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Hand Pollination of Cocoa Farms in Ghana: Cost and Benefits Analysis

Wisdom Akpalu
Francis Atsu
Enam K. Antonio
Richard Minkah

Abstract

Ghana's cocoa yield has been declining recently, primarily due to poor agricultural practices and a decline in pollinators owing to climate change. To offset yield and output losses, farmers have increased their plot sizes by intensifying the rate of deforestation. In response, the Government of Ghana initiated a hand pollination programme, an adaptation measure designed to augment natural pollination and combat deforestation. This case study examines the net financial benefits and the impact of the climate variable – temperature – on cocoa yield. Using cost-benefit analysis, this study offers the following insights. First, farmers who adopt hand pollination technology experienced a financial benefit 11 times greater, amounting to an additional GHS95,000/acre, over a 15-year fruiting lifespan of a cocoa tree, compared to non-participating farmers. Second, a Ricardian analysis reveals that a 1°C temperature increase results in a 13.4% decline in yield per acre, reducing the net financial benefit to around 9 times. To estimate the long-term effects of climate change, the study employs the scenarios of the Shared Socioeconomic Pathways-Representative Concentration Pathways framework of the Intergovernmental Panel on Climate Change (IPCC). Projections indicate that aligning with the Paris Climate Agreement (SSP1-2.6) scenario, limiting temperature to 2°C will lead to a 26.8% decline in cocoa yield by 2100, with a corresponding benefit-cost ratio of 8.7. Conversely, operating under the 'business as usual' scenario (SSP5-8.5), with warming exceeding 4°C, is projected to reduce cocoa yields significantly by over 67%, leading to a benefit-cost ratio of 3.6.

Keywords: Hand Pollination; climate change; cost-benefit analysis; cocoa yield; Ricardian model.

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About the authors

Prof Wisdom Akpalu is a Professor at Ghana Institute of Management and Public Administration (GIMPA).

Dr Francis Atsu is a Senior Lecturer at Ghana Institute of Management and Public Administration (GIMPA), Business School.

Dr Enam K. Antonio is a Senior Lecturer Ghana Institute of Management and Public Administration (GIMPA), School of Law.

Dr Richard Minkah is an Associate Professor at University of Ghana, Statistics and Actuarial Science Department.

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1. Introduction

Global climate change induces an adverse ecological impact with consequential reverberations on economic activities. This is evidenced by habitat loss and the decline in species populations. This ecological imbalance engenders a decline in certain species' provision of essential ecosystem services, leading to substantial societal costs. For instance, declining wild bee and midge populations due to climate events such as droughts, flooding, and bushfires can disrupt critical pollination services.

The productivity of cocoa and other crops faces a precarious situation. This poses a direct threat to the livelihood and food security of rural agrarian communities as well as national economies. Cocoa is an important cash crop grown in Ghana, other West African countries, and Asian and South American countries. In the early 1900s, Ghana (then Gold Coast) produced more than 50% of the world's cocoa until the late 1970s when Brazil and Cote d'Ivoire overtook Ghana. As of 2021, West Africa accounted for nearly 70% of the world's cocoa production, and the crop was the source of livelihood for approximately 20 million people (Wessel et al., 2015; AsokoInsight, 2021). Within that year (i.e., 2021), Ghana's cocoa production accounted for over 30% and 10% of export earnings and Gross National Product, respectively. Thus, the importance and the sustainability of the cocoa sector in Ghana's economic development cannot be overemphasised.

Notably, current research indicates that the world's top two cocoa producers' output is anticipated to diminish until 2050 (Laderach et al., 2013; Schroth et al., 2016). Specifically, Toledo-Hernandez et al. (2023) report that climate-related production challenges decreased the yield of cocoa worldwide by approximately 2.3%. With temperatures predicted to rise by about 2 degrees Celsius by 2050, there is a lingering fear of this trend exacerbating. Aside from climate-related factors, Aneani and Ofori-Frimpong (2013) attribute the poor yield of cocoa in Ghana to poor pollination and the wrong use of agricultural inputs. In addition, poor farm managerial skills have been illustrated by Tsiboe (2021) to contribute to the decline in cocoa output. The persistent reduction in the yield of cocoa exerts a dual social and economic impact on both cocoa farmers and the nation.

In the West African sub-region, the decline in cocoa output carries implications for the country's foreign exchange earnings and development (See, e.g. Kofi, 1994; Breisinger et al., 2008; Gilbert et al., 2013; Adeniyi & Fagbemi, 2019). Regarding Ghana, the Cocoa Marketing Company, the marketing arm of Ghana Cocoa Board (COCOBOD), a monopolised state-owned company, is required to engage in the forward sale of the country's cocoa beans to secure a syndicated loan in US dollars. The loan is used to finance cocoa activities and to shore up foreign reserves. Therefore, a persistent decrease in cocoa yield affects not only cocoa farmers and the cocoa value chain, but the entire Ghanaian economy.

Given the threats to cocoa production, the Government of Ghana, through COCOBOD, has adopted some sustainable strategies to improve cocoa yield. Chief among them is the introduction of hand pollination on cocoa farms under the Productivity Enhancement Programme (PEPs) of the Environmental and Social Management Plan of COCOBOD 2018. Wurz et al. (2021) noted that hand pollination (also referred to as artificial, controlled, assisted, manual or supplementary pollination) is a process whereby pollens are attached manually to the pistils of the cocoa flower to enable fertilisation of matured pollen grains from the anther of the stigma. COCOBOD implemented hand pollination to address the pollination-driven loss in yield. The programme aimed at complementing natural pollination with hand pollination in areas where the former is either irregular or deficit.

Under the PEP programme, COCOBOD contracted an estimated 10,000 youth in 2017 to hand-pollinate approximately 19,200 hectares of cocoa farms. This was scaled up to 30,000 pollinators to pollinate over 57,000 hectares of cocoa farms as of 2019. COCOBOD believes farmers will adopt hand pollination if they witness enhanced farm yields. To assess the programme's effectiveness, Wongnaa et al. (2021) conducted an impact evaluation study using 206 cocoa farmers in the Amani West District of the Western North region of Ghana. They found that the programme positively impacted farmers' productivity. The increased yield of cocoa trees led to elevated income levels and reduced poverty among cocoa farmers. Similarly, Toledo-Hernandez et al. (2023) found a positive impact of hand pollination on cocoa yield in Brazil and Indonesia.

To the best of our knowledge, no cost-benefit study has been conducted on the impact of implementing this intervention, accounting for the loss of pollinators (ecosystem services) due to climate change. Notably, hand pollination's effects on yield are conditioned on complementary natural pollination. Therefore, the study's main objective is to conduct a cost-benefit analysis of climate effects leading to the loss of natural pollinators. The study also uses a Ricardian model to establish the impact of climate variables on cocoa yields and computes the impact of climate variables on the net revenue derived from cocoa production.

The analysis finds that (i) hand pollination generates substantial financial benefits over their costs, as evidenced by a significant increase in yield, which could mitigate agricultural deforestation; and (ii) cocoa production in Ghana, (and, by extension, other parts of the world) and the global cocoa value chain face an existential threat if the Paris Agreement's goals are not achieved.

The rest of the study is organized into four sections. Section 2 briefly describes the geographical study area, comprising the cocoa-producing regions. Section 3 presents the theoretical model underpinning this study. Section 4 presents the empirical analysis and a discussion of the results. Lastly, Section 5 concludes.

2. Study Area

Cocoa is cultivated in the Eastern, Ashanti, Brong Ahafo, Volta, Central, Western North, and South Regions. Figure 1 presents the map of the cocoa-growing areas within administrative regions of the country (Akpoti et al., 2023). As can be seen from the figure, the cocoa-growing areas lie in the southern belt of the country, which spans eight administrative regions. These regions have a tropical climate, with annual rainfall averages of over 1200 and 2000 mm, temperatures between 21 and 32 degrees Celsius, and relatively high humidity (Kabo-Bah et al., 2016; Akpoti et al., 2023).

3. Theoretical Models

The model for this case study proceeds as follows. Firstly, we employ a cost-benefit analysis to investigate how the benefits from hand-pollinating cocoa farms compare to the associated costs. The costs and benefits are computed at national and regional levels, focusing on the cocoa-producing regions such as Ashanti, Volta, Oti, Eastern, Brong Ahafo, Western South, and Western North in Ghana. According to COCOBOD (2018), the hand pollination programme entails (i) recruiting and training hand pollinators: 20,000 pollinators to manually pollinate 38,000 and four hundred hectares (38,400 ha) of cocoa farms; (ii) training farmers to adopt good agricultural practices as part of the hand pollination programme; (v) training the youth to acquire entrepreneurial skills.

It is expected that after implementing hand pollination: (i) cocoa yield will increase by over 100 per cent on average; (ii) farmers' will acquire the skills such that that they can pollinate their own farms successfully after the programme; (iii) community-based service companies will offer pollination services to farmers who cannot do their own pollination ; (iv) farmers will acquire knowledge of best agricultural practices; and (v) jobs will be created for the youth leading to an increase in income levels for some households.

Benefit-Cost Analysis - Based on data from the Cocoa Board of Ghana, the operational cost per hectare or acre is estimated using the following variables: (i) the cost of hand pollination; (ii) the cost of the required number of litres of liquid fertilizer; (iii) the cost of the required number of litres of insecticide; (iv) the harvesting cost; (v) the cost of the cocoa pod breaking after harvest; (vii) the cost of drying the cocoa beans; and (viii) the cost to transport bags of cocoa to sales points. On the other side, we compute the benefits by focusing primarily on the yield gain attributable to hand pollination's implementation. Mathematically, the intertemporal net benefit (NB_t) is the benefit-cost ratio (BCR_t) expressed as follows:

$$NB_t = B_t - C_t \tag{1}$$

$$BCR_t = {}^{B_t}\!\big/\!{}_{C_t} \tag{2}$$

where B_t and C_t are aggregate instantaneous benefits and costs, respectively.

The Ricardian Model - The Ricardian model assumes that rent or (farm) land value is determined by the output value the land can generate in perpetuity. Thus, changes in climate conditions impact agricultural productivity and, hence, land value. For profit-maximising farmers, differences in per hectare value of a farm or the net present value of the stream of productivity are attributable to climate variables. Suppose the value of an acre of cocoa farm is denoted V_L , and P_{Lt} is the net benefit of the annual productivity of the land. Mathematically, following Mendelsohn et al. (2003), we have:

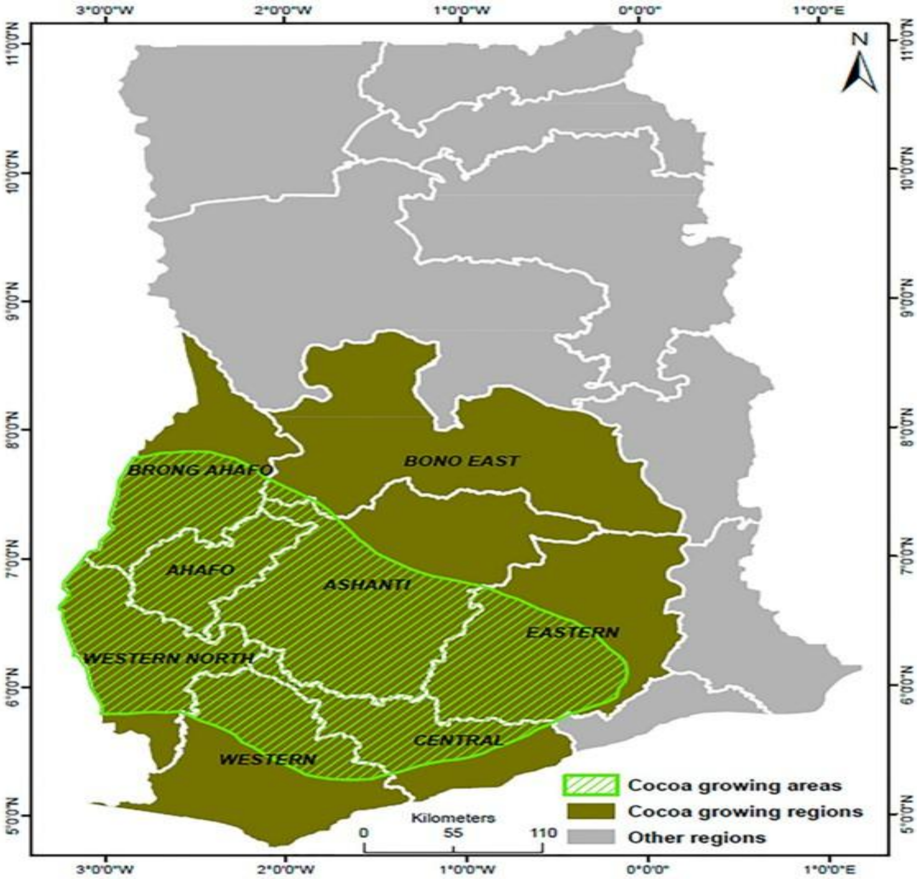
$$V_L = \int_0^\infty p_{Lt} e^{-\delta t} dt \tag{3}$$

where δ is the discount rate, and $t = 0,1,2,...$ is time. Note that if farm inputs are chosen optimally (i.e., to maximise net revenue or profit), then p_{Lt} is only a function of exogenous variables such as input and output prices and climate variables. Thus,

$$V_{Li} = \alpha + \mathbf{X_i}\boldsymbol{\beta} + \mathbf{Z_i}\boldsymbol{\eta} + \mu_i \quad (3)$$

where $\mathbf{X}$ and $\mathbf{Z}$ are vectors of climate variables and other exogenous factors, respectively; $\boldsymbol{\beta}$ and $\boldsymbol{\delta}$ are vectors of coefficients; α is the intercept of the regression; u is a normally distributed error term, and i is farm identifier. For this case study, we draw on the estimates of $\boldsymbol{\beta}$ from previous studies (see e.g., Fonta et al. (2018).

Figure 1. Map of Cocoa growing areas [1]



4. Data

The data for the benefit-cost analysis comes from COCOBOD, Ghana, the statutory board responsible for cocoa activities, and from published works. The elements considered when estimating costs are worth noting. The average labour cost of hand-pollinating an acre of the cocoa farm was computed and assumed to be output invariant (i.e., constant returns to scale).

In addition, the other elements include the cost of fertiliser, insecticide, harvest, pod breaking, drying, and transportation to the shed. It is assumed that the cost difference between pollinated and non-pollinated farms is primarily due to the cost of engaging hand pollinators. This assumption is reasonable since farms, regardless of whether they are hand-pollinated or not, incur the same input costs. All the costs were computed in the local currency (i.e., Ghana Cedis). On the revenue side, the average yield (in bags) of hand-pollinated and nonpollinated farms was valued at the price per unit (bag) of cocoa.

For this case study, the impact of climate change on cocoa yield (i.e., the Ricardian Model) was not directly estimated owing to a lack of data. An estimate from Fonta et al. (2018) was used to compute the impact of future climate scenarios based on the integrated Shared Socioeconomic Paths – Representative Concentration Pathways (SSP-RCP) Framework on yield. The SSP-RCP framework is the global reference scenario used by the IPCC. Hence, we employ these scenarios with their corresponding temperatures to explore their impact on cocoa yield for comparability. From the Ricardian model, the effect of climate change on yield is established. Using the values from the SSP-RCP model, the corresponding loss in yield is then calculated.

5. Empirical Analysis and Discussion

This section is divided into two sub-sections. Section 5.1 provides the cost-benefit analysis. Section 5.2 explores the Ricardian analysis of the relationship between cocoa yield and climate variables, such as temperature.

5.1 Cost-Benefit Analysis of Hand Pollination

The national average cocoa yield is approximately 400kg/hectare (i.e., 160kg/acre), equivalent to about 2.5 bags at 64kg/bag (Aneani et al., 2013; Wongnaa et al., 2021). However, the cocoa hand pollination project has significantly increased the yield per acre to around 928kgs, implying approximately 14.5 bags/acre at 64kg/bag. The project has generated a positive yield gap of 768kg/acre (i.e., the difference between 928kg and 160kg), representing around 480% compared to the yield of a non-pollinated cocoa farm. This has implications for both the cost and revenue components of cocoa farms at an individual level and for the country. For 1-acre hand-pollinated farms and 1-acre non-pollinated farms, the cost and benefits components are detailed in Panels A and B in Table 1 below[1].

Table 1: Benefit and Cost components of 1-acre pollinated and 1-acre non-pollinated farms.

	Panel A: Cost Components		
No	Cost item (per acre in GHS)	Pollinated Farm	Non-Pollinated Farm
1	Hand Pollination (GHS)	800	0
2	Others (GHS)		
	a. A litre of Liquid Fertilizer	65	65
	b. A litre of insecticide	85	85

[1] The hand pollination program aims to increase yield, create jobs, and enhance skills. Since there is a high level of youth unemployment, it is assumed that the wage rate associated with hand-pollination is constant over the scale of production. The cost components are denominated in the local currency (Ghana Cedis), which experienced depreciation over time. However, it is assumed that the depreciation does not impact the ratio since the cost and revenues are equally affected. The cost and benefits values are within a specified period: i.e., the fruiting periods of the tree. It is assumed that the Benefit-Cost ratios will not be affected by inflation since an increase in the cost of hand pollination may correspond to a proportionate increase in revenue.

	c. Harvesting cost	240	240
	d. Pod breaking	240	240
	e. Drying (GHS50/day for six days)	300	300
	f. transportation to shed	75	75
	Sub-total (GHS)	1005	1005
	Grand-Total (GHS)[2]	**GHS1,805**	**GHS1,005**
	Panel B: Revenue Components		
		Pollinated Farm	Non-Pollinated Farm
	Revenue Item (per acre) (GHS)		
1	Minimum average number of pods	21,750	3750
2	Number of pods in a bag (64kg)	1,500	1500
3	Number of bags	14.5	2.5
4	Revenue (per bag)	800	800
	Total Revenue (per acre)	**GH11600**	**GH2000**

Notes: On a single acre, there is an average of 435 cocoa trees, each producing 50 pods through hand pollination, in contrast to an average yield of around 9 pods per tree without hand pollination.

Referring to Panel B of Table 1, the revenue generated from a one-acre hand-pollinated farm yielding 14.5 bags at GHS800/bag amounts to GHS11,600. The corresponding revenue for a one-acre non-pollinated farm, producing 2.5 bags, is GHS2,000. Thus, the revenue difference is GHS9,600, representing a substantial 480% gain over the non-pollinated farm. This indicates an average 480% increase in revenue nationwide owing to the hand pollination programme.

Examining the cost breakdown in Panel A of Table 1, costs of hand pollination and other input costs are GHS800/acre and GHS1005/acre, respectively. Therefore, the total cost for a hand-pollinated acre is GHS1,805, while the corresponding value for a non-pollinated farm is GHS1,005. Thus, the cost difference is GHS800, indicating a 79.60% higher cost for an acre of the hand-pollinated cocoa farms. The instantaneous annual net benefit of hand pollination, as presented in Table 2, is GHS8,800/acre. It takes an average of 5 years for cocoa trees to fruit, and the trees have a viable lifespan of 15 to 20 years. This implies the farm will only begin to generate revenue from year 5. However, the analysis begins in the year preceding the first year of harvest. It is assumed that harvest occurs a year after the hand pollination. Thus, the instantaneous annual net benefit is from year 2, while the corresponding yearly net cost for the first year is GHS800. If a discount rate of 5% is applied, the discounted cost and

[2] As of November 1, 2024, the exchange rate is US$1.00 =GHS16.28.

revenue difference are GHS9,104 and GHS73,502, respectively (see Table 3). The corresponding benefit-cost ratio for operating a hand-pollinated acre cocoa farm for 15 years is 10.9. This suggests that farmers who engaged in the hand pollination programme are financially (approximately) 11 times better off than their counterparts who did not engage in it.

This estimate is based on some assumptions. First is the choice of a discount rate of 5%. A lower (higher) rate than the 5% generates a higher (lower) benefit-cost ratio. For example, a 3% discount rate, all else equal, produced a ratio of 11.03, which is higher than the ratio corresponding to a 5% discount rate. Secondly, it is assumed that the cost of hand pollination will remain the same regardless of the number of farmers adopting the technology. If, for example, the demand for hand pollinators increases as more farmers adopt the practice, all else equal, the benefit-cost ratio will decrease accordingly. Specifically, a 25% increase in the cost of hand pollinators (from GHS800 to GHS1,000) will lower the benefit-cost ratio to 8.72 at a 5% discount rate. Thirdly, depending on the quality of maintenance and the variety cultivated, the optimal fruiting duration could last 20 years. If the benefit and cost streams are extended to 20 years, the benefit-cost ratio increases to 11.08. Fourthly, some varieties start fruiting earlier than the fifth year but peak after the fourth year. All else equal, the benefit-cost ratio will be higher than the original estimate. Furthermore, if climate change or deforestation leads to a further reduction in natural pollinators, all else equal, the ratio will increase, signifying an elevated gain in hand pollination.

Table 2: Cost and Benefit Difference Between Hand Pollination and Non-Hand-Pollinated Cocoa Farms in Ghana.

Item	Pollinated Farm	Non-Pollinated Farm	Cost and Benefit difference
Cost (GHS/per acre)	GHS1,805.00	GHS1,005.00	GHS800.00
Benefit (GHS/per acre)	GHS11,600.00	GHS2,000.00	GHS9,600.00
Net Benefit (GHS/per acre)			GHS8,800.00

Note: The cost-benefit analysis is done on an acre basis. Source: Ghana COCOA BOARD.

Table 3: Cost-Benefit Analysis of Hand Pollinated and Non-Hand-Pollinated Cocoa Farms

Year	Cost Difference (GHS)	Benefit Difference (GHS	Discounted Cost	Discounted Revenue	Discounted Cost	Discounted Revenue
			3%		5%	
1	800	0	800.00	0.00	800.0	0.0
2	800	9600	776.70	9320.39	761.9	9142.9
3	800	9600	754.08	9048.92	725.6	8707.5
4	800	9600	732.11	8785.36	691.1	8292.8
5	800	9600	710.79	8529.48	658.2	7897.9

6	800	9600	690.09	8281.04	626.8	7521.9
7	800	9600	669.99	8039.85	597.0	7163.7
8	800	9600	650.47	7805.68	568.5	6822.5
9	800	9600	631.53	7578.33	541.5	6497.7
10	800	9600	613.13	7357.60	515.7	6188.2
11	800	9600	595.28	7143.30	491.1	5893.6
12	800	9600	577.94	6935.24	467.7	5612.9
13	800	9600	561.10	6733.25	445.5	5345.6
14	800	9600	544.76	6537.13	424.3	5091.1
15	800	9600	528.89	6346.73	404.1	4848.7
		Total	**9836.86**	**108442.30**	**8718.9**	**95027.0**
		BCR	**11.03**		**10.90**	

Note: The cost-benefit analysis is done on an acre basis. Source: Ghana COCOA BOARD

5.2 Ricardian analysis of Cocoa yield

Fonta et al. (2018) conducted a Ricardian analysis based on climate and crop yield data on Nigeria in West Africa. A similar model (equation 3) could not be estimated for this case study due to a lack of relevant data. Since Ghana and Nigeria have similar climatic conditions for cocoa production, the benefits of Fonta et al.'s work were transferred.[3]

The Fonta et al. (2018) Ricardian model results indicate that a 1-degree Celsius temperature increase would lead to a 13.4% reduction in cocoa yield (output per acre). Consequently, using this estimate, under these temperature conditions, non-pollinated farms, with the current national average yield of 160kg/acre, are projected to decline to approximately 138.56kg/acre (86.6% of 160kg). If the hand-pollinated and non-hand-pollinated farms are impacted uniformly by climate change, the BCR will reduce to 9.4 from the estimated 10.9. To further assess the impact of various climate scenarios (with corresponding temperature levels) on yield, we employ the integrative Shared Socioeconomic Paths-Representative Concentration Pathways (SSP-RCP) framework presented in Table 3. This framework involves analysing climate projections obtained under the RCP scenarios against the variations in various SSPs (IPCC, 2023; GARP, 2023; http://iconics-ssp.org).[4]

[3] West Africa lies between latitudes 4°N and 28°N and longitudes 15°E and 16°W. The Gulf of Guinea is the southern boundary (https://www.fao.org/4/X6543E/X6543E01.htm).

[4] The SSP scenarios (SSP1 through SSP5) show potential future developments in demographics, economy, technology, and climate policies, aiding in projecting future emissions and corresponding temperature outcomes. For instance, SSP1 envisions a sustainable world with eco-friendly practices, reaching negative emissions by 2075, resulting in a low-emission trajectory linked to a 2°C temperature increase. RCPs (RCP1.9 to RCP8.5) represent different greenhouse gas concentration trajectories utilized in climate models to forecast temperature levels.

Table 4: Ricardian estimates of yield loss using IPCC SS-RCP Framework

No	GHG emissions scenarios	Rise of global average temperature by 2100	Impact status	Yield decline
1	SSP1-1.9	Limit warming to 1.5°C	Very low	20.10%
2	SSP1-2.6	Limit warming to 2°C	Low	26.80%
3	SSP2-4.5	Limit warming to 3°C	Intermediate	40.20%
4	SSP3-7.0	Limit warming to 4°C	High	53.60%
5	SSP5-8.5	Exceed warming of 4°C	Very High	< 67.00%

Notes: *The Ricardian model estimates a 13.4% loss in yield per acre for a 1% increase in temperature. The yield decline (column 5) values are based on this estimate. The SSP1-1.9 and SSP1-2.6 are aligned with the 1.5 degrees Celsius and 2 degrees Celsius of the Paris Climate Agreement, while SSP5-8.5 is Ghana's current business-as-usual scenario.*

In the GHG emissions scenario SSP1-1.9, a sustainable economy with renewables as the primary energy source will lead to harmful net emissions, limiting warming to 1.50°C by 2100. Based on the Ricardian estimate, a temperature level of 1.50°C will lead to a 20% decline in cocoa yield[5], with a corresponding BCR of 8.7, all else equal. Conversely, there is substantial economic expansion under SSP5-8.5, emphasising economic growth over sustainability and relying significantly on fossil fuels. In this scenario, emissions sharply increase, warming exceeding 4.0°C, translating into a 67% loss in cocoa yield by 2100, and the corresponding BCR is 3.6. Thus, the BCR remains strongly positive under the worst project climate scenario (i.e., the rising global average temperature exceeding 4°C) and yield decline, thereby underscoring the potential benefits of hand pollination. Moreover, these findings underscore the severe consequences of climate change on cocoa, considering its significant role as a source of employment supporting numerous households and foreign exchange for the government. While the Government of Ghana's hand-pollination cocoa trees initiative partly mitigates these effects, additional support through mitigation and adaptation efforts is crucial.

[5] Note that a 1% increase in temperature is projected to decrease yield by 13.4%, according to Fonta et al. (2018).

6. Conclusion

Ghana's national average cocoa yield ranks among the lowest globally, primarily attributed to suboptimal agricultural practices and a decline in pollinators, including Forcipomyia Midges. Unfavourable environmental and climate conditions have exacerbated the ongoing yield decline, leading to deforestation as farmers intensify production to offset losses. In response to these challenges, the Government of Ghana implemented an adaptation programme – hand pollination of cocoa trees – to enhance limited natural pollination and check deforestation.

This study investigates the net benefits and the impact of temperature on cocoa yield. Employing cost-benefit and Ricardian analyses, the study reveals significant insights. Firstly, farmers that engage in hand pollination experience a nearly 11 times greater financial benefit, equating to an additional GHS95,000 revenue per acre compared to non-participating farmers. Secondly, Ricardian analysis indicates that a one °C temperature increase results in a 13.40% decline in yield per acre.

Furthermore, to forecast the long-term impact of climate change, the study adopts the Shared Socioeconomic Pathways-Representative Concentration Pathways (SSPs) framework of the Intergovernmental Panel on Climate Change (IPCC). Projections indicate that adhering to the Paris Climate Accord (SSP1-1.9) scenario, which restricts temperature increase to 2°C, will result in a 26.80% decline in cocoa yield by 2100. In contrast, operating under the 'business as usual' scenario (SSP5-8.5), leading to warming exceeding 40°C, is expected to reduce cocoa yield by over 67%. This shows the urgent need for robust climate change mitigation and adaptation strategies, including building farmers' capacity to undertake hand pollination.

Notably, due to a lack of data, we considered only the financial benefits of hand pollination. Future research may consider other benefits such as (i) avoided losses like agriculture deforestation and yield loss, (ii) induced economic activities from the established community-based pollination services – increased productivity and profitability of cocoa, and (iii) social and environmental benefits like biodiversity and ecosystem services, improved microclimate, enhanced livelihoods and community wellbeing. Furthermore, a cross-country comparison would be an interesting subject for future research if any country within the cocoa-producing sub-region with similar climatic conditions undertakes a hand pollination programme.

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