.15)	(83.89)	(84.87)
Observations	314	314	416	416
R-squared	.22	.22	.18	.21

*Robust standard errors are in parentheses, *** p<.01, ** p<.05, * p<.1*

Table A9: Effects of reduced rainfall and the interaction with shade trees density for less suitable and suitable regions including inverse probability weights

	Less suitable region			Suitable region		
	(1) Cocoa Yield (kg/ha)	(2) Cocoa Yield (kg/ha)	(3) Cocoa Yield (kg/ha)	(4) Cocoa Yield (kg/ha)	(5) Cocoa Yield (kg/ha)	(6) Cocoa Yield (kg/ha)
Shade trees density						
Reduced rainfall (mm) (abs.)	-2.67***	-3.01***	-1.97	-2.14*	-3.94***	-4.44***
	(.91)	(.91)	(1.3)	(1.29)	(1.46)	(1.41)
Shade trees density* Reduced rainfall (mm) (abs.)		.03*		.02		.06*
		(.02)		(.02)		(.03)
Age HH head	-.11	-.1	.11	.13	-.29	-.32
	(.45)	(.43)	(.61)	(.59)	(.63)	(.59)
Female HH head	13.88	16.03	3.55	5.12	21.09	24.54
	(13.19)	(13.4)	(25.51)	(25.55)	(15.11)	(15.64)

Yrs of educ. HH head	-1.3	-1.21	-.54	-.46	-1.58	-1.61
	(.95)	(.95)	(1.23)	(1.21)	(1.36)	(1.41)
HH dependency ratio	-1.74	-2.1	2.91	2.28	-5.28	-4.3
	(3.59)	(3.55)	(4.43)	(4.4)	(5.25)	(5.25)
HH hired labour	-7.67	-5.5	7.06	8.34	-24.3	-22.72
	(10.4)	(10.33)	(11.55)	(11.72)	(15.66)	(15.2)
Manages non-cocoa plots	-4.25	-3.3	-1.12	-1.46	-15.92	-12.72
	(8.05)	(8)	(11.38)	(11.45)	(11.54)	(11.14)
Cocoa land cultivated (ha)	-3.34*	-2.35	-4.64**	-4.01**	-3.01	-1.46
	(1.91)	(1.93)	(1.83)	(1.99)	(2.66)	(2.59)
HH experienced pest attack	6.34	7.71	.74	.6	10.38	15.94
	(6.75)	(6.94)	(8.57)	(8.67)	(10.42)	(11.01)
Share of rich soil	5.92	5.78	10.28	9.37	-1.58	-1.06
	(7.81)	(7.71)	(11.78)	(11.89)	(11.87)	(11.21)
Share cocoa trees < 5 years	-40.02**	-40.88**	-38.83**	-41.63**	-38.58	-31.68
	(15.98)	(16.07)	(18.86)	(19.5)	(28.15)	(28.35)
Share cocoa trees > 25 years	-8.85	-7.21	-16.51	-17.19	-8.82	-3.53
	(10.86)	(11)	(17.29)	(17.35)	(14.32)	(14.52)
At least 3x manual weeding	7.51	9.61	14.99	15.84	6.56	10.84
	(7.19)	(7.28)	(11.22)	(11.34)	(8.82)	(9.17)
Pruning	4	4.84	15.81	16.28	5.56	7.67
	(8.3)	(8.31)	(13.46)	(13.45)	(11.14)	(11.41)
Sanitary harvest	15.51	14.79	-11.29	-12.37	26.3*	26*
	(11.14)	(11.22)	(16.75)	(16.69)	(13.99)	(13.99)
Use of pesticide	4.77	2.08	27.57**	26.16**	-13.15	-17.55
	(9.13)	(9.12)	(13.16)	(13.18)	(12.66)	(13.19)
Use of syn. fertilizer	23.48***	23.77***	16.77	17.41	31.29***	30.57***
	(8.5)	(8.39)	(11.64)	(11.62)	(11.84)	(11.41)
Community has electricity	9.66	9.14	-5.46	-5.43	8.77	.7
	(12.03)	(11.96)	(16.48)	(16.19)	(18.01)	(17.83)
HH to input shop (km)	.42	.37	-.61	-.68	1.32**	1.36**
	(.42)	(.43)	(.51)	(.54)	(.52)	(.54)
Level of urbanization	31.22*	33.79*	-4.58	-3.72	69.62**	73.68**
	(17.33)	(18.13)	(22.72)	(22.51)	(31.19)	(33.7)
Western region						
Brong Ahafo region						
Eastern region						
Central region						
Ashanti region						
Year 2022	75.41**	69.29**	55.22	52.31	117.07***	104.84**
	(29.33)	(29.27)	(44.56)	(44.81)	(41.83)	(41.23)
Constant	5.71	-6.99	73.59	68.96	-42.08	-57.6
	(55.09)	(56.65)	(81.5)	(81.61)	(83.89)	(87.74)
Observations	730	730	314	314	416	416
R-squared	.13	.15	.22	.22	.18	.22

*Robust standard errors are in parentheses, *** p<.01, ** p<.05, * p<.1*