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UNIVERSITY CHEIKH ANTA DIOP (UCAD)

ECOLE DOCTORALE SCIENCES JURIDIQUES, POLITIQUES, ECONOMIQUES ET DE GESTION (ED – JPEG)

FACULTE DES SCIENCES ECONOMIQUES ET DE GESTION (FASEG)

PROGRAMME DOCTORAL EN ECONOMIE DU CHANGEMENT CLIMATIQUE

ANNEE: 2025 N° D'ORDRE:

Améliorer la Résilience Climatique: Le Rôle des Institutions, l'Adoption de l'Agriculture Intelligente au Climat et les Politiques de Subvention des Engrais au Bénin

Thèse de Doctorat

Présentée et soutenue publiquement pour l'obtention du titre de
Docteur ès Sciences Economiques
Par:

Moustapha Adéwolé LAWANI

Membres du Jury :

Président : M. Ahmadou Aly MBAYE, Professeur Titulaire, Université Cheikh Anta Diop de Dakar,
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Enhancing Climate Resilience: The Role of Institutions, Climate-Smart Agriculture Adoption, and Fertilizer Subsidy Policies in Benin

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Declaration

I, Moustapha A. LAWANI, hereby declare that the work presented in this dissertation is my original research and has not been submitted, either in whole or in part, to any degree or diploma at any other institution. All sources of information and data utilized in this thesis have been appropriately acknowledged and referenced. This dissertation is the result of my independent work and any assistance received has been duly credited.

I confirm that The research reported in this dissertation was conducted according to the ethical guidelines and principles of the University of Cheikh Anta Diop (UCAD). I also declare that this dissertation has been prepared following the academic and research integrity policies set forth by the University of Cheikh Anta Diop (UCAD).

Dedication

This dissertation is dedicated to my beloved family, whose unwavering love, support, and encouragement have been the foundations of my academic journey.

Thank you for being my pillar of strength and my greatest supporter.

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Acronyms and abbreviations

ADP	Agricultural Development Poles
ATE	Average Treatment Effects
ATT	Average treatment effect on the treated
ATU	Average treatment effect on the untreated
CA	Conservation agriculture
CBA	Cost-Benefit Analysis
CIAT	International Centre for Tropical Agriculture
CSA	Climate-Smart Agriculture
CSATPs	CSA practices and technologies
CSI	Climate-Smartness Index
CV	Contingent valuation
DEA	Data Envelopment Analysis
DTMV	Drought-tolerant maize varieties
ECOWAP	Economic Community of West Africa Agricultural Policy
ECOWAS	Economic Community of West African States.
EF	Eco-efficiency
EIF	Eco-inefficiency
ESR	Endogenous Switching Regression
EUT	Expected Utility Theory
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GHG	Greenhouse gas
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IIA	Independent of irrelevant alternatives
IV	Instrumental Variables
LCA	Life-Cycle Assessment
LP	Linear programming
MESR	Multinomial Endogenous Switching Regression
MNL	Multinomial logit
NGOs	Non-Government Organizations
NIE	New Institutional Economics
NPK	Nitrogen, Phosphorus, and Potassium
PANA	National Adaptation Programme of Action
PCA	Principal Component Analysis
PES	Payments for Environmental Services
PMP	Positive Mathematical Programming
PNIA	National Agricultural Investment Plan
PPP	Public-private partnerships
RHoMIS	Rural Household Multi-Indicator Survey
SAIPs	Sustainable agricultural intensification practices
SAPs	Sustainable agricultural practices
SDG	Sustainable Development goal
SFA	Stochastic Frontier Analysis
SLMPs	Sustainable land management practices
STRVs	Stress-tolerant rice varieties

TBI	Tree-based intercropping
TPB	Theory of Planned Behavior
TTA	Technology Acceptance Theory
UEMOA	Union Économique et Monétaire Ouest-Africaine
VAT	Value Added Tax
WCIS	Weather and climate information services

Abstract

This thesis examines the resilience of smallholder farmers in the Republic of Benin by analyzing the interconnected roles of institutional frameworks, Climate-Smart Agriculture (CSA) adoption, and policy interventions. It addresses how institutional support, CSA adoption, and targeted policy reforms can build resilience and promote sustainable agriculture. The thesis is structured around three main objectives. First, it investigates how governance structures, stakeholder interventions, and policy environments influence CSA adoption. Second, it assesses the impact of CSA adoption on the climate-smartness of smallholder farming systems in northern and central Benin, considering productivity, resilience, and greenhouse gas (GHG) mitigation. Third, it evaluates the sustainability of fertilizer subsidy policies, focusing on their economic benefits and environmental consequences. To achieve these objectives, the thesis combines econometric and bioeconomic models. An ordered probit model with instrumental variables is applied to secondary data for the first objective. The second and third objectives rely on household survey data and are analyzed using a multinomial endogenous switching regression and an economic mathematical programming model, respectively. Findings show that adaptation-oriented policies and stakeholder engagement promote CSA adoption, while mitigation-focused interventions may discourage it, highlighting a potential trade-off. Comprehensive CSA packages, especially those incorporating water management and integrated systems, are more effective for sustainable outcomes. Adoption is influenced by household characteristics such as education, marital status, labor, and access to land. Increased fertilizer subsidies improve farm revenues but also raise GHG emissions, with the Eco-Inefficiency Index indicating that marginal profit gains often come at the cost of environmental sustainability. Overall, this thesis emphasizes the importance of developing balanced policies that align adaptation and mitigation goals to promote resilient and sustainable agriculture.

Keywords: Climate-smart agriculture, Adoption, Farmers, Stakeholder cooperation, Policy environment, Fertilizer Subsidy Policy, Sustainability, Developing countries, Republic of Benin

General Introduction

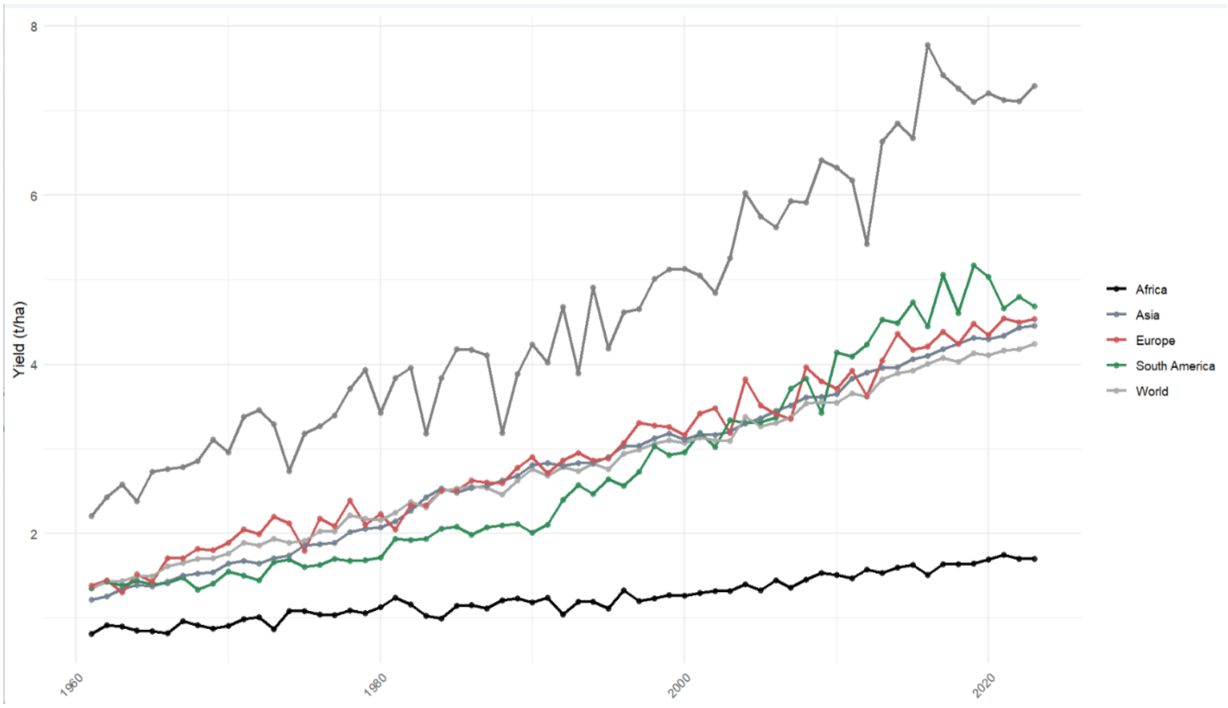
Climate change poses a severe global threat, with its manifestations—especially global warming—disrupting critical ecosystem services essential for agriculture, such as land, biodiversity, and water (IPCC, 2022). Developing countries, particularly those in Sub-Saharan Africa (SSA), are disproportionately vulnerable to these impacts due to the heavy reliance of their agricultural sectors on seasonal or rainfed systems (Kakpo, Mills, & Brunelin, 2022; Stadtbäumer, Ruesink, & Gronau, 2022). As the global population continues to rise, SSA faces increasing risks of food insecurity and poverty, which are compounded by the inability of fragile agricultural systems to cope with recurrent shocks and adverse weather events.

Recent theoretical developments in resilience and poverty have significantly advanced our understanding of how agricultural systems cope with shocks. Resilience theory, pioneered by (Holling, 1973), has evolved to capture the capacity of socio-ecological systems to absorb disturbances, adapt, and transform in the face of change (Folke, 2006; Walker, Holling, Carpenter, & Kinzig, 2004). In agriculture, resilience is not only about withstanding extreme events such as droughts or floods but also about the system's ability to reorganize and learn over time (Adger et al., 2009). The concept of social-ecological resilience further emphasizes the role of adaptive governance and community participation in fostering robust, flexible systems (Starzomski, 2004). Complementing this, modern poverty theory has expanded our understanding of vulnerability by looking beyond income deprivation to incorporate multidimensional factors such as access to credit, education, technology, and social capital (Chambers, 1996; Sen, 1999). These dimensions reveal how poverty exacerbates vulnerability, limiting a community's capacity to invest in adaptive strategies and respond effectively to shocks (Collins and Mayer, 2010). This broader perspective on poverty underscores that both structural and immediate factors contribute to long-term instability in agricultural livelihoods.

Integrating these insights, Climate-Smart Agriculture (CSA) emerges as a promising strategy. CSA is designed to enhance agricultural productivity while simultaneously building resilience and reducing environmental impacts (FAO, 2014a). CSAPTs (CSA practices and technologies) seek to achieve three objectives: (1) increase agricultural productivity and income, (2) bolster resilience against climate change, and (3) reduce or eliminate greenhouse gas (GHG) emissions (FAO, 2014a). In recent years, research has focused on CSA adoption, its impacts on farmers' livelihoods, and how to scale up CSAPTs among farming communities.

The adoption of CSAPTs is highly dependent on farmers' perceptions of climate change and their awareness of CSA (Autio, Johansson, Motaroki, Minoia, & Pellikka, 2021; Branca, Cacchiarelli, Haug, & Sorrentino, 2022; Sova et al., 2018; Tambet & Stopnitzky, 2021). For farmers who are aware of CSA, adoption decisions are influenced by socioeconomic and institutional factors, which serve as both barriers and drivers (Abegunde, Sibanda, & Obi, 2019; Kifle, Ayal, & Mulugeta, 2022; Mizik, 2021). When successfully adopted, CSAPTs can provide significant productivity, adaptation, and mitigation benefits (Israel, Amikuzuno, & Danso-Abbeam, 2020; Mesfin, 2019; Selbonne et al., 2022; Tambet & Stopnitzky, 2021). Furthermore, CSA adoption has the potential to reduce poverty and improve rural livelihoods (Habtewold, 2021; Komarek, Thurlow, Koo, & De Pinto, 2019).

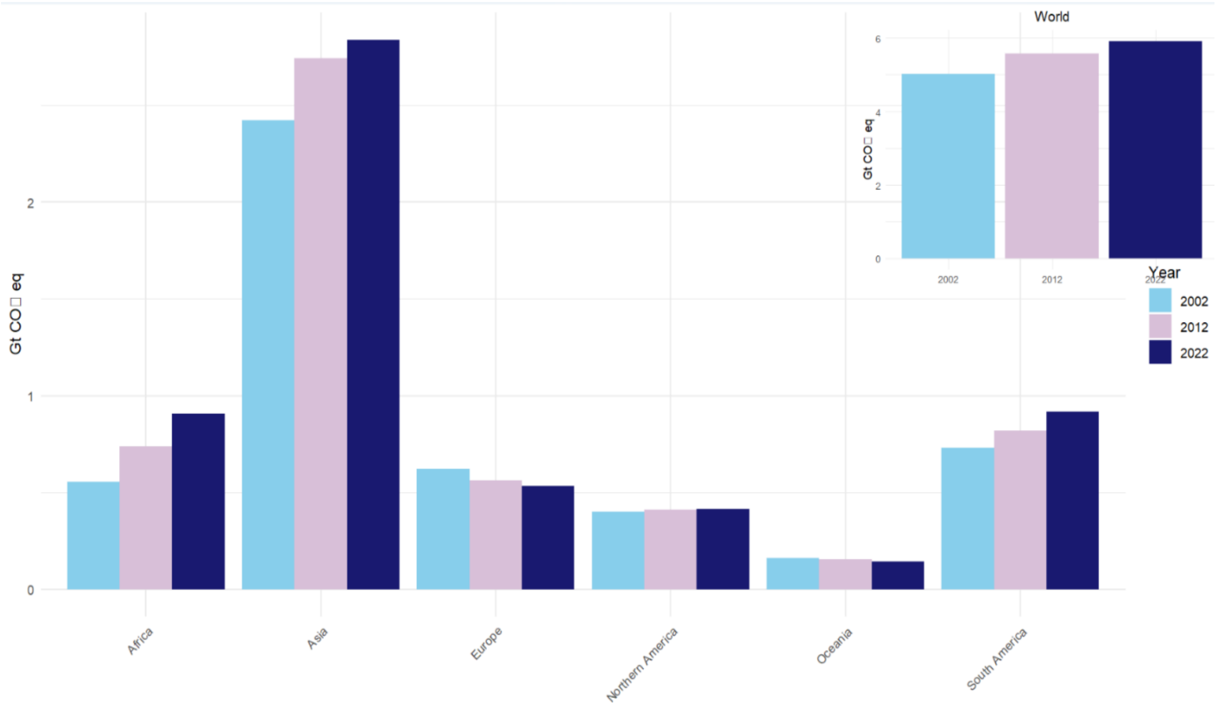
Figure 1: Trends in regional and global cereal yield (1961–2022)



Source: FAOSTAT (2025)

However, despite these advantages, challenges persist, which call into question CSA's overall effectiveness. One notable concern is whether CSA truly achieves its core objectives in real-world contexts. Empirical trends in cereal yields and agricultural GHG emissions across African regions suggest a mixed picture: while cereal yields have generally improved over time, agricultural emissions have also risen sharply (Figure 1, Figure 2). In addition, the recent report on vulnerability, impact, and adaptation of IPCC points out that African countries are experiencing an increasingly high vulnerability of food insecurity (IPCC, 2022). This indicates that productivity gains may be coming at the cost of increased vulnerability and environmental degradation, particularly in terms of emissions from fertilizer use and land-use change. Such trends call into question the extent to which CSA strategies are fulfilling their core goals and suggest a possible decoupling between productivity, adaptation, and mitigation objectives. These observations underscore the need for a more critical assessment of CSA interventions, taking into account not only their agronomic outcomes but also their environmental trade-offs. They also point to the importance of integrating context-specific institutional, ecological, and policy considerations to ensure that CSA contributes effectively to both climate adaptation and mitigation in vulnerable agricultural regions.

Figure 2: Trends in regional and global emissions due to agriculture



Source: FAOSTAT (2025)

The first challenge is the low adoption and promotion of CSAPTs, which undermines the potential for resilience-building and leaves many farmers vulnerable to climate change (Autio et al., 2021; Kifle et al., 2022; Tesfaye, Blalock, & Tirivayi, 2021). Although institutional factors have been widely identified as key to CSA adoption, most focus on national contexts, overlooking the significant heterogeneity across countries and regions (Sova et al., 2018). Institutional factors, such as access to extension services, markets, and credit, have been shown to correlate positively with CSA adoption (Abegunde et al., 2019; Kifle et al., 2022; Sova et al., 2018). Extension services provide training and information that enable farmers to make informed decisions about CSA practices. Market access ensures that CSA practices are economically viable, while access to credit allows farmers to invest in the required technologies. However, these institutional factors are themselves shaped by broader institutional arrangements, formal and informal rules, norms, and organizations, including policy frameworks, stakeholder coordination mechanisms, and financial systems (North, 1990).

Climate change has prompted a global commitment to action, as reflected in key events like the Paris Agreement. In response, a variety of stakeholders have become actively engaged, especially in developing countries, aiming to promote sustainable agricultural practices and influence climate-related policies. According to CSA country profiles (Sova et al., 2018), government actors, international development partners, and research institutions are the most prominently involved in CSA initiatives. In contrast, other important stakeholders, such as financial institutions, NGOs, the private sector, and farmers' organizations, are less represented.

Despite the diversity and involvement of stakeholders across regions, major barriers to CSA adoption remain. These challenges are primarily institutional, encompassing environmental constraints, socio-cultural norms, limited access to training and information, inadequate policy and institutional support, and economic limitations (Sova et al., 2018). The persistence of these barriers suggests that low CSA adoption cannot be attributed solely to the absence of institutions or policy frameworks, as commonly cited in the literature. Rather, it raises questions about the effectiveness and coordination of existing stakeholders and institutional arrangements.

Relatively few empirical studies have rigorously examined the role of institutions, in particular CSA Policies and Stakeholder Ecosystems, in promoting the adoption of CSA, particularly given the significant heterogeneity observed across countries and regions. This gap is particularly critical in Sub-Saharan Africa, where agriculture is predominantly rainfed and highly vulnerable to climate variability. In such contexts, institutional capacity—particularly the ability to deliver timely information, ensure financial inclusion, and foster market integration—is crucial to facilitating

CSA adoption. Research by Kifle et al. (2022) and Sova et al. (2018) highlights the institutional weaknesses in these areas that can hinder CSA uptake, making institutional strengthening a central focus of this research.

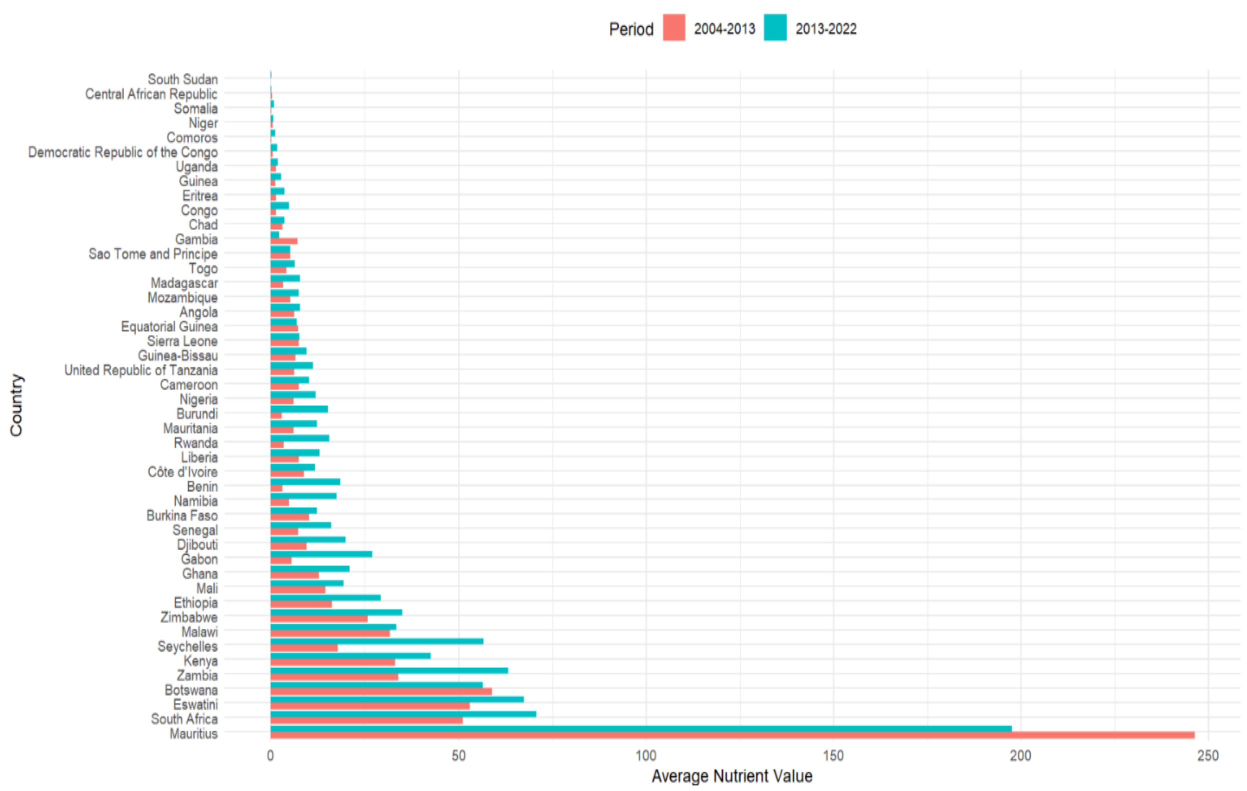
From the theoretical perspective, the thesis is anchored in the theoretical frameworks of new institutional economics and rational choice theory. These theories provide insights into how formal and informal institutions, transaction costs, and individual utility-maximization behavior shape farmers' decision-making in uncertain environments. While rational choice theory emphasizes the role of individual agency and perceived benefits in decision-making, institutional theory highlights how rules, norms, and governance structures constrain or enable these choices. The tension and complementarity between these frameworks are particularly relevant in the context of CSA, where adoption decisions are influenced not only by expected utility but also by institutional support and stakeholder dynamics. By situating the thesis within these theoretical debates, this research contributes to a deeper understanding of the structural and behavioral drivers behind CSA adoption, with practical implications for designing more effective agricultural policies and interventions.

The second challenge lies in the theoretical and empirical controversy surrounding the actual effectiveness of CSA in achieving its dual goals—enhancing climate resilience and reducing greenhouse gas (GHG) emissions. The recent trends in cereal yields (Figure 1) and agricultural GHG emissions (Figure 2) alongside the increasingly high vulnerability of food security prediction (IPCC, 2022) suggest a disconnect between CSA's intended outcomes and its on-the-ground impacts (FAO, 2014a). One reason for this discrepancy may lie in the limitations of current CSA assessment tools, which often fail to capture the socioeconomic and environmental dimensions fully (Challinor, Arenas-Calles, & Whitfield, 2022; Wijk, Merbold, Hammond, & Butterbach-Bahl, 2020). For instance, many studies focus primarily on biophysical factors, neglecting the socioeconomic aspects of food security and environmental sustainability, thereby offering an incomplete picture of CSA's effectiveness (Wijk et al., 2020). These measurement gaps risk misinforming policy decisions and obscuring the real impacts of CSA interventions.

From a theoretical perspective, this concern aligns with the maladaptation theory, which argues that well-intended adaptation measures may inadvertently increase vulnerability or reinforce existing inequalities if not contextually appropriate (Schipper, 2020; Lisa, 2020). For instance, Shah et al. (2024) demonstrate how some CSA practices, when not aligned with local realities or implemented without adequate stakeholder engagement, can contribute to unintended negative outcomes such as social exclusion or environmental degradation. These findings underscore the importance of addressing systemic issues—such as institutional weaknesses, power asymmetries, and context-specific trade-offs—within CSA planning and evaluation. Therefore, a key theoretical and empirical gap lies in the failure to adequately consider how CSA may lead to maladaptive outcomes when narrowly assessed or poorly contextualized, highlighting the need for a more nuanced and integrative framework for evaluating CSA interventions.

The third challenge stems from agricultural policies, particularly fertilizer subsidy policies, which may exacerbate GHG emissions and undermine sustainable production. Fertilizer subsidy policies are defined as public interventions aimed at lowering the cost of fertilizers to farmers, typically through direct price reductions, voucher systems, or targeted distribution, to improve input access, boost yields, and enhance food security. The dual crises of COVID-19 and the Russian-Ukrainian conflict have led to a spike in fertilizer prices, intensifying the risk of climate-induced food insecurity in developing countries (FAO, 2022; Kinkpe et al., 2023). In response, several African countries, including the Republic of Benin, have implemented fertilizer subsidy policies aimed at mitigating food insecurity (future, 2018, 2020). However, while these subsidies may boost productivity, their environmental consequences, such as increased GHG emissions, are concerning (Honfoga, 2018; Jote, 2023). Given that nitrogen-based fertilizers are a significant source of nitrous oxide (N2O), a potent GHG, there is a need to assess the sustainability of these production systems and the long-term impacts of fertilizer subsidy policies on climate change (Chai, J. Pannell, & G. Pardey, 2023; Kanter, 2018).

Figure 3: Average fertilizer[1] use by country in SSA for 2004-2013 and 2013-2022



Source: FAOSTAT (2025)

Recent trends further underscore this concern. Data from FAOSTAT reveal that average fertilizer use in Sub-Saharan Africa has increased markedly in the last decade (2013–2022) compared to the previous one (2004–2013), with pace disparities among countries. Around 87% of countries (40 out of 46 countries) have seen substantial increases in fertilizer application, likely driven by subsidy programs and agricultural intensification efforts. However, a few countries, including the Central African Republic, The Gambia, Sao Tome and Principe, Equatorial Guinea, Botswana, and Mauritius, have shown limited or no progress in fertilizer use. Particularly striking is the growth in fertilizer application in East and West African countries, many of which have seen increases of at least 50% over the last decade. In some countries, such as Seychelles, Rwanda, Namibia, Gabon, Burundi, and the Republic of Benin, average fertilizer use has risen more than fivefold compared to the previous period. This growing trend signals an imperative to ensure that

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[1] kg of fertilizer nutrients (Nitrogen (N), Phosphates (P205), Potash (K20)) per ha of arable and permanent cropland

fertilizer use contributes to sustainable and climate-resilient agriculture rather than merely boosting short-term yields. Without integrated approaches that link fertilizer subsidy policy with climate-smart agriculture goals, current strategies risk reinforcing unsustainable production patterns while leaving vulnerable farmers in a vicious circle.

The Republic of Benin Case Study

The Republic of Benin was chosen as a case study because it presents a distinct context that illustrates the gap between the theoretical promise of CSA and its practical outcomes, as highlighted in the thesis. In the Republic of Benin, where agriculture contributes 25% to the national GDP and plays a central role in national adaptation plans (NDC, 2021), CSA practices in both crop and livestock sectors are vital for building resilience. However, despite the adoption of CSA practices, agricultural emissions are projected to rise by 71% between 2018 and 2030, and vulnerability scenarios reveal that climate risks to both natural and human systems are likely to persist or intensify, depending on the sector in question (NDC, 2021). According to projections for 2025, 2050, and 2100, Benin faces a wide range of climate impacts, including coastal flooding, saline water intrusion into rivers and groundwater, and significant yield declines for key crops such as maize, particularly in vulnerable agroecological zones like ZAE5. Moreover, anticipated shifts in flooding patterns in the Beninese portion of the Niger River Basin compound these risks (NDC, 2021). This raises critical questions about the effectiveness of CSA in achieving national climate adaptation and food security goals. With over half of Benin’s population (51.3%) relying on agriculture for their livelihood, these mounting vulnerabilities underscore the urgent need to critically reassess how CSA adoption and related policy interventions contribute not only to productivity but also to long-term climate resilience, poverty reduction, and environmental sustainability.

Recent data reveals a concerning picture. In 2021, smallholder farmers recorded a resilience index of just 51.9, below the national average of 53.8 (DSA, 2023a; RNA, 2023). The adoption of CSA practices remains low in sub-Saharan Africa, with West Africa showing the lowest rate (38.9%) compared to 56.7% in Eastern Africa (Mnukwa, Mdoda, & Mudhara, 2025). In Benin, only 25% of smallholders have adopted at least one CSA practice, with adoption concentrated in the northern regions (World Bank, 2022). Institutional support is also uneven: while 45% of farmers in the north report access to extension services, only 28% do in the central region (MAEP, 2022).

Fertilizer subsidies, introduced in 2017, have led to a 30% increase in nitrogen fertilizer use; however, GHG emissions from agriculture have also risen by 15% during the same period (FAOSTAT, 2023). Historically, fertilizer subsidies have long been a cornerstone of Benin's agricultural policy. Initially covering over 50% of input costs in the early 1980s, subsidies declined during the structural adjustment era due to fiscal constraints and the 1994 CFA franc devaluation (Kormawa, Munyemana, & Soule, 2003). The cotton sector, contributing around 90% of export earnings, has consistently benefited from a more structured subsidy framework supported by a corporatist contract farming model that ensures access to fertilizers at uniform prices through credit systems, tax exemptions, and transport subsidies (Kuhn, Gaiser, & Gandonou, 2010). Despite UEMOA reforms reducing import duties from 29% to 7% by 2000, VAT remained at 18%, and cotton-specific inputs often continued to receive partial or full tax exemptions. Between 2000 and 2009, direct fertilizer subsidies rose from covering 4.6% to 32% of input costs, with market prices fluctuating widely, particularly after the 1994 devaluation.

In recent years, faced with inflation and global price spikes, the government has shifted its subsidy focus to maize and cotton—key to both food security and export revenue—targeting improved access to Urea and NPK fertilizers (Hounnou et al., 2023). Between 2022 and 2024, about $181.5 million in fertilizer subsidies, resulting in a 9.4% increase in fertilizer imports in 2022 and a 26.8% increase in 2023 (Benin, 2022b, 2024). For the 2024/2025 season, the subsidy budget was set at 24.4 billion FCFA (approximately US$39.7 million), with fixed prices significantly below market levels. While these policies aim to safeguard national food systems, they also present a fiscal dilemma, as the government must balance farmer affordability with macroeconomic and environmental sustainability amid rising global uncertainty.

Beyond their immediate benefits for smallholder farmers, fertilizer subsidies carry significant macroeconomic implications. With over $180 million allocated in just three years, these programs place substantial strain on the national budget—resources that could otherwise support infrastructure, health, or education. The fiscal sustainability of such subsidies is increasingly questioned in light of Benin's public debt levels and limited revenue mobilization capacity. Additionally, subsidies may distort input markets, reduce incentives for private sector engagement, and expose the country to external shocks due to its dependence on imported fertilizers. Overapplication or misuse of subsidized inputs can also degrade ecosystems and pose public health risks, generating hidden long-term costs. These factors highlight the urgent need to reassess subsidy design to ensure it aligns with broader sustainability, climate resilience, and structural transformation goals.

Benin’s policy landscape reflects a clear commitment to climate adaptation through agriculture. National strategies such as the National Adaptation Programme of Action (PANA) and the National Agricultural Investment Plan (PNIA) emphasize CSA as a means to achieve sustainable productivity, resilience, and environmental stewardship. At the regional level, frameworks like ECOWAP and the WAEMU/ECOWAS Climate Strategy advocate for climate-resilient technologies, improved soil management, and enhanced institutional capacity across West Africa. These policies aim to reduce vulnerability by building adaptive capacity among smallholder farmers. This research contributes to these goals by examining how institutional and policy interventions influence CSA adoption in Benin, thereby offering insights into how to scale up CSA effectively and equitably in support of national and regional resilience-building efforts.

Thesis Research Questions, Objectives, and Hypotheses

To address the gap between the theoretical promise of CSA and its practical outcomes, this thesis seeks to answer the following general question: *How do institutions, CSA adoption, and fertilizer subsidy policies influence the resilience and environmental sustainability of the agricultural sector in developing countries?* In this regard, the thesis answers the following specific research questions: (1) What is the effect of institutions on the adoption of CSA in developing countries? (2) What is the impact of CSA adoption on the climate-smartness of farming systems in the Republic of Benin, particularly in terms of food security, adaptation, and mitigation? (3) How do fertilizer subsidy policies affect the sustainability of agricultural production in Benin?

This thesis aims to contribute to the literature on the adoption of CSA by highlighting the mechanisms through which CSA can build resilience and sustainability. The overall objective is *to explore how institutions, CSA adoption, and fertilizer subsidy policies influence resilience and sustainability in the agricultural sector*. Specifically, the thesis aims to: (1) Analyze the effects of institutions on the adoption of CSA in developing countries; (2) Assess the impact of CSA adoption on the climate-smartness of farming systems in the Republic of Benin; and (3) Assess the impact of fertilizer subsidy policies on the sustainability of agricultural production in Benin.

Based on these objectives, the following hypotheses are proposed: (1) Institutions significantly influence the likelihood of CSA adoption among smallholder farmers in developing countries; (2) CSA adoption enhances the climate-smartness of farming systems in the Republic of Benin by improving each CSA objective; (3) The current fertilizer subsidy policy promotes the overuse of fertilizers, contributing to increased GHG emissions in Benin.

Added Value of the Thesis

This thesis contributes to the growing literature on sustainable agriculture and climate resilience by examining how institutional arrangements and policy interactions shape the adoption of CSA in Benin. It fills a critical gap by analyzing not only the effectiveness of CSA interventions but also the roles of policy coherence, stakeholder cooperation, and institutional design in influencing outcomes for climate-vulnerable smallholders. Chapter 1 adopts a macro-institutional lens to assess how national and subnational actors interact to create synergies or conflicts in CSA implementation, shedding light on adaptation–mitigation governance. Chapter 2 uses farm-level data to empirically evaluate the impacts of CSA packages on productivity, resilience, and mitigation, offering a more holistic and contextualized assessment than previous studies. Chapter 3 provides one of the few integrated evaluations of fertilizer subsidy policy from an environmental sustainability and resilience-building perspective. Together, these chapters offer an original contribution by linking institutional economics with sustainability policy analysis and delivering actionable recommendations for enhancing agricultural resilience in West Africa. The findings are highly relevant to policymakers, development partners, and researchers aiming to align productivity, adaptation, and environmental goals.

Methodology and Structure

To achieve these objectives, the thesis employs a combination of quantitative methodologies. The analysis of institutions' effects on CSA adoption was conducted using a logit model with an instrumental variable approach. For evaluating the climate-smartness of farming systems, a multinomial endogenous switching regression model was utilized, which is well-suited for addressing issues of endogeneity and selection bias. The impact of fertilizer subsidy policies on sustainability was assessed through integrated bioeconomic modeling to evaluate fertilizer use efficiency.

This thesis is organized into three chapters, each corresponding to one of the research objectives. The first chapter analyzes the role of institutions in CSA adoption across regions. The second chapter evaluates the impact of CSA adoption on farming systems in Benin. The third chapter assesses the sustainability of fertilizer subsidy policies. The thesis concludes with a synthesis of findings and implications for policy and practice.

Chapter 1 Analysis of the Effect of Institutions on the Adoption of Climate-Smart Agriculture

Abstract

Climate-Smart Agriculture (CSA) holds significant promise for enhancing food security and climate resilience in developing countries; however, its adoption remains low due to weak institutional frameworks and fragmented stakeholder engagement. This research investigates how climate policies and stakeholder interventions influence CSA adoption in developing countries, emphasizing the institutional conditions that facilitate or hinder implementation. Grounded in New Institutional Economics, this research examines the effect of institutions on adoption outcomes. Using empirical data, it finds that globally, climate policies in agriculture positively influence CSA adoption, particularly policies in the field of adaptation. In addition, CSA adoption is indirectly and positively influenced by stakeholders engaged in adaptation or both adaptation and mitigation. However, the negative effect of policies and stakeholders' contributions in the mitigation field suggest a potential trade-off between the two objectives. Regarding policy environment establishment, the findings show that multilateral cooperation among stakeholders—especially between governments, farmers, and research institutions—is more influential than isolated stakeholder efforts. Based on these insights, the research recommends prioritizing well-designed policies focusing on both adaptation and mitigation objectives, fostering and institutionalized stakeholder cooperation, improving climate finance's efficiency, and investing in institutional capacity-building. By highlighting the institutional dynamics underlying CSA adoption, this research provides actionable guidance for developing integrated policy frameworks that align productivity, adaptation, and sustainability goals across sub-Saharan Africa.

Keywords: stakeholders, policies, adoption, climate-smart agriculture, cooperation, developing countries

Résumé

L'Agriculture Intelligente face au Climat (AIC) représente une opportunité majeure pour renforcer la sécurité alimentaire et la résilience climatique dans les pays en développement ; cependant, son adoption demeure faible en raison de cadres institutionnels fragiles et d'une implication fragmentée des parties prenantes. Cette recherche examine comment les politiques climatiques et les interventions des parties prenantes influencent l'adoption de l'AIC dans les pays en développement, en mettant l'accent sur les conditions institutionnelles qui facilitent ou entravent sa mise en œuvre. Ancrée dans la Nouvelle Économie Institutionnelle, cette étude analyse l'effet des institutions sur les résultats en matière d'adoption. À partir de données empiriques, elle révèle que, à l'échelle mondiale, les politiques climatiques dans le secteur agricole ont un effet positif sur l'adoption de l'AIC, notamment celles axées sur l'adaptation. Par ailleurs, l'adoption de l'AIC est également influencée de manière positive et indirecte par les parties prenantes engagées dans l'adaptation, ou dans les deux dimensions — adaptation et atténuation. Cependant, l'effet négatif des politiques et de l'implication des acteurs dans le domaine de l'atténuation suggère un possible arbitrage entre ces deux objectifs. Concernant l'établissement d'un environnement politique favorable, les résultats montrent que la coopération multilatérale entre les parties prenantes — notamment entre les gouvernements, les agriculteurs et les institutions de recherche — a un impact plus important que les efforts isolés. À partir de ces constats, la recherche recommande de privilégier des politiques bien conçues intégrant à la fois les objectifs d'adaptation et d'atténuation, de promouvoir une coopération institutionnalisée entre les parties prenantes, d'améliorer l'efficacité du financement climatique et d'investir dans le renforcement des capacités institutionnelles. En mettant en lumière les dynamiques institutionnelles qui sous-tendent l'adoption de l'AIC, cette recherche fournit des orientations concrètes pour l'élaboration de cadres politiques intégrés alignant les objectifs de productivité, d'adaptation et de durabilité à travers l'Afrique subsaharienne.

Mots-clés : parties prenantes, politiques, adoption, agriculture intelligente face au climat, coopération, pays en développement.

1.1 Introduction

Climate-smart agriculture (CSA) offers a promising solution to mitigate the adverse effects of climate change while ensuring food security, particularly in developing countries where agriculture is highly climate-dependent (Ariom et al., 2022; Jones et al., 2023). Despite its potential, CSA adoption remains significantly low, leaving farmers vulnerable to productivity loss, income reductions, and heightened food insecurity. Recent data shows that Western Africa shows the lowest adoption (38.9%) of CSA practices compared to the highest rate of 56.7% in Eastern Africa (Mnukwa et al., 2025). This gap in adoption can largely be attributed to weak institutional frameworks, including the absence of supportive policy environments and insufficient stakeholder cooperation (Lewis & Rudnick, 2019; Trnka et al., 2022; Zougmoré et al., 2019). Understanding how climate policies and stakeholder interventions in agriculture influence CSA adoption and how stakeholders contribute to creating conducive institutional conditions are crucial to scaling up CSA globally in alignment with the Sustainable Development Goals (SDGs). The institutions affect the adoption decision of farmers through a policy environmental framework that shapes the institutional factors. Studies demonstrated that a robust policy environment can help manage trade-offs, minimizing challenges and constraints to adoption (Makate, 2019a). In addition, it can leverage private investment to address significant financial gaps for adaptation in sub-Saharan African countries (Khatri-Chhetri et al., 2021; Lewis & Rudnick, 2019; Mungai, Ndiritu, & Silva, 2021; Patra & Babu, 2023).

CSA integrates farming practices, technologies, and services aimed at increasing agricultural productivity, building resilience to climate impacts, and reducing greenhouse gas emissions (FAO, 2014a). However, achieving these objectives often involves trade-offs, particularly between short-term adaptation goals and long-term mitigation objectives. For CSA to be widely adopted, it is essential to address these trade-offs through comprehensive policy frameworks that facilitate both adaptation and mitigation (Lewis & Rudnick, 2019). New Institutional Economics (NIE) offers a valuable theoretical foundation for examining the institutional barriers that hinder CSA adoption. NIE emphasizes the role of institutions—formal and informal rules, regulations, and organizations—that shape economic behavior and decision-making (North, 1990). In the context of CSA, key institutions include government policies, stakeholder interactions, and financial systems, all of which influence farmers' decisions to adopt sustainable agricultural practices (Kherallah & Kirsten, 2002; Ménard & Shirley, 2008).

According to NIE, institutions help reduce uncertainty in economic transactions by establishing a framework for coordination and cooperation (Kherallah & Kirsten, 2002). In the case of CSA, this institutional framework includes not only formal policies, such as climate change adaptation and mitigation strategies, but also the informal norms and practices that guide how stakeholders—governments, NGOs, the private sector, and farmers—interact and cooperate. Without effective institutional support, such as well-coordinated policies or strong stakeholder networks, transaction costs may rise, reducing farmers' incentives to adopt CSA practices (Williamson, 2000). These barriers are particularly pronounced in developing countries, where institutional capacity may be lower, exacerbating the challenges of CSA implementation (Khan, Gao, & Abid, 2020; Markkanen & Anger-Kraavi, 2019; Nyiwul, 2021; Shilomboleni, 2020).

Recent research has highlighted the weak policy frameworks in many African countries, with insufficient adaptation and mitigation policies posing significant barriers to CSA adoption (Lewis & Rudnick, 2019; Nyiwul, 2021). Furthermore, these weak frameworks often exacerbate existing social inequalities and leave countries more vulnerable to climate shocks (Markkanen & Anger-Kraavi, 2019; Nyiwul, 2021). New Institutional Economics theory suggests that enhancing the formal institutional environment, through effective, coordinated policies that align adaptation and mitigation efforts, can lower transaction costs and facilitate CSA adoption. In this context, the interaction between adaptation and mitigation policies represents an institutional challenge, as policies focusing solely on one objective may undermine the other (Barasa, Botai, Botai, & Mabhaudhi, 2021; Newell et al., 2019; Shilomboleni, 2020).

Stakeholders play a crucial role in shaping the institutional environment that governs CSA adoption. As defined by NIE, institutions are not just formal rules, but also the networks and relationships between stakeholders that influence policy development and implementation (North, 1990). In the context of CSA, effective cooperation among stakeholders is essential for creating a supportive policy environment that reduces barriers to adoption. However, in many developing countries, stakeholder cooperation is weak, hindering the establishment of robust CSA frameworks (Lewis & Rudnick, 2019; Zougmoré et al., 2019). Stakeholders—including government agencies, NGOs, the private sector, and farmer organizations—bring unique perspectives and resources, but without strong cooperation, the implementation of CSA policies will be fragmented and ineffective (Lewis & Rudnick, 2019; Sova et al., 2018).

This research examines the effects of institutions on CSA adoption in developing countries. Specifically, it will investigate how climate policies and stakeholder interventions in agriculture impacted CSA adoption and explore the role of stakeholders in shaping the policy environment framework for CSA. By addressing these questions, this research seeks to contribute to the design of more effective policy frameworks that promote the global adoption of CSA, as the lack of such a supportive environment affects nearly 90% of CSA interventions worldwide, leaving farmers vulnerable to climate change (Sova et al., 2018). Furthermore, this understanding will also shed light on the delays in CSA policy implementation observed in many developing countries (Kooffreh, Anyatang, & Aminone, 2023; Sova et al., 2018).

Results indicate that globally, climate policies in agriculture positively influence CSA adoption, particularly policies in the field of adaptation. In addition, CSA adoption is indirectly and positively influenced by stakeholders engaged in adaptation or both adaptation and mitigation. However, the negative effect of policies and stakeholders' contributions in the mitigation field suggests a potential trade-off between the two objectives. Regarding policy environment establishment, the findings show that multilateral cooperation among stakeholders, especially between governments, farmers, and research institutions, is more influential than isolated stakeholder efforts.

This research contributes to the literature by empirically analyzing the effect of climate policies and stakeholder involvement on CSA adoption, while also highlighting the institutional trade-offs between adaptation and mitigation objectives. In addition, it underscores the importance of stakeholder cooperation in building supportive CSA policy environments and identifies the most effective forms of collaboration for establishing robust policy environments that facilitate CSA adoption.

The remainder of this research is organized as follows. Section 2 reviews the literature related to policies, stakeholders, and CSA adoption practices. Section 3 outlines the methodology. Section 4 presents and discusses the results. Sections 5 and 6 present the hypotheses validation and policy implications, respectively. Finally, Section 7 concludes.

1.2 Literature review

1.2.1 Theoretical Review

The adoption of CSA practices is influenced by a complex interaction of institutions, social resilience, and individual behavioral factors. This research is grounded in the theoretical perspectives of New Institutional Economics (NIE), resilience theory, and technology adoption theories, each offering critical insights into the determinants of CSA adoption among smallholder farmers.

New Institutional Economics (NIE), as developed by North (1990), emphasizes the role of institutions—formal rules, informal norms, and enforcement mechanisms—in shaping economic behavior. In the context of CSA, institutions such as extension services, input markets, and governance structures shape farmers' access to information, resources, and incentives. NIE posits that institutions influence adoption by altering transaction costs and creating the incentives and constraints that condition farmers' decisions (Williamson, 2000; Coase, 2000). Effective institutions can reduce uncertainty and risk, facilitate coordination among stakeholders, and lower the costs of accessing CSA technologies. Conversely, weak institutions raise transaction costs and hinder adoption. Institutional arrangements—such as public-private partnerships or multi-actor coordination platforms—can play a critical role in enabling CSA by aligning incentives across actors (Kherallah & Kirsten, 2002; Ménard & Shirley, 2008).

Resilience theory contributes an ecological and systems-based perspective, focusing on the capacity of agricultural systems to absorb disturbances and adapt to climatic stressors. According to Folke (2006) and Walker et al. (2004), resilience is both biophysical and social, encompassing adaptive capacity, flexibility, and institutional learning. Smallholder farmers' ability to adopt CSA practices depends on their capacity to respond to and prepare for climatic risks, which in turn is shaped by local knowledge systems, social networks, and enabling institutions. The theory thus underscores the importance of adaptive governance, learning processes, and community participation in enhancing the uptake of CSA innovations.

Technology adoption theories explain how individual perceptions, attitudes, and behavioral intentions shape the decision to adopt innovations. The Diffusion of Innovations Theory (Rogers, 2003) highlights key determinants such as relative advantage, compatibility, complexity, and trialability. More recently, behavioral frameworks like the Theory of Planned Behavior (TPB) and the Technology Acceptance Theory (TTA)—both derived from the Theory of Reasoned Action (Fishbein & Ajzen, 1975)—have been used to understand CSA adoption. TPB emphasizes social-psychological factors such as subjective norms, perceived behavioral control, and attitudes toward behavior (Zhang et al., 2020). However, in the context of smallholders facing acute climate risks, the TTA may be more applicable. TTA emphasizes perceived usefulness, ease of use, and credibility as the main drivers of technology acceptance (Lin, Wu & Nga, 2013). When facing urgent climate vulnerabilities, farmers are less influenced by social expectations and more motivated by the perceived reliability and practicality of CSA practices.

This research integrates New Institutional Economics (NIE), resilience theory, and technology adoption theories to provide a comprehensive understanding of CSA adoption. Institutions, as emphasized by NIE, influence adoption by shaping the transaction costs and incentive structures that determine access to and use of agricultural innovations. These institutions—through policies, market mechanisms, and stakeholder cooperation—can reduce uncertainties and create an enabling environment for CSA. At the same time, resilience theory highlights the importance of adaptive capacity, where institutions and social networks support farmers in responding to climatic shocks through flexible, knowledge-driven strategies. In this context, institutions not only reduce economic barriers but also foster system-wide resilience. Finally, technology adoption theories, particularly the Technology Acceptance Theory (TTA), focus on farmers' behavioral responses, suggesting that adoption decisions are shaped by perceptions of credibility, usefulness, and ease of use. Crucially, these perceptions are themselves influenced by the institutional and social environment—supportive institutions increase trust in CSA solutions, enhance access to information, and reduce complexity.

While all three perspectives enrich the understanding of CSA adoption, this research places NIE at the core of its theoretical framework. This focus is justified by the research's central objective: to examine how CSA policies and the ecosystem of stakeholders influence adoption outcomes. Given that NIE provides the most robust tools for analysing the role of institutions, transaction costs, and stakeholder arrangements in shaping economic behaviour and organizational performance, it offers the most relevant lens for exploring the institutional dynamics driving or constraining CSA adoption. Thus, resilience theory and technology adoption models are used as complementary lenses, helping to contextualize behavioural and systemic responses within the institutional frameworks emphasized by NIE.

1.2.2 Empirical review

Socioeconomic factors alone have failed to fully explain this limited adoption, prompting increasing attention to the policy, institutional, and financial dimensions of CSA adoption (Lewis & Rudnick, 2019; Mungai, Ndiritu, & Da Silva, 2022; Patra & Babu, 2023). The literature on CSA adoption focuses on three key areas: policy frameworks for climate adaptation, the role of climate finance, and the importance of stakeholder cooperation in driving CSA adoption.

1.2.2.1 Climate-smart agriculture and policy

Effective policymaking for climate change adaptation in agriculture requires a strong national commitment. (Sorgho et al., 2020) note that most countries have integrated climate adaptation strategies into their national development plans, with agriculture being a key sector. This integration demonstrates a high level of commitment to climate adaptation in agriculture. However, the actual implementation of these policies reveals critical challenges. (Raile, Young, Kirinya, Bonabana-Wabbi, & Raile, 2021)Using semi-structured interviews, they argue that despite this apparent commitment, weak political will and insufficient public support hinder the practical implementation of these policies. The authors highlight the lack of agricultural extension services, infrastructure, and incentives as barriers to CSA adoption, emphasizing that these elements are crucial for scaling CSA practices and technologies (Raile et al., 2021).

While some studies emphasize the importance of public policy in implementing climate adaptation strategies, others focus on the adaptive capacity of farmers. Researchers such as (Hengesbaugh, King, & Zusman, 2020) and (Vanschoenwinkel, Moretti, & Van Passel, 2019) stress that building farmers' adaptive capacity is a prerequisite for effective climate adaptation in agriculture. This capacity depends on access to resources, including infrastructure, institutions, finances, human capital, and natural assets (Maldonado-Méndez & Romo-Lozano, 2022). Strengthening these dimensions is essential for farmers to adapt to climate risks and adopt CSA practices.

The human dimension, particularly training and capacity-building initiatives, plays a vital role in CSA adoption. (Hengesbaugh et al., 2020) emphasizes that policy reforms should prioritize the promotion, monitoring, and financing of educational programs related to climate-smart farming practices. Furthermore, (Budiman, 2019) is against potential climate injustice, where smallholders bear disproportionate costs in emission reduction efforts, highlighting the need for farmer-centered policy approaches to ensure equitable CSA adoption.

1.2.2.2 Climate-smart agriculture and institutions

Beyond policy, institutions—both formal and informal—play a central role in shaping CSA adoption. This section focuses on institutions as organizations and stakeholders that influence CSA interventions. Several studies have explored the role of institutional capacity and cooperation in driving the effective adoption and scaling of CSA practices. Although public institutions demonstrate a growing awareness of climate change issues (Sorgho et al., 2020), their capacity to support climate adaptation and risk management in agriculture is often constrained by limited resources and institutional arrangements (Khan et al., 2020). Strengthening the physical and financial capacities of these institutions, particularly through collaboration between public and private sectors, has been identified as a crucial solution (Khan et al., 2020).

Stakeholder cooperation is widely recognized as a critical factor for effective climate adaptation and risk management in agriculture (Dinesh et al., 2018; Makate, 2019b; Patra & Babu, 2023; Rosenstock, Nowak, & Girvetz, 2019; Trnka et al., 2022; Zougmoré et al., 2019). (Trnka et al., 2022) emphasize the need for consistent levels of knowledge about climate change among all stakeholders, identifying disparities between research institutions and both government and private sector actors as key barriers to cooperation. These differences in knowledge regarding climate change adaptation and mitigation are sources of disagreement that hinder the formation of a cohesive climate policy framework.

Recent studies highlight the importance of a participatory approach in scaling CSA practices. (Makate, 2019b) argues that promoting CSA benefits, securing stakeholder support, and ensuring appropriate policy frameworks are critical for sustainable adoption. Participatory platforms, innovation networks, and social movements are identified as successful drivers of CSA uptake (Makate, 2019c; Rosenstock, Lamanna, Namoi, Arslan, & Richards, 2019). These platforms facilitate the engagement of stakeholders in collaborative decision-making processes, ensuring that diverse expertise is utilized to create effective CSA interventions.

Agricultural research also plays a pivotal role in CSA adoption. Studies such as those by (Dinesh et al., 2018) and (Zougmoré et al., 2019) emphasize the importance of science-policy engagement in supporting CSA interventions. The integration of evidence-based research with policy development ensures that CSA practices are grounded in scientific rigor and are more likely to be successfully implemented.

1.2.2.3 Climate-smart agriculture and climate finance

Climate finance is essential for supporting developing countries to transition to sustainable agricultural practices and achieve climate resilience. However, the scale of funding required to meet these goals necessitates innovative financing mechanisms. (Valverde, Grüning, König, Menzel-Hausherr, & Pauw, 2022) highlight the potential of policy-based finance instruments, such as the Green Climate Fund, to support policy development frameworks that drive CSA adoption.

In the agricultural sector, where adaptation finance is particularly limited (Coayla & Jiménez, 2022), there is an urgent need for new mechanisms to finance the transition to low-carbon agriculture. (Khatri-Chhetri et al., 2021) suggest that integrating public and private capital is critical to reducing greenhouse gas emissions from agriculture. Public interventions are needed to mobilize private investments, especially given the perception of high risk and low profitability in agriculture (Mungai et al., 2021). Public-private partnerships can thus play a key role in financing CSA, as illustrated by successful initiatives in the cocoa sector (Dalaa, Kofituo, & Asare, 2020). Studies also highlight the potential of social protection programs to enhance CSA adoption. (Scognamillo & Sitko, 2021), for instance, demonstrate that integrating social protection with CSA initiatives improves smallholder productivity and welfare, further emphasizing the importance of innovative financing models that combine public and private resources.

Overall, the literature reviewed highlights two key themes: the critical role of policy, institutional support, and financing in promoting CSA adoption, and the importance of multi-stakeholder cooperation in ensuring the effectiveness of these efforts. While various studies have examined these factors in specific country contexts, gaps remain in understanding the most effective mechanisms for driving CSA adoption at scale, particularly across diverse regions. By addressing these gaps, this research aims to contribute to a more comprehensive understanding of how policies and stakeholder cooperation can jointly influence the global uptake of CSA practices.

1.2.3 Methodological Approaches in the Literature on CSA Adoption

The growing body of literature on CSA adoption employs a wide array of methodological approaches to analyze the roles of policy, institutions, climate finance, and stakeholder cooperation. Systematic reviews have been used to synthesize existing knowledge and identify key policy and institutional barriers to CSA implementation. For example, Sorgho et al. (2020) employ a systematic review to map national climate strategies and assess the degree of policy integration in agricultural sectors across African countries. Similarly, Makate (2019) and Rosenstock et al. (2019) rely on literature reviews, sometimes combined with qualitative interviews, to highlight stakeholder involvement and participatory mechanisms in scaling CSA.

Qualitative approaches, such as case studies and interviews, are commonly used to examine governance issues and the role of political and institutional will. Raile et al. (2021) adopt the Political Will and Public Will (PPW) framework using semi-structured interviews to assess the disconnect between formal climate commitments and their practical implementation. Budiman (2019) also combines document analysis with interviews to explore smallholder vulnerability and climate justice in CSA programs.

Quantitative methods offer a complementary perspective by attempting to measure and statistically assess the impact of institutional or policy variables. Vanschoenwinkel et al. (2019) apply the Ricardian method to evaluate climate impacts on agriculture and derive policy implications for adaptation. Khan et al. (2020) develop index-based models to quantify institutional capacity and assess its correlation with adaptive agricultural practices. Other studies, such as Patra and Babu (2023), adopt indicators-based approaches to evaluate climate resilience and the effectiveness of institutional interventions. Innovative survey techniques have also been used. Trnka et al. (2022) apply interactive surveys to reveal knowledge gaps between stakeholders, highlighting the need for consistent climate information sharing across institutions. Likewise, Dinesh et al. (2018) use comparative case research analyses to identify success factors for CSA adoption across different stakeholder configurations.

This diversity in methodological approaches reflects the complex interplay between socioeconomic, institutional, and environmental variables influencing CSA adoption. However, many studies are either context-specific or constrained by data limitations, such as small sample sizes, cross-sectional designs, or the lack of causal identification strategies. These limitations underscore the need for more robust empirical approaches capable of addressing endogeneity, heterogeneity, and dynamic interactions between policies, institutions, and farmers' decisions. This research builds on these existing approaches by adopting an ordered probit model with an instrumental variables approach, which allows for these endogeneity, heterogeneity, and dynamic interactions between policies, institutions, and farmers' decisions. This contributes to a deeper and more generalizable understanding of the institutional drivers of CSA adoption in developing countries.

1.2.4 Hypothesis

This research hypothesizes that "*Institutions significantly influence the likelihood of CSA adoption among smallholder farmers in developing countries*". This means that institutional arrangements, policy frameworks, and the interactions among key stakeholders—such as governments, NGOs, research institutions, and private actors—play a pivotal role in shaping farmers' decisions to adopt CSA practices.

1.3 Methodology

1.3.1. Theoretical framework

New Institutional Economics (NIE) offers a comprehensive framework for analyzing the interplay between institutions and economic performance. It extends the traditional economic analysis by integrating the role of institutions, defined as the formal and informal rules, norms, and organizations that govern social interactions, into the understanding of economic behavior (North, 1990). The foundational premise of NIE is that institutions shape the incentives and constraints faced by individuals and organizations, thereby influencing their decision-making processes and economic outcomes (Kherallah & Kirsten, 2002; Ménard & Shirley, 2008).

NIE posits that transaction costs—the costs associated with the exchange of goods and services, including costs related to negotiating, enforcing contracts, and managing risks—are critical in understanding economic behavior. These costs arise from the uncertainties inherent in economic transactions, which institutions can help mitigate by providing a stable framework for interaction (Coase, 2000; Williamson, 2000). Institutions can reduce transaction costs by establishing clear property rights, facilitating cooperation, and ensuring the enforcement of agreements (North, 1990). Consequently, a well-functioning institutional environment can lower transaction costs, enhance economic efficiency, and promote investment in innovative practices.

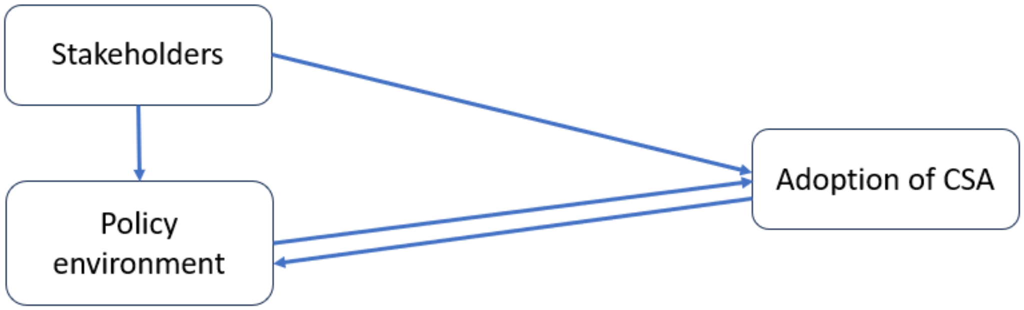
In the context of agriculture, NIE emphasizes that institutional arrangements significantly affect farmers' decisions to adopt new practices and technologies. Agricultural institutions—such as government policies, regulatory frameworks, financial systems, and extension services—play a pivotal role in shaping the incentives for farmers to engage in CSA. By providing essential resources, support services, and clear guidelines, these institutions can empower farmers to overcome barriers to adoption, such as risk aversion and uncertainty about the benefits of CSA practices (Kherallah and Kirsten, 2002).

Moreover, NIE recognizes that institutions are not static; they evolve over time in response to changing economic, social, and environmental conditions. This dynamic perspective allows for a nuanced understanding of how institutions can adapt to promote resilience and sustainability in agricultural systems (Williamson, 2000). The theory underscores the importance of stakeholder cooperation in the institutional landscape, as collaborative relationships among various actors—governments, NGOs, private sector entities, and farmers—can lead to more effective policy frameworks and enhance the overall effectiveness of CSA interventions.

1.3.2. Conceptual framework

The conceptual framework of this research consists of three interconnected components: (1) Stakeholders component, which includes all stakeholders involved in the CSA field, categorized by types of institutions such as government agencies, international development partners, research institutes, financial and non-profit organizations, private sector entities, and farmers' networks; (2) Policy Environment refers to non-physical institutions, encompassing the institutional environment and arrangements that include laws, public policies, and other documented frameworks (Raymond & Weldon, 2013); and (3) Adoption, a component that focuses on the Decision to Use CSA Practices.

Figure 4: The relationship between institutions and the adoption of CSA



Source: authors inspired by (Omamo, 2006)

Figure 4 illustrates the relationships among these components, with straight lines indicating the positive or negative effects one component may have on another. As outlined in the theoretical framework, institutions are expected to influence the decision to use CSA practices, for example, through transaction costs. In turn, this decision will affect the overall adoption of Climate-Smart Agricultural Practices and Technologies (CSAPTs).

According to NIE, the relationship between policy and institutional frameworks is bidirectional. While policies and institutional arrangements influence the rate of CSA adoption, this adoption rate can also provide feedback that leads to potential changes in these frameworks (Kherallah & Kirsten, 2002).

1.3.3. Specification of the models

1.3.1.1 CSA adoption model

The dependent variable in this model is the rate of CSA adoption under the name "adoption" categorized into three levels: "high" (adoption rate greater than 60%), "medium" (adoption rate between 30 and 60%, both inclusive), and "low" (adoption rate less than 30%). This ordinal classification implies that the dependent variable is inherently ordered, making an ordered probit model suitable for analysis (Greene, 2003). The model is specified as follows:

Equation 1

$$y_i^* = x_i'\beta + \varepsilon_i \qquad (1)$$

Where y_i^* is a latent variable representing the unobserved propensity to adopt a CSA practice i. x_i' is a vector of explanatory variables capturing climate policies, stakeholder interventions, and other factors influencing adoption. β is a vector of parameters to be estimated. ε is a normally distributed error term over $N[0, 1]$.

The observed outcomes (adoption levels) are derived from the latent variable y_i^* using threshold or cut-point values values μ_1 and μ_2 as follows:

Equation 2

$$y = \begin{cases} 0 & if \quad y^* \leq 0 \\ 1 & if \quad 0 \leq y^* \leq \mu_1 \\ 2 & if \quad \mu_1 \leq y^* \leq \mu_2 \end{cases} \qquad (2)$$

The probabilities for each outcome are given by the cumulative distribution function of a standard normal distribution Φ:

Equation 3

$$\begin{cases} Prob(y = 0|x_i) & = & 1 - \Phi(x_i'\beta) \\ Prob(y = 1|x_i) & = & \Phi(\mu_1 - x_i'\beta) - \Phi(x_i'\beta) \\ Prob(y = 2|x_i) & = & 1 - \Phi(\mu_2 - x_i'\beta) \end{cases} \qquad (3)$$

Φ denotes a standard normal cumulative distribution function (CDF).

Given the possibility of endogeneity, particularly due to reverse causality between policy implementation and CSA adoption (i.e., policies may both influence and be influenced by adoption rates), the model is estimated using an instrumental variables (IV) approach (Hill, Johnson, Greco, O'Boyle, & Walter, 2021). Endogeneity arises when there is a correlation between the endogenous variable (e.g., stakeholder interventions) and the error term ε_i, leading to biased and inconsistent estimates (Wooldridge, 2010).

The climate policies variable includes implemented policies in the agriculture sector and policies in specific CSA areas such as adaptation, mitigation, or both. Similarly, the stakeholders' intervention variable is captured in the research through the financing of CSA and the CSA focal areas of stakeholders' activities. Therefore, examining the effect of institutions on the adoption of CSA also implies addressing the two-way causality between policy and adoption variables which is a potential endogeneity, namely reversal causality. Ignoring the reverse effect existing between these two variables may lead to biased estimations (Hill et al., 2021). The occurrence of an endogeneity issue corresponds technically to the correlation between the endogenous variable (z_i) and the error term (ε_i) in the equation (1) (i.e., $Cov(z_i, \varepsilon_i) \neq 0$) (Wooldridge, 2010).

To address this issue, the model is reformulated as:

Equation 4

$$y_i^* = x_i\beta + \theta z_i + \varepsilon_i \qquad (4)$$

Where z_i is the endogenous variable (Climate policies). θ is the coefficient vector for the endogenous variable.

The endogenous variable z_i is modeled as a function of instrumental variables w_i

Equation 5

$$z_i = \gamma w_i + \upsilon_i \qquad (5)$$

Where γ is the coefficient vector for the instrumental variables and υ_i is the error term associated with the instrumental equation.

The validity of the IV approach relies on the relevance of the instruments ($\gamma \neq 0$) and their exogeneity ($Cov(w_i, \varepsilon_i) = 0$). The relevance condition can be statistically tested, but the exogeneity condition is more challenging to verify directly (Hill et al., 2021).

1.3.1.2 Policy Implementation Process Model

The policy implementation process serves as a proxy for the establishment of a conducive policy environment (Patra & Babu, 2023). The policy implementation process is divided into three stages: formulation, formalization, and implementation, following the works of (Patra & Babu, 2023; Sova et al., 2018). At the formulation stage, a policy is documented as a program, plan, or strategy that has not been implemented. At the formalization stage, the policy becomes officially recognized and is prepared for execution. Finally, at the implementation stage, the policy is actively executed, and its outcomes are observable (Sova et al., 2018).

To capture the dynamics of the policy process, an ordinal variable, 'process', is created based on the ratio of policies at each stage. The variable takes values based on the dominant stage of the implementation process in each country:

Equation 6

$$process = \begin{cases} 0 \quad if \quad implementation \leq formalization < formulation \\ 1 \quad if \quad implementation \leq formulation < formalization \\ 2 \quad if \quad formalization \leq formulation < implementation \end{cases} \tag{6}$$

Like the adoption model, the dependent variable in this model is ordinal, and thus an ordered probit model is used (Greene, 2003). Therefore, the theoretical model in Equation 1 is fitted to assess how stakeholders can influence different stages of the policy process and ultimately accelerate the adoption of CSA practices.

1.3.4. Data description

To achieve the objectives of this research, we used a comprehensive CSA database obtained from the Harvard Dataverse (Nyakundi et al., 2020). This database was originally compiled by the International Centre for Tropical Agriculture (CIAT) in collaboration with various stakeholders across participating countries. It contains a combination of quantitative and qualitative data collected through a participatory approach, involving actors from multiple levels of the agricultural value chain: farmers, input suppliers, processors, traders, policymakers, and donors. The primary data were collected from country experts using various methods such as interviews, focus group discussions, and workshops. These sessions were guided by a semi-structured survey questionnaire for interviews and focus group discussions, while a structured questionnaire was employed during workshops. Secondary data on key agricultural indicators required for country-specific CSA profiling were sourced from national and global public repositories.

The database encompasses a wide range of CSA-related information, including CSA practices, CSA scores across the three CSA pillars (productivity, adaptation, and mitigation), existing climate-related policies at the national level, and Institutions involved in developing, overseeing, or implementing climate policies and interventions. Additionally, the data includes CSA adoption levels, barriers to adoption, and the types of farmers using each CSA practice most frequently. Over 1,500 experts were consulted during the data collection process (Nyakundi et al., 2020).

The CSA database has been updated with the most recent information from CSA country profile reports published by the World Bank in collaboration with CIAT, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), and the Food and Agriculture Organization of the

United Nations (FAO). The updated dataset used in this analysis includes data from 33 countries across Africa (16 countries), Asia (7 countries), and Latin America and the Caribbean (10 countries). Three key datasets were merged for the analysis: (1) National agricultural context which contains economic, climate, and agricultural sector characteristics of each country; (2) CSA adoption rates which record the adoption rates of key CSA practices and technologies in each country; (3) CSA-related institutions which include information on the institutions engaged in CSA activities, categorized into financial and non-financial organizations as well as policy and institutional frameworks.

Financial organizations refer to key climate-funding institutions accessible to the country. Non-financial organizations are institutions providing technical assistance and working on at least one of the three CSA pillars. Policy and institutional frameworks cover policies, strategies, and programs related to agriculture and climate change at different stages of implementation—whether in formulation, legally established, or actively implemented. These frameworks represent key entry points for CSA at the country level.

For the purposes of this research, control variables were incorporated, including: interaction between stakeholders, GDP per capita, agricultural infrastructure index, literacy rate, rural population, and value added per workers. Interaction variables were introduced to capture the level of cooperation among stakeholders, while GDP per capita, agricultural infrastructure index, and literacy rate represent the financial, physical, and human resources of each country, respectively. Additionally, rural population and value added per worker in agriculture were included to capture challenges to food security, which are pertinent issues in many developing countries.

Table 1 provides the definitions and measurements of all variables used in this research, along with their mean, standard deviation, and maximum and minimum values.

Table 1: Description of variables (n = 1,745)

Variables			***Description***	***Mean***	***SD***	***Min***	***Max***
Adoption			Adoption rate of CSA (1=low, 2=medium, 3=high)	1.62	0.72	1	3
Process			Process of implementation of policies (1=formulation, 2=formalization, 3=implementation)	2.54	0.65	1	3
Independent	Stakeholders by category	***Farmers networks***	National farmers' groups, unions, or associations	0.04	0.05	0	0.18
		Financial institutions	National, regional, international, or private finance fund (insurance companies, banks, etc)	0.04	0.05	0	0.21
		Government	Public institutions or organizations (ministry, national directorate, agency, etc)	0.33	0.12	0.09	0.67
		International development partners	International development partners	0.22	0.12	0	0.45
		NGOs	Non-government/non-profit organizations (Civil society networks or forums, community-based organizations, volunteer efforts for development, etc)	0.10	0.08	0	0.30
		Research	National and international research, training, or academic organizations (university, centre, institute, etc)	0.04	0.06	0	0.26
	Origin of CSA funds accessed	***National***	National funds accessed for CSA purposes (ratio)	0.14	0.11	0	0.6
		International	International funds accessed for CSA purposes (ratio)	0.58	0.17	0.23	0.9
	Policies by CSA focal areas	***Policies Implemented***	Policies actively implemented and considered as key points for CSA (ratio)	0.56	0.22	0.2	1
		Policies in adaptation	Policies with a focus on adaptation (ratio)	0.10	0.22	0	0.81
		Policies in mitigation	Policies with a focus on mitigation (ratio)	0.09	0.13	0	0.42
	Stakeholders by CSA focal areas	***Stakeholders in adaptation***	Stakeholders with activities oriented mainly to the adaptation objective (ratio)	0.05	0.06	0	0.25
		Stakeholders in mitigation	Stakeholders with activities oriented mainly to the mitigation objective (ratio)	0.03	0.05	0	0.16
		Stakeholders in both	Stakeholders with activities oriented mainly to both objectives (ratio)	0.09	0.06	0	0.22
Control variables		***GDP per capita***	Gross domestic product divided by midyear population (USD)	2553.68	3255.45	435.76	18131.58
		Agricultural infrastructure index	A higher score indicates more developed infrastructure (road, rail, port, air transport, and irrigation infrastructure, as well as investment in crop storage facilities)	43.14	11.09	20.4	70.4
		Literacy rate	Percentage of people ages 15 and above who can both read and write with understanding a short, simple statement about their everyday life	69.64	20.5	32.95	98.52
		Value added per worker	Value added per worker in agriculture (USD)	1500	2297.02	220	12065
		Rural population	Population living in rural areas (%)	62.25	19.59	5	94

Source: Author

1.4 Results

1.4.1 Descriptive statistics

Table 1 shows that the mean adoption rate is 1.62 (SD = 0.72), indicating that, on average, countries tend to fall between low and medium levels of CSA adoption. The wide range from 1 to 3 reflects varying degrees of CSA adoption across countries. The mean value of 2.54 (SD = 0.65) of the process of policy implementation suggests that most countries are either formalizing or actively implementing CSA policies, reflecting progress in establishing a supportive policy environment.

The independent variables representing stakeholder groups show that public institutions, represented by government organizations, exhibit the highest mean value (0.33, SD = 0.12), indicating their strong role in CSA activities. Other key stakeholders include international development partners (mean = 0.22, SD = 0.12) and NGOs (mean = 0.10, SD = 0.08). Lower involvement is seen among farmers' networks (mean = 0.04) and research institutions (mean = 0.04), suggesting a need for stronger engagement from grassroots and research actors. Regarding the origin of CSA funds, international funding is the most prominent, with an average contribution of 0.58 (SD = 0.17), underscoring the importance of global financial support. In comparison, private and national funds contribute less, with means of 0.12 and 0.14, respectively.

The average ratio of actively implemented policies is 0.56 (SD = 0.22), while adaptation and mitigation-specific policies are less prevalent, with means of 0.10 and 0.09, respectively. This indicates that while many policies are being implemented, fewer are explicitly focused on individual CSA pillars. Similarly, on average, 0.09 (SD = 0.06) of stakeholders work on both adaptation and mitigation simultaneously, suggesting that integrating both objectives is less common. Stakeholders focusing solely on adaptation have a mean of 0.05, while those concentrating on mitigation show a mean of 0.03.

On the side of control variables, the countries in the research exhibit significant economic diversity, with an average GDP per capita of $2,553.68 (SD = $3,255.45). This wide range, from $435.76 to $18,131.58, reflects the differing financial capacities of the countries included, which may influence their ability to adopt CSA practices. The mean score of 43.14 (SD = 11.09) of the agricultural infrastructure index shows moderate levels of infrastructure development; while the average literacy rate of 69.64% (SD = 20.50%) with a range from 32.95% to 98.52% indicate a high literacy across countries. The productivity of the agricultural sector, measured by value added per worker, has a mean of $1,500 (SD = $2,297.02) and varies from $220 to $12,065. The mean rural population is 62.25% (SD = 19.59%), with a maximum of 94%, reflecting the significant reliance on rural areas for agricultural production in most countries.

1.4.2 The influence of institutions on the adoption of CSA

Table 2 presents the results of the IV-ordered probit model, along with key statistics addressing potential endogeneity. The correlation between errors from the main and auxiliary equations is estimated to test for endogeneity. The error correlation test is highly significant at the 1% level, supporting the need to account for endogeneity in the analysis. The first-stage results show that all explanatory variables are significantly correlated with the endogenous variables ($p<0.01$), confirming that the instruments used in this research are relevant. Additionally, the model passes the identification test, as the number of instruments matches the number of endogenous variables. For instrument validity, export values, agriculture's contribution to GDP, and livestock's contribution to greenhouse gas (GHG) emissions were selected. These macro-level variables influence climate adaptation decisions at the policy-making level more than at the farm-level CSA adoption (Coayla & Jiménez, 2022; Schiavon, Taramelli, & Tornato, 2021). Hence, the selected instruments are valid for this analysis.

The IV-ordered probit results indicate that the proportion of financial institutions, regardless of origin (private, national, or international), is negatively and significantly associated with the probability of increasing CSA adoption rates. This suggests that financial resources accessed for CSA purposes have not effectively contributed to enhancing CSA adoption. This negative effect may reflect misalignment between the goals of financial institutions and the on-the-ground needs for CSA implementation. Specifically, the negative coefficient for private financial institutions supports the findings of Mungai, Ndiritu, and Da Silva (2022), who highlight the exclusion of private sector investments from climate finance mechanisms supporting CSA. Similarly, the negative effect of national financial institutions aligns with Scognamillo and Sitko's (2021) conclusion that public institutions often lack the capacity to adequately finance CSA, suggesting that a more integrated approach involving both public and private sectors is needed to sustainably support CSA. The international financial institutions also show a negative effect, consistent with Coayla and Jiménez's (2022) findings, which emphasize the insufficiency of international climate finance to support farmers' adaptation processes.

Table 2: Estimation of the effects of stakeholders' intervention on the adoption of CSA (IV-ordered probit)

Variables	***Rate of adoption***
Private	-0.93*** (0.27)
National	-0.81*** (0.29)
International	-0.49*** (0.15)
Stakeholders in adaptation	0.16 (0.35)
Stakeholders in mitigation	-0.24 (0.60)
Stakeholders in adaptation and mitigation	1.10*** (0.42)
Rural population	-0.003* (0.002)
Value added per workers	0.0001*** (0.00001)
Policies implemented	3.21*** (0.43)
Policies with focus on adaptation	0.51** (0.24)
Policies with focus on mitigation	-1.52 (1.01)
Policies with focus on adaptation and mitigation	0.34 (1.45)
Endogenous variables	
Policies implemented	
Exports values	-1.68e-06*** (1.49e-07)
Constant	0.58 (0.01)
Policies with focus on adaptation	
Agriculture contribution to GDP	0.01*** (0.001)
Constant	-0.14 (0.01)
Policies with focus on mitigation	
Livestock contribution to GHG	-0.001*** (0.0001)
Constant	0.14 (0.01)
Policies with focus on adaptation and mitigation	
Agriculture contribution to GDP	-0.001*** (0.0002)
Livestock contribution to GHG	0.0002* (0.0001)
Constant	0.07 (0.01)

IV validation statistics	
Corr (e.adoptation, e.policies actively-implemented)	-0.74*** (0.07)
Corr (e.adoptation, e.policies in adaptation)	-0.32*** (0.05)
Corr (e.adoptation, e.policies in mitigation)	0.32*** (0.11)
Corr (e.adoptation, e.policies in adaptation and mitigation)	0.33*** (0.07)
Number of observations	1,745
Wald $\chi2(11)$	1506.90
Prob > $\chi2$ =	0.0000

Notes: Standard deviations are reported in parentheses; ***p<0.01, **p<0.05.

Regarding stakeholders and policy interventions, the proportion of stakeholders working across both adaptation and mitigation strategies shows a significant and positive effect on CSA adoption. One possible explanation lies in the coherence and complementarity of the messages and interventions provided by these stakeholders. When an actor is involved simultaneously in adaptation and mitigation, they tend to adopt a more holistic approach—addressing both the immediate needs of farmers (such as resilience to droughts or floods) and long-term environmental concerns (such as reducing greenhouse gas emissions and ensuring sustainable soil and input management). Additionally, these stakeholders are often better organized institutionally, better trained, or equipped with more technical and financial resources, enabling them to offer more credible and attractive solutions to farmers. Their ability to articulate a consistent message around the co-benefits of CSA—for example, practices that improve yields while also reducing environmental impact—makes adoption more appealing, as farmers can more clearly perceive the added value of the promoted practices. Finally, this increased effectiveness may also stem from stronger trust-based relationships built over time between these stakeholders and the farmers, thanks to their multi-dimensional and sustained engagement. This suggests that aligning adaptation and mitigation objectives within agricultural extension and development programs could play a crucial role in the success of CSA-related policies. In contrast, stakeholders focusing solely on adaptation or mitigation individually have no significant effect, suggesting that integrated approaches are more effective at driving CSA adoption.

Similarly, the proportion of implemented policies has a positive and significant effect on CSA adoption. This demonstrates the critical role that agricultural and climate change policies play in supporting CSA. Specifically, policies focused on adaptation exhibit a positive and significant effect, indicating that policy-makers prioritize adaptation strategies to address the immediate impacts of climate change. Although mitigation policies have a negative coefficient, their effect is statistically insignificant, reinforcing the notion that adaptation remains the primary focus of policy interventions at present.

Control variables further illustrate the broader context influencing CSA adoption. Rural population has a small but negative effect (-0.0034, $p<0.1$), suggesting that higher rural populations may pose challenges to CSA adoption. In contrast, value added per agricultural worker positively affects CSA adoption (0.00008, $p<0.01$), indicating that increased agricultural productivity may facilitate the transition to CSA practices.

1.4.2.1 Robustness check

A robustness check was conducted by re-estimating the IV-ordered probit model on each instrument separately. As reported in Table 3, the direction of the effects of all variables, particularly the instruments, remained stable. While there were some changes in the significance of individual variables, the overall results confirm the reliability of the model.

Table 3: Robustness test results

Variables	***Rate of adoption***			
	(1)	***(2)***	***(3)***	***(4)***
Private	-0.78** (0.30)	-1.36*** (0.40)	-1.33*** (0.39)	-1.29*** (0.38)
National	-0.72** (0.31)	-1.20*** (0.40)	-1.06*** (0.41)	-1.004** (0.41)
International	-0.62*** (0.14)	-0.30 (0.21)	-0.44** (0.19)	-0.38** (0.19)
Stakeholders in adaptation	0.28 (0.37)	0.12 (0.531)	0.32 (0.52)	0.16 (0.50)
Stakeholders in mitigation	-0.52 (0.61)	-2.23*** (0.67)	-1.74** (0.74)	-1.60** (0.67)
Stakeholders in adaptation and mitigation	0.53 (0.42)	1.7327*** (0.5865)	1.29** (0.55)	1.38** (0.54)
Rural population	-0.003 (0.002)	-0.0081*** (0.0023)	-0.01*** (0.002)	-0.01*** (0.002)
Value added per workers	0.0001*** (0.00002)	0.0001*** (0.00002)	0.0001*** (0.00002)	0.0001*** (0.00002)
Policies implemented	3.34*** (0.47)			
Policies with focus on adaptation		0.56* (0.31)		
Policies with focus on mitigation			-1.85 (1.33)	
Policies with focus on adaptation and mitigation				-5.86** (2.55)
Endogenous variables				

Policies implemented				
Exports values	-1.41e-06*** (1.22e-07)			
Constant	0.57*** (0.01)			
Policies with focus on adaptation				
Agriculture contribution to GDP		0.01*** (0.0006)		
Constant		-0.14 (0.01)		
Policies with focus on mitigation				
Livestock contribution to GHG			-0.0011*** (0.0001)	
Constant			0.16 (0.01)	
Policies with focus on adaptation and mitigation				
Agriculture contribution to GDP				-0.001*** (0.0002)
Livestock contribution to GHG				-0.0002 (0.0001)
Constant				0.10 (0.01)
IV validation statistics				
Corr (e.adoptation, e.policies implemented)	-0.72*** (0.09)			
Corr (e.adoptation, e.policies in adaptation)		-0.17*** (0.06)		
Corr (e.adoptation, e.policies in mitigation)			0.26 (0.17)	
Corr (e.adoptation, e.policies in adaptation and mitigation)				0.42** (0.18)
Number of observations	1,745	1,745	1,745	1,745
Wald χ2(9)	420.24	122.87	125.79	155.66
Prob > χ2	0.0000	0.0000	0.0000	0.0000

1.4.3 Influence of stakeholders on the policy environment

Table 4 presents the results of the ordered probit model, which analyzes the influence of various stakeholders on the establishment of a conducive policy environment for CSA. The findings reveal that, in developing countries, the proportion of certain stakeholder categories—namely financial institutions and international development partners—has a significant and positive effect on the likelihood of establishing a policy environment for CSA. However, farmers' networks, NGOs, and research institutes show a negative effect, indicating that these stakeholders do not favorably influence the process of CSA policy implementation.

The positive and significant effect of financial institutions underscores the importance of financing in creating an enabling environment for CSA policy. This finding aligns with Coayla and Jiménez (2022), who highlight that insufficient climate finance remains a barrier to CSA adoption. The results also support Bhandary et al. (2021) and Mungai et al. (2021), who emphasize the need to mobilize private sector investments to address the financing gaps that hinder CSA progress. International development partners exhibit a positive and significant influence on the policy implementation process, indicating their crucial role in providing both financial and technical assistance. Their involvement not only facilitates policy development but also keeps climate resilience as a priority for policymakers. This result echoes the findings of (Kadzamira & Ajayi, 2019), who documented the positive impact of international partnerships in southern African countries. Conversely, the Farmers' Networks, NGOs, and research institutes show a negative effect on the likelihood of establishing a favorable policy environment for CSA. This suggests that these institutions have not effectively supported the policy implementation process. These findings resonate with studies by Khan et al. (2020), Patra and Babu (2023), and Raile et al. (2021), who argue that institutional capacity constraints, particularly in terms of infrastructure, hinder the provision of adaptation support. The results also point to the lack of physical infrastructure as a significant barrier, as indicated by the negative effect of the agricultural infrastructure index. In contrast, the positive effects of GDP per capita and literacy rates suggest that higher economic capacity and education levels may improve institutional performance in creating a policy environment for CSA. The negative effect of research institutes corroborates the findings of Dinesh et al. (2018), who stress that while science should inform policy, the role of research institutions in CSA policy-making has been limited. This could reflect a disconnect between scientific research and policy action in many developing countries.

Table 4: Estimation of the influence of stakeholders on the policy environment (Ordered probit model)

Variables	*Process of policy implementation*
Farmers networks	-113.37*** (20.156)
Financial institutions	7.12*** (1.348)
Government	3.52 (3.161)
International development partners	41.25*** (4.243)
NGOs	-27.87*** (2.958)

Research	-163.35*** (10.960)
Research × Government	274.04*** (24.893)
Research × Financial institutions	180.27** (72.184)
Research × International development partners	153.48*** (26.79)
Research × Farmers networks	1647.17*** (82.50)
Farmers networks × Government	286.07*** (48.96)
International development partners × Government	-112.65*** (13.28)
NGOs × Government	73.96*** (11.33)
International development partners × Farmers networks	-195.55*** (31.97)
Agricultural infrastructure index	-0.05*** (0.008)
Literacy rate	0.16*** (0.016)
GDP per capita	0.001*** (6.37e-5)
Number of observations	1,745
Wald χ2(17) =	3890.62
Prob > χ2 =	0.0000
Pseudo R2 =	0.6706

Table 4 also shows the effect of pairwise interactions between stakeholder groups on the process of CSA policy implementation, revealing the significant effect of stakeholder cooperation. Most interactions positively affect the probability of establishing a CSA policy environment, except for interactions between international partners and both government and farmers' networks. This result indicates that while stakeholder cooperation is generally beneficial, it is crucial to approach collaboration with caution, ensuring that the expertise of each participant is appropriately aligned with the task at hand. This finding aligns with studies that support stakeholder cooperation as an effective way to establish a CSA policy environment (Baba, Amanuma, & Kosugi, 2021; Lewis & Rudnick, 2019; Mkonda, 2022; Schiavon et al., 2021).

The positive effects of interactions between government agencies and each stakeholder group such as NGOs, Research institutes, and Farmers' networks, can be attributed to the complementary roles played by government agencies and each of these stakeholders. Government agencies typically have the authority to formulate and enforce policies, while NGOs, research institutes, and Farmers' Networks provide critical ground-level insights, scientific expertise, and community engagement (Alexander, 2019; Lewis & Rudnick, 2019; Yamoah, Kaba, Amankwah-Amoah, & Acquaye, 2020).

Similarly, the interaction between research institutes and each stakeholder group such as international development partners, Farmers' Networks, and financial institutions indicates a compatibility in their roles. Research institutes provide the scientific data and analysis needed to design effective policies, while international partners bring resources, technical support, and global best practices. This collaboration can combine global expertise with localized research to develop well-informed and context-specific CSA policies (Zougmoré et al., 2019). Additionally, Farmers' Networks play a crucial role in disseminating innovative CSA practices developed by research institutes, ensuring that new technologies and strategies reach the grassroots level. This interaction fosters a bottom-up approach to policy development, where the needs and experiences of farmers are integrated into policy frameworks, thereby increasing the likelihood of successful policy implementation. Financial institutions, on the other hand, rely on the credibility and data provided by research institutes to allocate resources toward initiatives that have proven potential. This collaboration ensures that funding is directed toward initiatives aligning with financial goals and environmental sustainability, thereby strengthening the policy environment. The results corroborate the findings of (Dinesh et al., 2018) and (Zougmoré et al., 2019), who emphasized the importance of research institutes in engaging decision-makers in policy development.

On the contrary, the negative effect of the interaction between international development partners and both Farmers’ networks and government agencies indicates a misalignment of priorities and the challenges posed by bureaucratic hurdles and power dynamics. International partners often operate with broad, top-down objectives that may not always align with the immediate, localized needs of farmers. In developing countries, this disconnect can lead to conflicts or inefficiencies in policy development, where the voices of Farmers' Networks are not adequately represented or their concerns are not fully addressed, resulting in less effective policies. Similarly, the complexities of coordinating between international partners and government agencies, particularly in developing countries, can exacerbate these challenges. For instance, international partners may advocate for policy directions that conflict with national priorities or governmental processes, causing friction or delays in policy establishment. Additionally, the power dynamics between these two stakeholders can create challenges in decision-making, with government agencies potentially resisting external influence or struggling to integrate international recommendations into local governance structures.

Overall, the effect of stakeholder cooperation provides evidence supporting the promotion of multilateral partnerships or multistakeholder platforms (MSPs) as effective approaches for establishing a CSA policy environment and achieving global adoption (Acosta et al., 2019; Kadzamira & Ajayi, 2019). Regarding control variables, the negative effect of the agricultural infrastructure index coupled with the positive effects of GDP per capita and the literacy rates, suggest that physical infrastructure remains a key capacity constraint, impeding the establishment of a CSA policy environment. This finding corroborates (Khan et al., 2020), who identified a lack of financial, physical, and human resources as obstacles to providing public adaptation support.

1.4.4 Hypothesis Validation

The results of the IV-ordered probit model provide empirical support for the hypothesis that "*CSA policies and the stakeholder ecosystem significantly influence the likelihood of CSA adoption among smallholder farmers in developing countries*". Specifically, the findings highlight that the effectiveness of these influences depends on the nature and coordination of policies and stakeholder involvement. In conclusion, the hypothesis is validated.

1.4.5 Policy Implications

The findings of this research highlight several key policy implications that can significantly enhance the adoption of CSA practices and the creation of a supportive policy environment for CSA.

- First, **prioritizing tailored and effective policies that focus on both climate adaptation and mitigation** objectives in an integrated manner. The results demonstrate that policies centered on adaptation have a positive and significant influence on CSA adoption, while those focused on mitigation negatively affect CSA. This suggests a misalignment between mitigation strategies and the immediate needs of smallholder farmers. Therefore, policymakers should move beyond siloed approaches and invest in coherent, context-specific frameworks that simultaneously reduce farmers' vulnerability to climate risks and contribute to long-term environmental goals. By aligning mitigation efforts with local realities and adaptation priorities, governments can enhance the effectiveness and acceptability of CSA policies.

- Second, **stakeholder cooperation must be fostered and institutionalized**. The research shows that stakeholders working across both adaptation and mitigation strategies are more effective in promoting CSA adoption than those working in isolation or focusing on a single strategy. To build on this, governments and development partners should create platforms and formal structures that encourage cross-stakeholder cooperation. This includes fostering partnerships between public institutions, private sector actors, NGOs, international development partners, and research institutes. These platforms should facilitate regular dialogue, resource sharing, and joint planning to ensure that stakeholder efforts are aligned and mutually reinforcing.
- Third, there is a need to **improve climate finance's efficiency**, particularly financial institutions' role in CSA. The research found that financial institutions—whether private, national, or international—have a negative effect on CSA adoption, signaling inefficiencies or a misalignment between funding goals and outcomes. This calls for innovative financing mechanisms that can better target CSA initiatives and ensure that funds are effectively channeled toward actions that directly benefit farmers. Public-private partnerships (PPPs) should be strengthened, with mechanisms that allow both sectors to contribute to sustainable and scalable CSA initiatives.
- Finally, **investment in institutional capacity-building is critical**. The negative effects of public institutions and research institutes on policy implementation suggest a gap in their capacity to effectively contribute to the establishment of enabling environments for CSA. Policymakers should focus on improving the capacities of public institutions, particularly in terms of infrastructure, governance, and financial management. Research institutions should be empowered to better integrate scientific knowledge into policy-making, ensuring that decisions are informed by the latest research and innovations in CSA.

1.5 Conclusion

This research examined the role of policies, stakeholder interventions, and cooperation in driving the adoption of CSA practices. Using an IV-ordered probit model, the findings highlight the significance of coordinated efforts among stakeholders and the need for a supportive policy environment to enhance CSA adoption rates. The results confirm that stakeholder interventions, particularly those involving both adaptation and mitigation strategies, positively influence CSA adoption. However, the research also reveals inefficiencies in the utilization of financial resources from private, national, and international institutions, pointing to a potential misalignment of climate finance objectives. The observed emphasis on adaptation over mitigation highlights a gap in policy priorities that may hinder the comprehensive scaling up of CSA. Furthermore, the analysis underscores the importance of stakeholder cooperation in shaping a conducive policy environment. While individual contributions from financial institutions and international development partners are crucial, the synergy between stakeholders, especially between research institutes and government entities, proves to be more effective in establishing policies that support CSA adoption. Conversely, the limited effectiveness of government and farmers' networks in influencing policy outcomes suggests a need for greater involvement and capacity-building efforts among these groups.

In conclusion, advancing CSA adoption requires a balanced approach that integrates both adaptation and mitigation objectives, stronger multi-stakeholder collaboration, and improved alignment of financial mechanisms with CSA goals. By fostering cooperation across different sectors and ensuring that policies reflect the needs of farmers, governments and development partners can enhance the resilience and sustainability of agricultural systems in the face of climate change.

The research presents certain limitations that can result in perspectives for future research. The research does not address the indirect effect of establishing a policy environment for CSA on the adoption of CSA. The cross-sectional data used has also been a barrier to exploring the country effect. Similarly, the lack of CSA country profiles for some countries leads to having a few countries in the analysis. Therefore, these limitations can be addressed in future research to obtain further results.

Chapter 2 Analysis of the impact of the adoption of climate-smart agriculture on the climate-smartness of farmers in the northern and central regions of the Republic of Benin

Abstract

The impact of climate-smart agriculture (CSA) on its objectives has often been evaluated without a comprehensive overview of its impacts on productivity, income, adaptation, and mitigation. This paper addresses this gap by assessing the impact of CSA adoption on the climate-smartness of farming systems. Climate-smartness was measured using the Climate-Smartness Index (CSI) through a Principal Component Analysis (PCA) approach. CSA practices were categorized into five groups: soil, nutrient, crop, water management practices, and integrated systems, from which specific CSA packages were defined. By using primary data collected on 716 farm households from the northern and central regions of the Republic of Benin and applying a multinomial endogenous switching regression model, the results revealed that larger CSA packages that include at least three CSA categories, with a priority on water management and integrated systems, or packages combining only water management and integrated systems, have a high potential to ensure sustainability for adopting farmers. The adoption of these CSA packages is further positively influenced by factors such as marital status, education, training, family size, hired labor, dependency ratio, land size, and access to extension services. The research highlights the importance of promoting comprehensive CSA packages, especially those focusing on water management and agroforestry, to enhance climate-smartness in farming systems in the Republic of Benin. It also emphasizes the need for increased access to education, training, and strengthened extension services to support farmers in adopting sustainable agricultural practices.

Keywords: Climate-smart agriculture, Adoption, Farmers, Principal component analysis, Multinomial endogenous switching regression model

Résumé

L’impact de l’Agriculture Intelligente face au Climat (AIC) sur ses objectifs est souvent évalué sans une vue d’ensemble complète de ses effets sur la productivité, le revenu, l’adaptation et l’atténuation. Cet article comble cette lacune en évaluant l’impact de l’adoption de l’AIC sur l’intelligence climatique des systèmes agricoles. L’intelligence climatique a été mesurée à l’aide de l’Indice d’Intelligence Climatique (IIC), construit selon une approche d’Analyse en Composantes Principales (ACP). Les pratiques AIC ont été regroupées en cinq catégories : gestion des sols, gestion des nutriments, gestion des cultures, gestion de l’eau et systèmes intégrés, à partir desquelles des paquets spécifiques de pratiques AIC ont été définis. À partir de données primaires collectées auprès de 716 ménages agricoles dans les régions nord et centre de la République du Bénin, et en appliquant un modèle de régression multinomiale à changement endogène, les résultats montrent que les paquets AIC les plus complets, incluant au moins trois catégories de pratiques, en particulier celles intégrant la gestion de l’eau et les systèmes intégrés, ou les paquets combinant uniquement la gestion de l’eau et les systèmes intégrés, présentent un fort potentiel pour assurer la durabilité chez les agriculteurs adoptants. L’adoption de ces paquets AIC est positivement influencée par plusieurs facteurs, notamment le statut matrimonial, le niveau d’éducation, la formation, la taille de la famille, le recours à de la main-d’œuvre salariée, le ratio de dépendance, la taille des exploitations et l’accès aux services de vulgarisation agricole. La recherche souligne l’importance de promouvoir des paquets AIC complets, en particulier ceux axés sur la gestion de l’eau et l’agroforesterie, afin d’améliorer l’intelligence climatique des systèmes agricoles au Bénin. Elle met également en évidence la nécessité de renforcer l’accès à l’éducation, à la formation et aux services de vulgarisation pour accompagner les agriculteurs dans l’adoption de pratiques agricoles durables.

Mots-clés : Agriculture intelligente face au climat, Adoption, Agriculteurs, Analyse en composantes principales, Modèle de régression multinomiale à changement endogène.

2.1 Introduction

Climate change poses severe risks to human systems, significantly undermining the adaptive capacities of individuals and communities (IPCC, 2023). In agriculture, shifting climate patterns threaten productivity and heighten food insecurity risks, particularly in regions like Sub-Saharan Africa, where reliance on rain-fed farming exacerbates vulnerabilities (Arata, Fabrizi, & Sckokai, 2020). These challenges prompt the need for effective strategies that not only enhance productivity but also mitigate environmental impacts. One such strategy is Climate-Smart Agriculture (CSA), which aims to achieve three key objectives: increasing agricultural productivity, enhancing resilience to climate shocks, and reducing greenhouse gas (GHG) emissions (FAO, 2014a).

The decision to adopt CSA practices, however, involves complex trade-offs. From an economic perspective, farmers face uncertainty about future climate outcomes and the effectiveness of CSA practices in improving yields, resilience, and environmental sustainability (Neumann & Morgenstern, 1944). Expected utility theory provides a framework for understanding this decision-making process. Under this theory, farmers are viewed as rational agents who weigh the expected benefits of adopting CSA against the costs and potential risks (Neumann & Morgenstern, 1944). The key factors influencing this decision include perceived risks to productivity from climate variability, the potential for long-term gains in resilience, and the opportunity costs of investing in new practices (Neumann & Morgenstern, 1944).

In this context, the adoption of CSA can be viewed as a strategy to maximize expected utility by balancing short-term gains in productivity with long-term benefits in adaptation and mitigation. However, as with any decision under uncertainty, farmers must assess the relative payoffs of adopting different CSA packages. Larger CSA packages incorporating a wider range of practices—such as water management, nutrient management, and integrated systems—may offer greater expected utility by simultaneously addressing multiple risks. Conversely, smaller, more targeted CSA interventions may deliver immediate productivity gains at the expense of long-term sustainability.

Nevertheless, both theoretical and empirical controversies question the effectiveness of CSA in achieving its intended triple-win outcomes. While CSA is widely promoted as a sustainable solution, empirical studies increasingly reveal inconsistent impacts, particularly concerning its ability to reduce GHG emissions and build long-term resilience. For example, recent assessments suggest rising vulnerability to food insecurity in African countries despite increasing CSA efforts (IPCC, 2022), and agricultural emissions have continued to rise in the region (FAO, 2021). These findings raise concerns about the on-the-ground performance of CSA interventions and highlight limitations in current evaluation frameworks, which often emphasize biophysical metrics while overlooking critical socioeconomic and institutional dimensions (Wijk et al., 2020; Challinor et al., 2022).

To better understand these inconsistencies, this research also draws on maladaptation theory, which offers a theoretical lens to analyze how well-intended adaptation strategies may inadvertently increase vulnerability, especially when interventions are poorly contextualized or reinforce systemic inequalities (Schipper, 2020; Lisa, 2020). For instance, Shah et al. (2024) demonstrate how CSA practices can sometimes contribute to negative outcomes, such as reinforcing power imbalances or generating ecological harm, if implemented without adequate consideration of local socio-environmental dynamics. This perspective underscores the importance of assessing not only whether CSA practices are adopted but also how they are integrated into existing farming systems and policy environments.

The Republic of Benin, where agriculture is a key economic sector, faces acute climate-related challenges. The country has experienced declining yields in staple crops and increased livestock mortality, which exacerbates poverty and food insecurity (Benin, 2021, 2022a). In 2018, agriculture accounted for 28.51% of total greenhouse gas emissions in Benin, and projections suggest that these emissions, along with energy-related emissions, will rise significantly without mitigation efforts (Benin, 2021, 2022a). Furthermore, agriculture employs 38% of Benin’s population and contributes around 25,4% of the national GDP, but the sector remains vulnerable due to its reliance on smallholder, rain-fed farming (DSA, 2023b; INSTAD, 2023). Limited access to agricultural land and irrigation infrastructure has compounded the country's vulnerability, resulting in food insecurity for 23% of households, particularly in the northern region (FAO, 2018). This situation highlights the need for climate-smart strategies that are not only effective but also contextually appropriate and resilient against maladaptive risks.

Few studies have comprehensively assessed the impact of CSA adoption on the climate-smartness of farming systems. Existing studies often focus on individual objectives of CSA — productivity, resilience, or GHG emission reduction—without evaluating the overall performance of CSA in achieving all three goals simultaneously (Asmare, Jaraitė, & Kažukauskas, 2022; Katengeza & Holden, 2021; Stetter & Sauer, 2022). While the adoption of CSA has been shown to improve productivity and resilience, studies often fall short of evaluating its broader, integrated impact (Adam & Abdulai, 2024). Moreover, few incorporate the theoretical implications of maladaptation, thus overlooking important risks that can arise when CSA interventions are not aligned with local needs or capacities.

This research addresses this gap by evaluating the impact of CSA adoption on the climate-smartness of farming systems in Benin; which is achieving the three CSA objectives. Specifically, we assess how different CSA packages influence the ability of farmers to achieve CSA's three objectives: productivity, adaptation, and mitigation. We hypothesize that while CSA adoption generally provides some level of climate-smartness, the extent of these benefits varies based on the specific CSA package adopted. Our results show that larger CSA packages—those that include at least three CSA categories, with an emphasis on water management and integrated systems—are more likely to achieve sustainability for farmers. Additionally, the adoption of these packages is influenced by factors such as marital status, education, training, family size, hired labor, dependency ratio, land size, and access to extension services.

This research contributes to the field of CSA in several significant ways. First, it addresses a key gap by evaluating CSA adoption impacts based on comprehensive objectives. Second, the research introduces an integrated, index-based approach to measure the effectiveness of CSA practices, providing a robust framework for future research. Third, by incorporating the maladaptation lens, it highlights potential unintended consequences of CSA when implemented without adequate alignment to local contexts. Moreover, it highlights the true attributes of CSA in climate adaptation processes and emphasizes the trade-offs involved in adopting different CSA packages. Finally, the research offers policy-relevant insights that support Benin's efforts to meet its net-zero emission commitments by 2050 and contribute to the achievement of Sustainable Development Goals (SDGs) 1, 2, and 13.

The remainder of this paper is organized as follows: Section 2 outlines the literature review, Section 3 deals with the methodology, Section 4 describes the analytical framework, Section 5 presents and discusses the results, and Sections 6 et 7 present the hypothesis validation and limitations and future research, respectively. Section 8 concludes with policy implications.

2.2 Literature review

The literature largely documents CSA's capacity to meet its three objectives, with less focus on the holistic aspect that characterizes the CSA concept. This section shows a literature review related to CSA impact studies on objectives targeted by CSA.

2.2.1 Impact of CSA on Productivity and Income

Adopting CSA practices plays a transformative role in enhancing productivity and income, particularly in the face of climate variability and resource constraints. CSA interventions, ranging from drought-tolerant crop varieties to sustainable soil amendments, have demonstrated significant potential in boosting agricultural efficiency and ensuring economic sustainability for smallholder farmers.

Drought-tolerant maize varieties (DTMVs) represent a vital CSA innovation, particularly in drought-prone regions. In Malawi, an increase of one hectare allocated to DTMVs results in a 44% increase in maize yield, underscoring their capacity to mitigate production losses under rainfall stress (Katengeza & Holden, 2021). Similarly, DTMVs provide higher yields during drought and offer resilience against yield variability, which is critical for food security and income stability (Paul, 2021). Organic soil amendments (OSAs), such as organic fertilizers and farmyard manure, also contribute significantly to productivity gains. Among wheat farmers in China, OSA adoption increased yields and net returns by 22% and 24%, respectively (Zheng, Ma, & Li, 2021). These benefits were particularly pronounced among larger-scale households, suggesting economies of scale in sustainable soil management practices.

In addition to yield improvements, CSA practices enhance cost efficiency, a critical factor in resource-constrained settings. For smallholder wheat producers in Pakistan, CSA adoption improved cost efficiency while increasing yields by approximately 20% compared to non-adopters (Mustafa, Wang, Mwalupaso, Yu, & Li, 2024). Similarly, stress-tolerant rice varieties (STRVs) in Nepal not only reduced yield risk but also encouraged greater use of complementary inputs such as fertilizers and pesticides, further contributing to productivity enhancements (Vaiknoras, Larochelle, & Alwang, 2024). Furthermore, the integration of digital tools and Internet use further amplifies the benefits of CSA practices. In China, Internet access significantly increased the adoption of sustainable agricultural practices (SAPs), with a pronounced impact on household income for wealthier farmers (Ma & Wang, 2020).

The adoption of bundled CSA practices often yields greater benefits than individual technologies. In Zambia, the joint adoption of multiple agricultural technologies resulted in significantly higher crop yields, household incomes, and poverty reduction compared to single practices (Khonje, Manda, Mkandawire, Tufa, & Alene, 2018). Similarly, sustainable agricultural intensification practices (SAIPs) in Ethiopia demonstrated that combining input-augmenting and agronomic practices reduced production costs while enhancing sustainability (Oumer, Burton, Hailu, & Mugera, 2020).

Overall, CSA adoption improves productivity and secures higher incomes for smallholder farmers, contributing to poverty alleviation and food security. However, ensuring these benefits requires targeted policies to promote bundled CSA options, improve access to complementary inputs, and integrate digital solutions.

2.2.2 Impact of CSA on climate adaptation

Climate adaptation, as the second pillar of CSA, refers to coping and bolstering resilience to climate change. This subsection does not focus on indicators of adaptation, since these indicators are more agronomic specificities. In agricultural economics, mostly well-known practices and/or technologies that successfully provide a climate adaptation to farmers are used to capture the adaptation skills of adopters. Thus, CSA practices, ranging from water-saving technologies to diversified cropping systems, are explored in this subsection.

The adoption of climate-smart adaptation practices improves technical efficiency and productivity. For instance, Ethiopian farmers adopting climate adaptation measures achieved greater efficiency in maize, wheat, and barley production, highlighting the dual benefits of resilience building and improved farm productivity (Asmare et al., 2022). Similarly, the adoption of organic fertilizer and maize–legume intercropping in Uganda not only mitigates the negative effects of high temperatures on crop production but also increases the total value of crop production, with sustained adoption yielding higher returns over time (Maggio, Mastrorillo, & Sitko, 2022).

Water conservation practices play a vital role in building climate resilience, particularly in regions prone to drought. Research in Malawi demonstrates that legume intercropping and green belts shield crop production against floods and droughts, showcasing the protective benefits of sustainable land management practices under extreme weather conditions (McCarthy, Kilic, Brubaker, Murray, & De La Fuente, 2021). In Punjab, India, the adoption of laser leveling technology, though underutilized, shows substantial potential for conserving groundwater and addressing water scarcity in agriculture (Larson, Sekhri, & Sidhu, 2016). Additionally, combinations of water-saving practices, such as drip irrigation and intercropping, complement each other and enhance resilience, as observed in various contexts (Apio, Thiam, & Dinar, 2023).

Access to climate and weather information further strengthens adaptation strategies. Farmers in Burkina Faso using weather and climate information services (WCIS) adjusted their crop management practices, resulting in higher yields and gross margins for cowpea production (Ouédraogo, Barry, & Zougmoré, 2023). Similarly, farmers' adaptation preferences are often shaped by local climatic and soil conditions. Incremental adaptation measures, such as improved soil and water management practices, are generally favored over transformative changes. However, preferences vary significantly based on temperature, precipitation, and soil quality, necessitating tailored policies that consider regional contexts (Stetter & Cronauer, 2024). In Kenya, agro-pastoral communities showed diverse preferences for drought adaptation support, influenced by behavioral factors such as risk perception and planned behavior, emphasizing the need for targeted interventions (Schrieks, Botzen, Haer, & Aerts, 2025). Gender dynamics also influence adaptation strategies. Women's bargaining power and access to CSA technology information positively influence investment in CSA combinations, as observed in Southern Africa. This underscores the importance of addressing intra-household decision-making and promoting gender-sensitive policies to enhance adaptation outcomes (Mutenje et al., 2019).

Overall, the adoption of CSA practices significantly enhances farmers' resilience to climate change by improving technical efficiency and/or productivity. Policies promoting bundled CSA options, participatory climate services, and access to essential resources can amplify the adoption of effective adaptation strategies, ensuring sustainable and resilient agricultural systems in the face of escalating climate risks. Similar to CSA impact studies on productivity and income, these findings also show impacts on technical efficiency and productivity. This indicates studies failed to assess the adaptation impacts of adopting CSA practices, probably due to the challenges of building an indicator that includes agricultural water availability and water use efficiency (water); soil health through reducing soil disturbance (soil); climate risk management capacity and agricultural diversification (information); and women participation in agriculture (gender) (Sova et al., 2018).

2.2.3 Impact of CSA on climate mitigation

Climate mitigation, as the third pillar of CSA refers to the objective of reducing or eliminating GHGs. Similar to climate adaptation, this subsection of the literature review gives more attention to practices that their implementation contributes to achieving this third objective than the measurement of indicators.

A micro-level analysis of GHG mitigation potential reveals significant farm-level heterogeneity in emissions and efficiencies. Studies from Bavaria illustrate that emission efficiency varies across farm types, and targeted measures are essential for reducing GHG emissions without compromising economic outcomes (Stetter & Sauer, 2022). Furthermore, an analysis of China's agricultural sector shows the cost-effectiveness of diverse carbon policies. By extending carbon markets to include agriculture, policymakers could facilitate a reduction of up to 40% in agricultural GHG emissions, particularly in regions with higher mitigation potential (Tang & Ma, 2022). Conservation agriculture (CA) and tree-based intercropping (TBI) systems are also effective CSA strategies. CA practices, such as minimum tillage and intercropping, not only enhance productivity but also sequester carbon, thereby reducing GHG emissions. In Ethiopia, these practices have shown potential to alleviate rural poverty while addressing climate risks (Tesfaye et al., 2021). Similarly, Payments for Environmental Services (PES) offer a promising approach to promote CSA adoption. By compensating farmers for implementing practices that reduce CO2 emissions, PES aligns economic incentives with environmental goals. However, the effectiveness of PES depends on careful design to address socioeconomic and ecological barriers (Engel & Muller, 2016). Such programs, when integrated with precision agriculture and other CSA practices, could maximize GHG mitigation benefits while fostering sustainable agricultural intensification.

In Latin America and the Caribbean, achieving a balance between operational and environmental efficiency remains a challenge. Data envelopment analysis reveals that while some countries attain full efficiency in unified economic and environmental performance, others exhibit significant inefficiencies, underscoring the need for targeted interventions to improve agricultural sustainability (Moreno-Moreno, Velasco Morente, & Sanz Diaz, 2018).

Overall, CSA practices provide robust pathways for mitigating climate change by reducing GHG emissions, improving resource efficiency, and fostering sustainable land management. However, it is scare to find studies assessing this CSA objective through indicator related to energy, carbon, and nitrogen (Sova et al., 2018). With these indicators, the CSA adoption is expected to decrease energy use from fossil fuel (energy); increase practices of biomass-ground above and below input, increase soil carbon stock, reduce methane emission from livestock (carbon); and enhance nutrient use efficiency (nitrogen) (Sova et al., 2018).

2.2.4 Impact of CSA on Mixed CSA Objectives

CSA practices aim to simultaneously achieve the threefold objectives of enhancing productivity, fostering resilience to climate change, and mitigating greenhouse gas emissions. While the literature provides substantial evidence on each of these objectives individually, fewer studies address their collective impact.

The adoption of CSA practices often results in improved productivity and resilience. For instance, adopting agronomic practices in black gram and green gram production in India was shown to increase crop yields and revenues, albeit with mixed effects on net income, depending on the type of practice (Varma & Manda, 2024). Similarly, conservation agriculture (CA) has demonstrated effectiveness in mitigating climate shocks, enhancing yields during extreme rainfall events while contributing to resilience and environmental benefits, even though its adoption remains limited due to perceived yield losses during normal rainfall seasons (Michler, Baylis, Arends-Kuenning, & Mazvimavi, 2019). In addition, incorporating digital innovations into CSA frameworks has further expanded opportunities to enhance productivity and resilience. Digital tools enable better decision-making, improved resource use efficiency, and greater resilience to climate variability, as evidenced by studies highlighting their potential to reduce environmental footprints and increase farm productivity (Finger, 2023).

Sustainable land management practices (SLMPs) provide another pathway for achieving multiple CSA objectives. In Ghana, SLMP adopters exhibited higher technical and environmental efficiency compared to non-adopters, despite some adverse environmental consequences associated with excess herbicide use (Issahaku & Abdul-Rahaman, 2019). From an environmental perspective, efforts to align income growth with sustainability goals are crucial. In China, coordinated advancements in agricultural carbon emission efficiency and farmers' incomes highlight the potential of CSA to balance economic and environmental objectives. These outcomes were driven by regional technological advancements and targeted policy interventions (Su, Shen, & Wang, 2024). Organic farming systems, while environmentally beneficial, require strategic market interventions to address challenges in demand estimation, pricing, and profitability (Chitra, Balasudarsun, Sathish, & Jagajeevan, 2023).

Despite these positive outcomes, studies often focus on specific objectives or contexts, leaving gaps in understanding the comprehensive impact of CSA on the three objectives simultaneously.

Most research addresses productivity, resilience, or mitigation in isolation, failing to capture their interdependencies. For example, while conservation agriculture and crop diversification improve resilience and productivity, their mitigation potential remains underexplored (Adam & Abdulai, 2024; Michler et al., 2019). Similarly, while digital innovations offer transformative potential, their combined effects on productivity, resilience, and mitigation require further investigation (Finger, 2023).

2.2.5 Theoretical review

This research draws on multiple theoretical frameworks to understand the factors influencing the adoption of CSA practices in Benin. Central to the analysis is the perspective offered by New Institutional Economics (NIE), which emphasizes the role of institutions—both formal and informal—in shaping economic behavior. As North (1990) posits, institutions are the "rules of the game" that govern interactions among agents, influencing access to resources, information, and opportunities. In the context of CSA adoption, institutional arrangements such as land tenure systems, input subsidies, access to credit and extension services, and the regulatory environment play a pivotal role in either enabling or constraining farmers' choices. Empirical studies (e.g., Smith et al., 2018; Jones et al., 2020) demonstrate that institutional support mechanisms, including targeted agricultural subsidies and training programs, help reduce the transaction costs and uncertainties that often hinder the uptake of CSA innovations.

In parallel, decision-making under risk and uncertainty is often analyzed through the lens of Expected Utility Theory (EUT), which posits that economic agents select among alternatives by maximizing the expected utility of outcomes (von Neumann & Morgenstern, 1944). Within this framework, farmers are presumed to adopt CSA practices when the expected benefits—in terms of productivity, risk reduction, and long-term sustainability—outweigh the immediate costs. However, while EUT offers useful insights into rational decision-making, it tends to overlook the behavioral complexities and psychological biases that characterize real-world choices, particularly in the context of climate change, where outcomes are uncertain and difficult to quantify.

To address these limitations, behavioral economic theories, particularly Prospect Theory, provide a more nuanced understanding of how farmers make decisions under uncertainty. Prospect Theory suggests that individuals evaluate outcomes relative to a reference point and tend to exhibit loss aversion—placing more weight on potential losses than equivalent gains. In the case of CSA, farmers may perceive the upfront costs of new practices as losses relative to their current situation, even if the long-term benefits are substantial. This behavior is exacerbated by climate-related uncertainties and the difficulty of accurately assessing future gains. Research by Berger and Marinacci (2020), Brekke and Johansson-Stenman (2008), and Osberghaus (2017) highlights that in the climate change context, where both biophysical impacts and economic consequences are uncertain, decisions are often driven by subjective perceptions of risk, social norms, and institutional trust rather than objective calculations. Moreover, the difficulty in quantifying the full economic costs and benefits of climate change impacts further challenges the applicability of EUT, reinforcing the relevance of behavioral models that incorporate psychological and contextual factors. These models suggest that farmers' perceptions of climate risks and their reference points—such as past yields, community norms, or expectations of government support—influence their willingness to engage in either adaptation or mitigation strategies, or both (Mairura et al., 2021).

Finally, the diffusion of CSA practices across communities can be better understood through the Diffusion of Innovations Theory (Rogers, 2003), which emphasizes the social dynamics of adoption. According to this theory, the spread of new agricultural practices depends on perceived relative advantage, compatibility with existing knowledge and practices, complexity, trialability, and observability. In the Beninese context, where farming communities are diverse and access to institutional support is uneven, the strength of social networks, trust in external actors, and exposure to successful adopters significantly shape the adoption trajectory. Hence, adoption is not only an individual decision driven by utility or perception of loss, but also a socially embedded process influenced by the interactions among farmers, local leaders, extension agents, and development organizations.

Together, these theoretical perspectives provide a comprehensive lens for analyzing CSA adoption. They highlight the importance of institutions and policies, the behavioral underpinnings of farmer decision-making under risk, and the social processes that govern the spread of innovations. This multi-theoretical approach ensures a more holistic understanding of how farmers respond to climate-related challenges and the conditions under which CSA practices can be scaled effectively.

2.2.6 Methodological Review

To empirically assess the impacts of CSA adoption on productivity, income, climate adaptation, and mitigation outcomes, this research builds on a diverse set of econometric strategies employed in recent literature. Given the multidimensional nature of CSA and the potential for selection bias in adoption decisions, our methodological approach addresses endogeneity and heterogeneity across farmers, practices, and contexts.

2.2.6.1 Addressing Selection Bias and Heterogeneity

A central methodological challenge in CSA impact analysis is accounting for both observed and unobserved heterogeneity in adoption decisions. Studies such as Khonje et al. (2018) and Mustafa et al. (2024) have demonstrated the importance of correcting for endogeneity using **Endogenous Switching Regression (ESR)** and **Multinomial Endogenous Switching Regression (MESR)**. These models are particularly effective in estimating counterfactual outcomes across multiple CSA adoption pathways and allow us to distinguish between self-selection effects and treatment effects.

Given the possibility that farmers adopting CSA are systematically different from non-adopters in both observable and unobservable characteristics (e.g., access to information, risk preferences), our analysis incorporates ESR/MESR where applicable. For multi-practice adoption scenarios, we draw from Ma and Wang (2020), employing **endogenous treatment models** that account for the count and intensity of CSA adoption, rather than treating adoption as a binary variable.

2.2.6.2 Measuring Efficiency and Productivity Gains

To evaluate CSA's impacts on productivity and technical efficiency, we utilize **Stochastic Frontier Analysis (SFA)**, following approaches by Oumer et al. (2020) and Mustafa et al. (2024). SFA allows us to decompose deviations from maximum output levels into inefficiency and random noise, offering robust insights into how CSA adoption influences production frontiers.

Where panel data is available, we employ **continuous treatment effect models** as in Katengeza and Holden (2021), which model the intensity of CSA adoption (e.g., area under CSA practices) rather than a simple binary treatment. This approach captures impact heterogeneity across different adoption levels and is especially relevant for practices like DTMVs or organic soil amendments, where intensity may influence outcomes.

2.2.6.3 Exploiting Spatial and Experimental Variation

We also leverage **quasi-experimental and survey experimental designs** to explore causal effects. For instance, following Paul (2021), we integrate geospatial climate data (e.g., rainfall variability) with yield trials to assess CSA's drought-resilience effects. This method is particularly useful for validating adaptation outcomes under varying climate shocks. Additionally, survey experiments, such as those implemented by Vaiknoras et al. (2024), inform the design of our survey instrument to reduce measurement error and understand behavioral responses to CSA adoption under different information treatments.

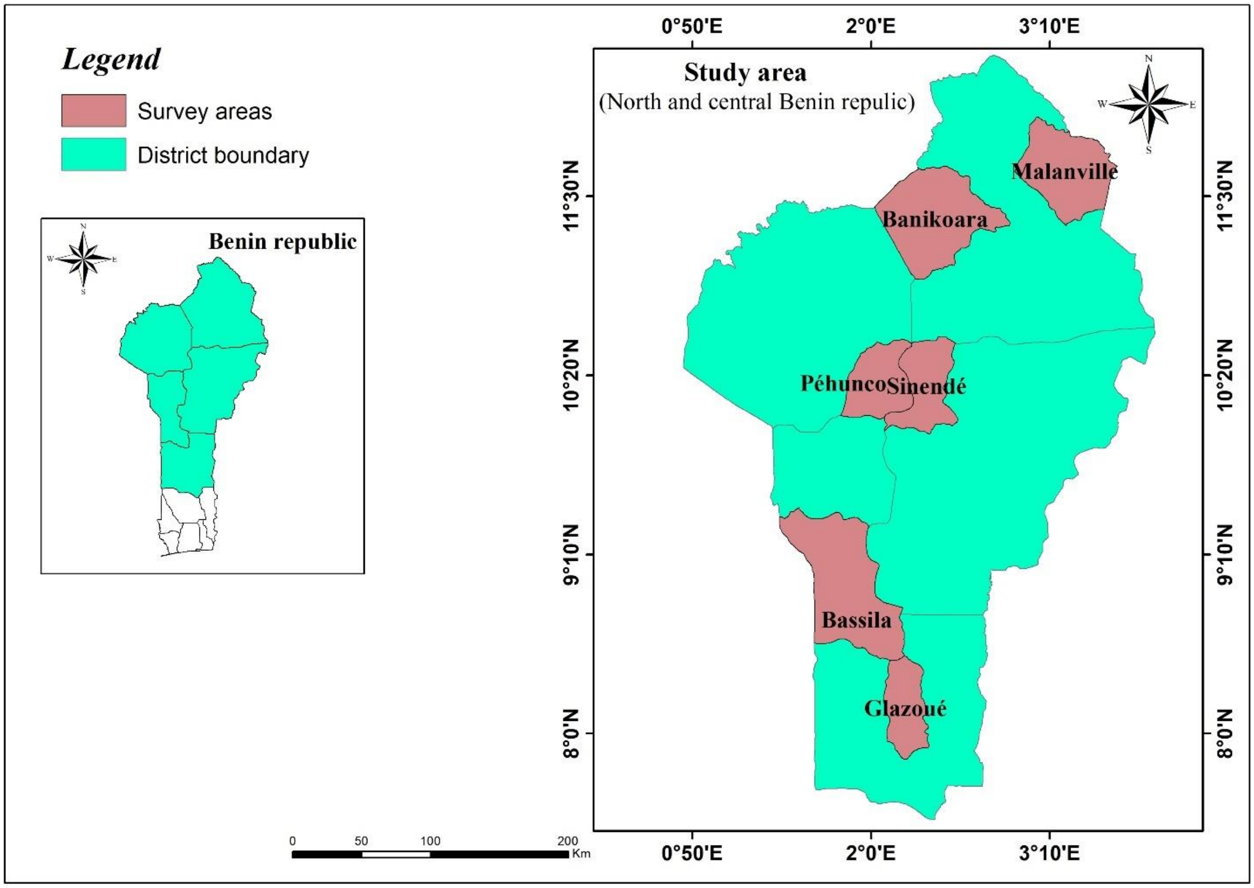
2.3 Methodology

2.3.1 Description of the research area

The research was conducted in the northern and central regions of the Republic of Benin, located between 0°50' and 3°10' North latitude and 7°50' and 12°40' East longitude. This area spans five of the twelve administrative departments: Alibori, Atakora, Borgou, Collines, and Donga. The focus of the research was on three Agricultural Development Poles (ADPs): Niger Valley (ADP 1), South Alibori-Borgou North-2KP (ADP 2), and South Borgou-Donga-Collines (ADP 4). ADP 3 was excluded from the analysis due to security concerns stemming from terrorist activities in the northern part of Benin. The selection of these regions aimed to maximize the inclusion of ADPs in the analysis, thereby enhancing the representativeness of the sample.

The research area covers 21 municipalities across these ADPs and represents a vital agricultural region in Benin, known for its diverse production. Key crops include cotton, maize, sorghum, and various types of livestock, making this zone essential to both local food security and the national economy. The region's agricultural importance is further enhanced by its role in supplying both staple and cash crops, supporting the livelihoods of a significant portion of Benin's rural population.

Figure 5: Geographic location of the research area



Source: Author

2.3.2 Sampling procedure and Data description

The research considered six municipalities: Malanville (ADP 1), Banikoara, Pehunco, and Sinendé (ADP 2), and Bassila and Glazoué (ADP 4). A three-stage sampling procedure was employed to gather survey data from farm households across northern and central Benin. The sampling strategy adopted in this research follows a proportional stratified random sampling approach focused on six administrative regions in northern and central Benin. In the first stage, we calculated the share of households in the six selected regions relative to the national total. This ratio was then used to determine the overall sample size for the research. In the second stage, the total sample size was distributed across regions based on the proportion of households within each of the six regions. Finally, a 10% adjustment rate was applied multiplicatively to the regional samples to account for potential non-responses and incomplete data. Within each stratum (region), households were then selected using a simple random sampling method to ensure representativeness and reduce selection bias.

The formulaic representation of this three-stage sampling process is described as follows:

Let:

- H_i: Number of households in region i
- H_T: Total number of households in Benin
- H_S: Total number of households in the six selected regions
- n: Total sample size for the six selected regions
- n_i: Number of households to be surveyed in region i
- r: Adjustment rate (e.g., 10%, or 0.10)

Step 1: Calculate the share of households in the six selected regions relative to the national total:

$$P_S = \frac{H_S}{H_T}$$

Step 2: Estimate the sample size for the six regions using that share:

$$n = P_S \times H_S$$

Step 3: Allocate the sample size to each region and apply the adjustment rate by multiplying directly:

$$n_i = \left(\frac{H_i}{H_S} \times n\right) \times r$$

This approach offers several practical advantages. First, it ensures proportional representation across diverse regions, which strengthens the regional validity of the findings. The incorporation of random selection within strata enhances the statistical robustness and reduces the risk of systematic bias. Furthermore, the 10% adjustment improves reliability by accounting for common survey issues, such as refusal to respond or incomplete questionnaires. Compared to standard stratified random sampling procedures, this method is largely consistent with best practices. However, it differs slightly in that it does not explicitly use statistical parameters—such as confidence levels, margins of error, or population variances—to calculate the overall sample size. Instead, it adopts a more pragmatic, proportion-based allocation. While this approach is efficient and operationally straightforward, especially for regional surveys, it may limit the precision of estimates when compared to statistically optimized sample designs.

Additionally, while the exclusion of certain regions (e.g., due to security concerns) is a practical necessity, it may affect the generalizability of the findings to the entire national context.

Nevertheless, by integrating random sampling within strata and adjusting for non-response, the approach ensures a solid balance between methodological rigor and field-level feasibility.

To ensure accurate representation, municipalities specializing in market gardening—notably Malanville and Bassila—were allocated larger survey samples (or the number of farm households to be surveyed). The sample size resulting from the final survey is 716 farm households across the six municipalities.

The number of households surveyed in each municipality is presented below:

Table 5: Number of farm households to be surveyed per municipality

ADPs	Municipalities	Number of farm households to be surveyed	surveyed
ADP 1	Malanville	150	118
ADP 2	Banikoara	125	125
	Pehunco	125	98
	Sinendé	125	103
ADP 4	Bassila	150	137
	Glazoué	125	135
TOTAL		800	716

Note: The number of surveyed farm households differs from the initial target (number to be surveyed) due to unforeseen circumstances that required adjustments during fieldwork.

Source: Author

The data collection process involved a structured and pretested questionnaire, administered by trained enumerators to the randomly selected farm households. The questionnaire was adapted from the Rural Household Multi-Indicator Survey (RHoMIS) and covered various topics, including Household demographics, Agricultural assets and production, Climate change and farm management about CSA practices, Livelihoods and incomes, Food security, assessing both quantity and quality, social networks related to agricultural practices.

This comprehensive data set provides insights into the factors influencing CSA adoption and farm-level outcomes in the research area.

2.3.3 Theoretical framework

This research is grounded in Expected Utility Theory (Neumann & Morgenstern, 1944). According to the expected utility theory, farm households decide to adopt CSA practices if the expected utility (or net benefit) of adoption exceeds that of not adopting. In this context, farmers face uncertainty about future outcomes, particularly regarding climate impacts and the effectiveness of CSA practices in improving yields, enhancing reliance, and reducing environmental impact. The expected utility theory assumes that farmers act as rational agents who aim to maximize their utility under uncertain conditions (Neumann & Morgenstern, 1944). They evaluate their options by comparing the expected outcomes of each alternative, factoring in both the risks and the potential payoffs associated with adopting CSA practices. Utility maximization thus implies that farmers rank their choices based on preferences for different outcomes (Baumol and Blinder, 2011), seeking the alternative that provides the greatest perceived value in terms of productivity, resilience, and environmental sustainability.

A farm household will choose to adopt CSA practices if the expected utility derived from adoption exceeds the utility of continuing with conventional practices or other agricultural strategies. For farmer i, who seeks to balance agricultural productivity and environmental sustainability over time, this decision can be formalized by comparing the expected utility of different CSA options. The farmer will adopt CSA practices j if the perceived utility of that option exceeds the utility of an alternative k.

This decision-making process can be expressed mathematically as follows:

$$U_{ij}\left(\beta_j' X_i + \varepsilon_j\right) > U_{ik}(\beta_k' X_i + \varepsilon_k), k \neq j \qquad (1)$$

where U_{ij} and U_{ik} represent the perceived utility by farmer i from adopting CSA practice j and alternatives k, respectively; X_i is a vector of socioeconomic factors influencing the farmer's decision; β_j' and β_k' are parameters associated with the independent variables; and ε_j and ε_k are random error terms assumed to be independently and identically distributed (Brooks, 2019).

Given that farmers make decisions based on expected benefits, the adoption of CSA can be modeled as a binary choice: the farmer adopts CSA if the net expected benefit (utility) is positive, and does not adopt it if it is negative. This can be expressed as:

$$Y_{ij} = \begin{cases} 1 & if \quad U_{ij} > 0 \\ 0 & if \quad U_{ij} < 0 \end{cases} \qquad (2)$$

Where Y_{ij} is a binary dependent variable equal to 1 if the farmer chooses a CSA alternative j, and 0 otherwise. The probability that the farmer i will adopt CSA practice j can be written as:

$$P(Y_{ij} = 1/X) = P(U_{ij} > U_{ik}/X) = P(\beta_j' X_i + \varepsilon_j > \beta_k' X_i + \varepsilon_k/X)$$

$$= P(\beta_j' X_i + \varepsilon_j - \beta_k' X_i - \varepsilon_k > 0/X) = P(\beta^* X_i + \varepsilon^* > 0/X) = F(\beta^* X_i) \qquad (3)$$

where P is a probability function; $\beta^* = \beta_j' - \beta_k'$ is an unknown vector parameter that can be justified as the net impact of the choice of CSA alternative determinants; $\varepsilon^* = \varepsilon_j' - \varepsilon_k'$ is a random error term; and $F(\beta^* X_i)$ is a cumulative distribution of ε^* estimated at $\beta^* X_i$ (Asteriou & Hall, 2021).

This framework allows us to model the factors that influence a farmer's decision to adopt CSA, considering the uncertainty inherent in climate conditions and agricultural outcomes. Expected Utility Theory provides a robust theoretical foundation for understanding the trade-offs and choices farmers face when adopting CSA practices, helping to identify the conditions under which adoption is most likely to occur.

2.3.3.1 Hypothesis

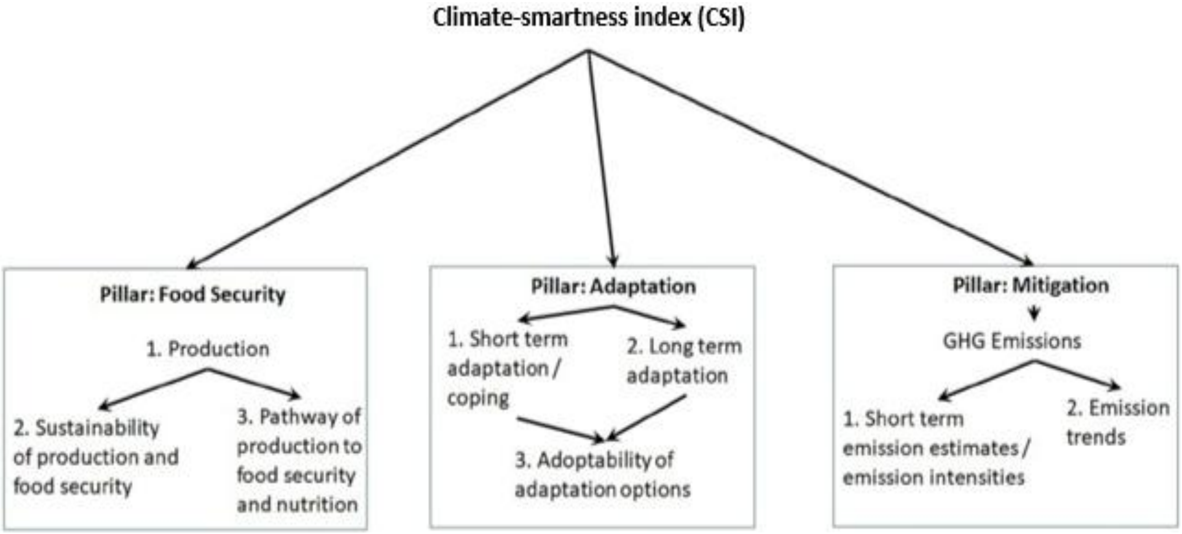
Following this theoretical framework, this research assumes that: “The adoption of CSA practices enhances the climate-smartness of farming systems in the Republic of Benin by improving productivity, increasing resilience to climate change, and reducing greenhouse gas emissions.”

2.3.4 Measurement of climate smartness

Climate smartness was assessed using an index-based approach, as suggested by the assessment framework of (Wijk et al., 2020). This choice addresses criticisms of previous CSA (Climate-Smart Agriculture) assessment frameworks, which often neglected the social and economic sustainability of production. Additionally, previous studies primarily focused on GHG emissions for environmental sustainability and rarely addressed climate change adaptation (Challinor et al., 2022; Wijk et al., 2020).

Our research applies the framework proposed by (Challinor et al., 2022; Wijk et al., 2020), emphasizing the aspects they highlighted. The climate smartness of a farming system is measured using the climate smartness index (CSI), which includes three dimensions: food security, adaptation, and mitigation (Figure 6).

Figure 6: Scheme of the three pillars of climate smartness and several subcomponents



Source: (Wijk et al., 2020)

The food security dimension comprises three components: production sustainability, food security, and the link between production and nutrition. The adaptation dimension includes short-term adaptation (or coping), long-term adaptation, and the adoptability of adaptation options. The mitigation dimension focuses on short-term emission estimates/intensities and emission trends (Wijk et al., 2020). The indicators identified and grouped for the PCA approach are detailed in Table 6.

Table 6: List of indicators for building climate-smartness index (CSI)

Index	Dimensions		Indicators	Justification
Climate-Smartness Index (CSI)	Pillar1: Food Security	1. Production	Yield of the primary staple crop (kg/ha)	(Hammond, Van Wijk, Teufel, Mekonnen, & Thorne, 2021)
			Total farm crop productivity (kCal/ha)[2]	
			Agricultural diversity (count)	
		2. Sustainability of production and food security	Food Insecurity Experience Scale	(Hammond et al., 2021)
			Household Dietary Diversity Score	
			Dependency ratio	
			Group membership (dummy)	
		3. Pathway of production to food security and nutrition	Crop consumption (kg)	
			Total value of agricultural activities (without livestock) (10^3 FCFA)	
			Number of independent sources of cash income	
			Off-farm income (10^3 FCFA)	
			Market orientation - farm produce sold out of the total value of farm produce - (\%)	
	Pillar2: Adaptation	1. Short-term adaptation (coping)	Total labor used (family + hired)	(Wiederkehr, Beckmann, & Hermans, 2018)
			Access to land (dummy)	
			Total livestock units (poultry + goat/sheep + cattle)	
			Total other assets	
			Access to credit	

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[2] Total farm crop productivity is calculated in terms of calorific energy content value per hectare

	2. Long-term adaptation	Access to institutions (extension agencies, NGOs, private enterprises)	(Ng'ang'a, Van Wijk, Rufino, & Giller, 2016)
	3. Adoptability of adaptation options	education age gender marital	
Pillar3: Mitigation	1. Short-term mitigation (estimates or intensity)	Fertilizers-induced field emissions- (kg CO2eq/ha)	(Hammond et al., 2021)
	2. Long-term mitigation (trend)	Number of land conservation practices applied (count)	

Source: Author

2.3.5 Analytical framework

This research focuses on a variety of agricultural practices adopted by farmers, classified as CSA practices. These include the use of agrochemicals (pesticides and herbicides), inorganic fertilizers (urea, NPK), organic fertilizers (manure, compost), minimum soil disturbance (no-tillage), irrigation, improved seed varieties, water conservation methods (e.g., stone bunds, contour farming, Zai pits), mulching, agroforestry, crop rotation, and intercropping. According to the Food and Agriculture Organization (FAO) classification, these practices are grouped into five categories: soil management, nutrient management, crop management, water management, and integrated systems (Lokonon & Mbaye, 2018). These practices were selected for the research based on their common use and affordability for smallholder farmers. Table 7 provides details of the eleven CSA practices used in this research.

Table 7: Description of CSA practices used

Practices	Description	Why is it climate-smart?
Use of agrochemicals	Application of pesticide and/or herbicide (Ogola & Ouko, 2021)	Increase crop productivity by controlling pests, weeds, and diseases
Efficient use of inorganic fertilizer	Application of optimum amount of artificial fertilizer (Tilahun, Bantider, & Yayeh, 2023)	Improve soil productivity
Use of organic fertilizer	Putting animal dung or manure on farmlands for soil fertility improvement Application of manure or compost (Tilahun et al., 2023)	Reduce nitrous oxide and methane emission
No-tillage	Minimum soil disturbance	Increase soil fertility through nutrient conservation
Small-scale irrigation	Irrigation on small plots, in which small farmers have the controlling influence of all activities (Tilahun et al., 2023)	Create carbon sink and improve yield frequency
Use of improved seed variety	Any variety that has been developed to enhance yield	Improve productivity, reduce insect and disease attack
Water conservation	Practices for retaining water for crops, (e.g. stone bunds, half-moon, and/or zaï pits) (Rhodes, Tambi, & Bangali, 2015)	Reduce runoff and increase infiltration of rainfall
Mulching	Covering the soil between plants with layer/s of material (Subedi et al., 2019)	Reduces existing emissions
Agroforestry	Planting of trees or shrubs in or around farmland or pastureland (Vaast, Harmand, Rapidel, Jagoret, & Deheuvels, 2016)	Providing shed to crops, trees store large amounts of CO2 and diversify income sources
Crop rotation	Planting different crops on the same area of farmland in consecutive planting seasons (FAO, 2014b)	Improves soil fertility and increases crop productivity
Intercropping	Cultivation of two or more crops simultaneously on the same field	Ensure food source and income

Source: Author, inspired by (Tilahun et al., 2023)

2.3.5.1 Multinomial Endogenous Switching Regression (MNLESR) model

Given the multidimensional nature of CSA practices, the research employed a Multinomial Endogenous Switching Regression (MNLESR) model to analyze two main aspects: The determinants of CSA practice choice (i.e., which factors influence farmers' decisions to adopt specific CSA practices or combinations of practices) and the impact of CSA adoption on the overall climate-smartness of farming systems. The analysis follows a two-stage approach:

A. Stage 1 : Multinomial adoption selection model

In this stage, the research uses a multinomial logit (MNL) model to identify the determinants of CSA package choice. This model assumes that the probability of choosing one CSA package over another is independent of irrelevant alternatives (IIA) (Hoffman & Duncan, 1988). Farm households aim to improve the climate-smartness of their farming systems by selecting the CSA package that offers the greatest expected benefits, whether for food security, climate adaptation, or mitigation. A farmer will choose package j over other alternatives k (where $k \neq j$) if the expected benefit Y_{ij} exceeds Y_{ik}. Household and farm characteristics and unobserved factors influence the latent variable representing the expected benefit:

$$Y_{ij}^{*} = x_i\beta_j + \varepsilon_{ij} \qquad (4)$$

where x_i denotes observed exogenous variables and ε_{ij} captures unobserved factors, assumed to follow a Gumbel distribution.

The probability of a farmer choosing a specific CSA package **j** can be expressed as:

$$P_{ij} = p\left(\varepsilon_{ij} < 0/x_i\right) = \frac{\exp\left(x_i\beta_j\right)}{\sum_{k=0}^{j}\exp(x_i\beta_k)} \qquad (5)$$

B. Stage 2 : Endogenous switching regression model

In the second stage, the research examines the impact of CSA adoption on climate-smartness using an Endogenous Switching Regression (ESR) model. This model corrects for potential selection bias that arises because CSA adopters may differ from non-adopters in ways that influence their outcomes. The ESR model specifies different regimes for farm households, where Regime 1 represents the reference (non-adoption) category. The climate-smartness status for each regime is modeled as:

$$Q_{ij} = z_i\alpha_j + \mu_{ij} \qquad (6)$$

where Q_{ij} represents climate-smartness status, z_i represents exogenous variables (household, location, farm characteristics, institutional variables, and climate shocks), and μ_{ij}, error terms, with $E(\mu_{ij}/x,z) = 0$ and $var(\mu_{ij}/x,z) = \sigma_j^2$.

The correlation between the error terms in equations (4) and (6) must be considered to correct for selection bias. The inverse Mills ratio **(λ_j)** is included as a correction term in equation (6), ensuring unbiased estimates of the impacts of CSA adoption:

$$Q_{ij} = z_i\alpha_j + \sigma_j\lambda_j + \omega_{ij} \qquad (7)$$

where the covariance between μ and ε is represented by σ_j and the inverse Mills ratio formula is:

$$\lambda_j = \sum_{k\neq j}^{j} \rho_j \left[\frac{P_{ik}In(P_{ik})}{1-P_{ik}} + In(P_{ij})\right] \qquad (8)$$

where ρ signifies the correlation coefficient of μ and ε, whereas ω_{ij} are error terms with zero expected value. In the multinomial choice setting, there were $j-1$ correction selection terms, one for each CSA practice alternative. Standard errors in equation (7) were bootstrapped to address heteroskedasticity from regressors generated by λ_j.

Estimation of average treatment effects

The average treatment effect on the treated (ATT) and the average treatment effect on the untreated (ATU) are estimated by comparing the climate-smartness status of adopters and non-adopters. The ATT reflects the change in climate-smartness status for adopters, while the ATU estimates the potential change for non-adopters if they were to adopt CSA practices (Liang, Zhang, Li, Zhang, & Frewer, 2021).

- For adopters:

Climate-smartness with adoption: $E(Q_{ij}/j \neq 1) = z_i\alpha_j + \sigma_j\lambda_j \qquad (10a)$

Climate-smartness without adoption: $E(Q_{ij}/j = 1) = z_i\alpha_1 + \sigma_1\lambda_j \qquad (10b)$

- For non-adopters:

Climate-smartness with adoption: $E(Q_{i1}/j = 1) = z_i\alpha_1 + \sigma_1\lambda_1 \qquad (11a)$

Climate-smartness without adoption: $E(Q_{i1}/j \neq 1) = z_i\alpha_j + \sigma_j\lambda_1 \qquad (11b)$

The ATT is the difference between the climate-smartness of adopters and non-adopters under actual and counterfactual scenarios:

$$ATT = z_i(\alpha_j - \alpha_1) + \lambda_j(\sigma_j - \sigma_1) \qquad (12)$$

Similarly, the ATU is the difference between the expected outcomes for non-adopters under actual and counterfactual scenarios:

$$ATU = z_i(\alpha_j - \alpha_1) + \lambda_1(\sigma_j - \sigma_1) \qquad (13)$$

For the econometric analysis, Table 8 presents variables derived from a review of past studies.

Table 8: List of variables for the econometric analysis

Variables	Description	Mean (SD)	t-test
	Socioeconomic characteristics		
Age	The age of the household head (years)	38.64 (10.37)	1.57
Family size	People in a household (number)	9.04 (5.14)	2.09**
Dependency	Dependency ratio or proportion of adults (ratio)	0.12 (0.12)	-0.32
Assets	Owned assets (number)	3.10 (2.34)	4.03***
Gender	The sex of the household head (1=male, 0=female)	0.84	3.01***
Marital	Marital status of household head (1 = married, 0=unmarried)	0.85	-0.25
Education	Level of education (1=No education, 2=Non formal, 3=Primary, 4=Secondary, 4=Postsecondary)	2.69	1.40
	Production inputs		
Tenancy	Rent in land for production (1=Rent, 0=No rent)	0.10	1.34
Land	Land size for production activity (hectare)	5.29 (4.35)	4.11***
Hire	Use of hired labor (1=Hired labor, 0=No labor hired)	0.45	-0.24
membership	Membership of a group (1=Member of a group, 0=No membership)	0.46	1.12
	Institutional factors		
Training	Participation in any agricultural training/workshop (1=participated, 0=Never participated)	0.35	1.56
Extension	Extension workers visit field (1=been visited, 0=never)	0.28	2.15**

2.4 Results

2.4.1 Descriptive statistics of the CSA packages

Table 9 presents descriptive statistics for the five CSA categories. Among these, crop management is the most commonly adopted category, with 99.16% of farmers using at least one practice from this category. This category includes crop rotation, intercropping, agrochemical use, and improved seed variety use. Nutrient management, used by 89.66% of farmers, involves practices such as the application of inorganic and organic fertilizers, as well as mulching. Soil management practices, adopted by 86.03% of farmers, include minimum tillage (or zero tillage), water conservation, and mulching. The integrated system category, primarily agroforestry, and the water management category, primarily irrigation, are less common, with adoption rates of 66.48% and 13.40%, respectively.

Table 9: *List of climate-smart categories based on FAO classification*

Category	Percentage of users	Components
Crop management (C)	99.16%	Crop rotation, Intercropping, Agrochemical use, Improved seed variety
Nutrient management (N)	89.66%	Inorganic fertilizer, Organic fertilizer, Mulching
Soil management (S)	86.03%	Minimum tillage, water conservation, Mulching
Integrated system (I)	66.48%	Agroforestry
Water management (W)	13.40%	Irrigation

Source: Author

2.4.2 Econometric results

Table 10 illustrates the different combinations of CSA practices adopted by farmers in the research area. Out of 32 possible combinations, only seven were commonly used by the farmers. The full table, including the unused combinations, is provided in the appendix. We adopted a simplified naming convention for the combinations of practices in the 'Binary quadruplicate' column to generate the packages adopted by farmers. When a combination consists of two categories, the package name is derived from those categories. Combinations involving soil, nutrient, and crop management serve as the baseline for full management packages. Any combination that incorporates more than these three core categories is named after the additional category included in the package. To meet statistical requirements, choices 8, 11, and 14 are grouped under the label ‘Crop Management’ since they share the crop management category. This label will be consistently used throughout the rest of the paper.

Table 10: Specification of CSA practice combinations to form the packages

Choice (j)	Packages	Binary quadruplicate	Frequency	Percentage
1	No-Adoption	$S_0N_0C_0W_0I_0$	19	02.65
8	Soil-Crop Management	$S_1N_0C_1W_0I_0$	14	01.95
11	Nutrient-Crop Management	$S_0N_1C_1W_0I_0$	14	01.95
14	Water-Crop Management	$S_0N_0C_1W_1I_0$	04	00.56
15	Agroforestry	$S_0N_0C_1W_0I_1$	31	04.33
17	Full Soil-Crop	$S_1N_1C_1W_0I_0$	128	17.88
24	Partial Agroforestry	$S_0N_1C_1W_0I_1$	35	04.88
27	Full Water Management	$S_1N_1C_1W_1I_0$	59	08.24
28	Full Agroforestry	$S_1N_1C_1W_0I_1$	379	52.93
32	Full CSA	$S_1N_1C_1W_1I_1$	33	04.60
Total			716	100

Source: Author

The most commonly adopted CSA package, representing 52.93% of farmers, was the Full Agroforestry package, which includes all CSA strategies except water conservation practices such as stone bunds and Zai pits. Water conservation is crucial for reducing runoff and improving water infiltration. The second most common package, the Full Soil-Crop package, adopted by 17.88% of farmers, combines soil, nutrient, and crop management practices but excludes both water conservation and integrated systems (agroforestry). A smaller percentage, 8.24%, adopted the Full Water Management package, which includes all CSA practices except agroforestry. 4.60% of farmers adopted the Full CSA package, which includes all five CSA categories, and 4.33% adopted Agroforestry, focusing on crop management and integrated systems. Additionally, the Crop

Management package was adopted by 4.47% of farmers. Finally, a small group of farmers (2.65%) did not adopt any CSA package at all, which represents a No-Adoption package.

2.4.2.1 Determinants of choice of specific CSA packages

The adoption of CSA practices by farmers passes through the process of selecting packages. The first stage of the MNLESR model is to identify factors influencing the choice of CSA packages using the MNL model. Table 11 reports the marginal effects from the multinomial logit regression model, with the No-Adoption package as the reference category. The results show seven sets of parameter estimates, indicating substantial differences across the alternative packages [Wald test: $X^2(105) = 466.16$, $p < 0.000$].

Table 11: Marginal effect estimates for the determinants of CSA packages by MNL

Packages Variables	Agroforestry	Crop Management	Partial Agroforestry	Full Soil-Crop	Full Water Management	Full Agroforestry	Full CSA
Demographic factors							
Age	0.001	-0.001	0.001	0.001	0.002**	-0.01***	0.002**
Gender	0.03*	-0.03	0.03	-0.02	-0.03	0.04	-0.01
Marital	-0.02	-0.01	0.04**	-0.06	-0.01	0.03	0.01
Family size	0.0002	-0.003	-0.003	-0.002	0.01***	0.001	-0.0004
Socio-economic factors							
Education	0.002	-0.01	-0.01	-0.01	0.01	0.001	0.01*
Asset	0.01	-0.001	0.01	-0.04***	0.002	0.02	0.01
Land size	-0.01**	-0.003**	0.001	0.01**	-0.03***	0.04***	-0.01*
Tenancy	-0.002	0.02	-0.013	0.05	-0.02	-0.09*	0.03
Dependency	0.13**	-0.11	-0.16	-0.17	0.10	0.32*	-0.19*
Hire	0.02	-0.01	-0.04***	0.031	0.01	-0.05	0.04**
Institutional and training factors							
Training	-0.003	-0.30***	-0.01	0.08**	0.11***	0.11*	0.04*
Extension	-0.06***	0.62***	-0.03**	-0.14***	0.05**	-0.44***	0.01
Membership	0.04	-0.01	-0.001	-0.14***	0.05	0.05	0.04

Number of observations = 716
Wald X2 (105) = 466.16, p < 0.000
No-Adoption is the reference category base in the MNL
***p<1%, **p<5%, *p<10%

Source: Author

A. Demographic factors

Age: Age positively influenced the adoption of the Full Water Management and Full CSA packages while negatively affecting the Full Agroforestry package. Specifically, a one-year increase in age raised the probability of adopting the Full Water Management and Full CSA packages by 0.2% each. Still, it decreased the likelihood of Full Agroforestry adoption by 0.5%. This suggests that older farmers prefer more familiar and less risky practices. Being risk-averse, they are inclined to maintain well-established packages like water management, which align with their long-term practices. These findings are consistent with (Haq, Boz, & Shahbaz, 2021), who demonstrated that older farmers often avoid shifting to new practices due to perceived risks.

Marital Status: Being married positively affected the adoption of the Partial Agroforestry package. Married farmers were 3.7% more likely to adopt this package. This is likely due to larger family labor pools, which can help manage labor-intensive practices like the Partial Agroforestry package.

Gender: Gender played a significant role in the adoption of the Agroforestry package. Male farmers were 3% more likely to adopt agroforestry practices compared to women. This can be attributed to cultural norms where men are more involved in field-based activities such as crop management and agroforestry, as noted by (Kpadenou, Tama, Dado Tossou, & Yabi, 2020; Obossou, Chah, Anugwa, & Reyes-Garcia, 2022). This difference is also reflected in male-headed households, which tend to adopt more labor-intensive practices like agroforestry (Tilahun et al., 2023; Wekesa, Ayuya, & Lagat, 2018).

Family size: Family size was significantly associated with the adoption of the Full Water Management package at the 1% level. A one-member increase in family size raised the likelihood of adopting this package by 0.7%. This suggests that larger families have greater labor capacity, which is especially useful for labor-intensive practices like soil and water conservation and irrigation. These results are consistent with (Haq et al., 2021), who found that households in joint-family systems are more likely to adopt CSA packages that include crop diversification, soil, and water conservation, as well as modern inputs. Additionally, the hiring labor force negatively influenced the adoption of the Partial Agroforestry package, while positively influencing the Full CSA package suggesting that farmers hire labor when intensive labor investments are required.

B. Socio-economic factors

Education: Education positively influenced the adoption of the Full CSA package, with an additional year of education raising the probability of adoption by 1.3%. Educated farmers are more likely to be aware of climate-resilient practices and their benefits, making them more inclined to adopt comprehensive CSA packages. This finding aligns with studies by (Sardar, Kiani, & Kuslu, 2021) and (Pangapanga-Phiri & Mungatana, 2021), which highlights the role of education in promoting climate-smart practices.

Asset Ownership: Ownership of assets, including physical farming equipment (e.g., ox plows, machetes, tractors) and communication tools (e.g., radios, TVs, mobile devices), negatively affected the adoption of the Full Soil-Crop Management package. An increase in asset ownership by one unit reduced the probability of adopting this package by 3.7%. This suggests that farmers with greater access to resources may shift to more productive or advanced CSA packages. This aligns with the findings of (Mujeyi, Mudhara, & Mutenje, 2021) and (Obi & Maya, 2021), who showed that farmers with higher asset levels often seek more efficient farming systems.

Land Size: Larger land size positively influenced the adoption of the Full Soil-Crop Management and Full Agroforestry packages but negatively affected the adoption of other packages, including Agroforestry, Crop Management, Full Water Management, and Full CSA packages. A one-hectare increase in land size raised the likelihood of adopting the Full Soil-Crop Management and Full Agroforestry packages by 10% and 3.8%, respectively, but reduced the probability of adopting other packages by 0.3% to 2.7%. This suggests that larger landholdings encourage farmers to experiment with more integrated CSA practices, a finding supported by (Wekesa et al., 2018).

Conversely, the Crop Management and the Agroforestry packages were less likely to be adopted as land size increased. A possible explanation is that these farmers might prefer renting out their additional land rather than farming it, as smaller packages may not yield meaningful production under harsh weather conditions. Renting farmers may not be motivated to implement long-term packages, reducing CSA package usage on such farms. Additionally, large packages (the Full CSA), especially the Full Water Management packages were less adopted when land size increased, highlighting the issue of water availability in harsh weather conditions, leading farmers to prioritize the Full Soil-Crop Management package. This trend was consistent across surveyed regions, except for Malanville and Bassila, where water management or irrigation is not a primary choice because farmers grow more food crops than market garden products. The results corroborate those of (Tadesse & Ahmed, 2023) where farm size is negatively associated with irrigation adoption but positively influences soil and water conservation practices.

Tenancy: Renting land reduced the likelihood of adopting the Full Agroforestry package by 9.2%. Farmers who rent land may be less likely to adopt long-term, labor-intensive practices such as agroforestry, which require significant time and investment.

Dependency ratio: The dependency ratio, which represents the proportion of adults capable of working relative to the total family size, had a mixed effect on CSA adoption. It positively influenced the adoption of the Agroforestry and Full Agroforestry packages, increasing their likelihood by 12.8% and 31.6%, respectively. In contrast, a higher dependency ratio negatively impacted the adoption of the Full CSA package, reducing its likelihood by 18.6%. This suggests that households with more working-age adults are more inclined to adopt labor-intensive practices like Agroforestry. Conversely, in families with a higher proportion of dependents (such as children and the elderly), farmers may not be capable of adopting the Full CSA package.

C. Institutional and training factors

Training: Training played a significant role in influencing the adoption of CSA packages. Participation in CSA training reduced the likelihood of adopting the Crop Management package by 28.8% but increased the probability of adopting the Full Management packages. This suggests that farmers exposed to more comprehensive CSA training are likely to experiment with a wider range of practices, highlighting the effectiveness of holistic training programs.

Membership Groups: Belonging to a farmer group negatively affected the likelihood of adopting the Full Soil-Crop Management package, reducing the probability by 13.6%. This contrasts with findings by (Tilahun et al., 2023) and (Wekesa et al., 2018), who observed that farmer group membership often promotes CSA adoption. A possible explanation is that in the research regions, farmer groups may not actively exchange best practices or encourage intensive management techniques, limiting the impact on specific CSA packages.

Extension Services: Access to extension services positively influenced the adoption of the Crop Management and Full Water Management packages, increasing the probability of adoption by 61.7% and 5%, respectively. This finding is consistent with (Martey, Etwire, & Abdoulaye, 2020), who found that extension contact significantly boosts the adoption of climate-smart practices. However, extension services negatively influenced the adoption of other CSA packages, except for the Full CSA package, suggesting a need for more tailored extension efforts that promote comprehensive management approaches.

2.4.2.2 Average adoption treatment effects for the adoption of CSA packages

In the second stage, the impact of CSA package adoption on the climate-smartness status of farming systems was evaluated using an ordinary least squares (OLS) regression of the Climate Smartness Index (CSI), while correcting for selection bias terms derived from the first stage. Discussing treatment effects is crucial in this stage to assess how different CSA packages influence farming systems.

The CSI measures the level of climate-smartness in farming systems, with higher CSI values indicating a stronger alignment with CSA objectives. The analysis focuses on how each CSA package performs across the three dimensions of climate-smart agriculture: food security, adaptation, and mitigation. Table 8 presents the average effects of adoption under actual and counterfactual conditions. In this context, X1 indicates the adopters (treated category), and X2 denotes the non-adopters (untreated category). β1 represents the treated characteristics (adoption state), and β2 reflects the untreated characteristics (non-adoption state). The difference between β1X1 and β2X2 reflects the impact or return of adopting a specific CSA package, which measures the change in CSI as a result of adoption.

Table 12: Impact of adoption and non-adoption of CSA Packages on the Climate Smartness of Farming Systems

CSA Packages		Climate-smartness (CSI)			Food security (FS)			Adaptation (A)			Mitigation (M)		
		Treated (β1)	**Untreated (β2)**	**Impact/ return**	**Treated (β1)**	**Untreated (β2)**	**Impact/ return**	**Treated (β1)**	**Untreated (β2)**	**Impact/ return**	**Treated (β1)**	**Untreated (β2)**	**Impact/ return**
Agroforestry	*Treated*	0.0974	0.0979	-0.0005	0.0888	0.0896	-0.0007	0.4680	0.4617	0.0063	0.0129	0.0145	-0.0016
	(X1)	(0.006)	(0.006)		(0.004)	(0.004)		(0.031)	(0.031)		(0.010)	(0.010)	
	Untreated	0.1088	0.1079	0.0009	0.0991	0.0978	0.0013	0.4248	0.4369	-0.0120	0.0418	0.0386	0.0031
	(X2)	(0.001)	(0.001)		(0.0006)	(0.0006)		(0.007)	(0.007)		(0.001)	(0.003)	
	Level effects	-0.0114***	-0.01***	-0.0105***	-0.0103***	-0.0082***	-0.009***	0.0432***	0.0248***	0.0311***	-0.0289***	-0.0241***	-0.0257***
Crop Management	*Treated*	0.0991	0.0983	0.0008	0.0932	0.0927	0.0004	0.3406	0.3387	0.0018	0.0573	0.0561	0.0012
	(X1)	(0.005)	(0.005)		(0.003)	(0.003)		(0.027)	(0.027)		(0.0098)	(0.0098)	
	Untreated	0.1088	0.1096	-0.0008	0.0990	0.0995	-0.0005	0.4307	0.4329	-0.0021	0.0398	0.0411	-0.0013
	(X2)	(0.001)	(0.001)		(0.0007)	(0.0007)		(0.007)	(0.007)		(0.002)	(0.002)	
	Level effects	-0.0097***	-0.0113***	-0.0105***	-0.0058***	-0.0068***	-0.0063***	-0.0901***	-0.0942***	-0.0923***	0.0175***	0.015***	0.0162***
Partial Agroforestry	*Treated*	0.1306	0.1294	0.0012	0.1082	0.1087	-0.0005	0.4356	0.4299	0.0056	0.1176	0.1096	0.0079
	(X1)	(0.005)	(0.005)		(0.003)	(0.003)		(0.026)	(0.026)		(0.007)	(0.007)	
	Untreated	0.1072	0.1085	-0.0012	0.0982	0.0976	0.0006	0.4262	0.4324	-0.0061	0.0366	0.0451	-0.0085
	(X2)	(0.001)	(0.001)		(0.0007)	(0.0007)		(0.007)	(0.007)		(0.002)	(0.003)	
	Level effects	0.0234***	0.0209***	0.0221***	0.01***	0.0111***	0.0106***	0.0094***	-0.0025***	0.0032***	0.081***	0.0645***	0.0725***
Full Soil-Crop	*Treated*	0.1018	0.1018	8.96e-7	0.0946	0.0947	-0.0001	0.4158	0.4158	-4.08e-7	0.0301	0.0290	0.0011
	(X1)	(0.002)	(0.002)		(0.001)	(0.001)		(0.015)	(0.015)		(0.004)	(0.004)	
	Untreated	0.1098	0.1098	-1.32e-6	9.96e-2	9.93e-2	2.67e-4	0.4291	0.4291	5.80e-7	0.0428	0.0445	-0.0016
	(X2)	(0.001)	(0.001)		(7.81e-4)	(7.79e-4)		(0.006)	(0.007)		(0.002)	(0.002)	
	Level effects	-0.008***	-0.008***	-0.008***	-0.005***	-0.0046***	-0.0047***	-0.0133***	-0.0133***	-0.0133***	-0.0127***	-0.0155***	-0.0144***

Full Water Management	*Treated*	0.1158	0.1158	5.75e-5	0.1074	0.1065	0.0008	0.4095	0.4252	-0.0157	0.0423	0.0399	0.0023
	(X1)	(0.004)	(0.004)		(0.002)	(0.002)		(0.024)	(0.024)		(0.004)	(0.004)	
	Untreated	0.1077	0.1078	-1.26e-4	0.0979	0.0999	-0.002	0.4282	0.3937	0.0345	0.0404	0.0456	-0.0052
	(X2)	(0.001)	(0.001)		(0.0007)	(0.0007)		(0.007)	(0.008)		(0.002)	(0.002)	
	Level effects	0.009***	0.008***	0.008***	0.0095***	0.0066***	0.0075***	-0.0187***	0.0315***	0.0158***	0.0019***	-0.0057***	-0.0033***
Full Agroforestry	*Treated*	0.1088	0.1091	-2.13e-4	0.0985	0.0991	-0.0006	0.4376	0.4336	0.0039	0.0395	0.0390	0.0005
	(X1)	(0.002)	(0.002)		(0.0009)	(0.0009)		(0.010)	(0.010)		(0.003)	(0.003)	
	Untreated	0.1078	0.1073	0.0005	0.0989	0.0975	0.0014	0.4145	0.4236	-0.0091	0.0417	0.0430	-0.0012
	(X2)	(0.002)	(0.002)		(0.0009)	(0.0009)		(0.0096)	(0.0096)		(0.003)	(0.003)	
	Level effects	0.001***	0.0018***	0.0015***	-0.0004***	0.0016***	0.001***	0.0231***	0.01***	0.014***	-0.0022***	-0.004***	-0.0035***
Full CSA	*Treated*	0.1160	0.1153	0.0007	0.1052	0.1045	0.0007	0.4166	0.4267	-0.0101	0.0536	0.0487	0.0048
	(X1)	(0.005)	(0.005)		(0.003)	(0.003)		(0.028)	(0.028)		(0.012)	(0.012)	
	Untreated	0.1080	0.1092	-0.0012	0.0984	0.0996	-0.0012	0.4272	0.4102	0.0169	0.0399	0.0480	-0.0080
	(X2)	(0.001)	(0.001)		(0.0007)	(0.0008)		(0.007)	(0.008)		(0.002)	(0.003)	
	Level effects	0.008***	0.0061***	0.0068***	0.0068***	0.0049***	0.0056***	-0.0106***	0.0165***	0.0064***	0.0137***	0.0007***	0.0056***

Source: Author

Out of the seven CSA packages analyzed, four packages including Partial Agroforestry, Full Water Management, Full Agroforestry, and Full CSA, had a positive impact on the CSI, indicating potential synergies i.e. their overall contribution to climate-smart farming systems. These packages typically include more comprehensive management practices, particularly in water management or integration across CSA categories. On the other hand, three packages, including Agroforestry, Crop Management, and Full Soil-Crop Management, exhibited negative CSI impacts. This suggests that these less comprehensive packages may lead to trade-offs between CSA objectives.

To gain a deeper understanding of these impacts, the CSI was disaggregated into its constituent dimensions: food security, adaptation, and mitigation. The results show a strong correlation between positive CSI values and superior performance in at least two dimensions, while negative CSI values tend to align with poor performance in at least two dimensions. Especially, the Partial Agroforestry and Full CSA packages scored positively across all dimensions, indicating that these packages are capable of achieving the three CSA objectives simultaneously, fostering synergies among food security, adaptation, and mitigation. These packages, by integrating comprehensive management practices, demonstrate a balanced performance across the key CSA dimensions. Similarly, the Full Water Management and Full Agroforestry packages also performed well, but their positive impacts were primarily observed in food security and adaptation. While these packages support resilience-building and ensure food security, they are less effective in mitigating emissions, indicating some trade-offs. On the other hand, Agroforestry and Crop Management packages, which incorporate fewer CSA practices, both showed negative impacts on food security and individual negative impacts on mitigation (for Agroforestry) and adaptation (for Crop Management). These findings suggest that more narrowly focused CSA practices may enhance specific outcomes (e.g., crop productivity) but fail to meet the broader goals of climate-smart agriculture.

2.4.3 Hypothesis validation

The results of the Average Treatment Effects (ATE) analysis for CSA package adoption do not support the validation of our hypothesis. The findings indicate that not all CSA packages contribute positively to the Climate-Smartness Index (CSI), suggesting that sometimes CSA adoption leads to trade-offs rather than universal improvements across all dimensions of climate-smart agriculture. Specifically, while some CSA packages may enhance productivity or resilience, they do not necessarily lead to simultaneous gains in all three key objectives: productivity enhancement, climate resilience, and greenhouse gas (GHG) reduction.

Therefore, our initial hypothesis—"The adoption of CSA practices enhances the climate-smartness of farming systems in the Republic of Benin by improving productivity, increasing resilience to climate change, and reducing greenhouse gas emissions"—is not validated. Instead, the results underscore the complexity of CSA adoption, where the benefits vary depending on the specific package implemented and the local agroecological and socio-economic context.

2.4.4 Limitations and Future Research

While this research underscores the positive impacts of CSA adoption on farming systems, several limitations and challenges must be acknowledged. First, the research's reliance on self-reported data presents a potential bias, as farmers may overestimate or underestimate their adoption of CSA practices. This could affect the accuracy of the adoption rates and the associated impacts observed in the research. Additionally, security concerns led to the exclusion of certain municipalities, which limits the generalizability of the findings to the entire Republic of Benin. Furthermore, the diverse climate conditions and agricultural practices across regions present challenges in developing universally applicable CSA packages. The variability in environmental and socio-economic contexts makes it difficult to offer CSA solutions that are equally effective across different agroecological zones.

To address these limitations, future research should aim to adopt a more holistic and robust approach. One key area is improving data collection methods. Incorporating more objective data sources, such as remote sensing or farm-level monitoring systems, alongside self-reports, could enhance the reliability of the findings. Longitudinal studies that track the long-term impacts of CSA adoption on farming systems are particularly needed to capture dynamic changes over time.

2.5 Conclusion and implications

This research has evaluated the impacts of CSA package adoption on the climate-smartness of farming systems, focusing on food security, adaptation, and mitigation outcomes in the Republic of Benin. The analysis reveals both synergies and trade-offs among CSA objectives, underscoring the complex dynamics of CSA adoption in diverse agricultural systems. Comprehensive CSA packages, such as Full CSA, Full Agroforestry, and Full Water Management, were found to deliver significant positive outcomes, especially in food security and adaptation dimensions. In contrast, less comprehensive packages, such as Crop Management and Full Soil-Crop Management, often fell short of achieving holistic CSA objectives, indicating the presence of trade-offs, particularly in the areas of mitigation and long-term sustainability.

The findings highlight **the importance of tailoring CSA interventions to regional and household-level contexts**, as different CSA packages deliver varied impacts based on the specific agroecological and socio-economic conditions. Importantly, more complex packages with integrated water management and agroforestry practices tend to generate the most significant climate-smartness outcomes, suggesting that broader adoption of such comprehensive approaches could be vital in enhancing resilience against climate change in agriculture. However, the results also indicate that the adoption of CSA practices must consider labor availability, family structure, and dependency ratios, which influence a household's capacity to implement labor-intensive practices.

The findings highlight **the importance of adopting comprehensive CSA packages that integrate multiple dimensions of climate-smart agriculture**. For policymakers and farmers, focusing on Full CSA and Partial Agroforestry packages is recommended, as these packages show the potential to achieve all three CSA objectives. However, it is important to recognize the trade-offs associated with more narrowly focused packages, such as Agroforestry or Crop Management, which may prioritize short-term gains at the expense of long-term sustainability.

2.6 Appendix

Table 13: Specification of CSA practice combinations to form the packages

Choice (j)	Binary quadruplicate	S=soil management		N=Nutrient management		C=Crop management		W=water management		I=integrate system		Frequency	percentage
		S_0	S_1	N_0	N_1	C_0	C_1	W_0	W_1	I_0	I_1		
1	**$S_0N_0C_0W_0I_0$**	✓		✓		✓		✓		✓		**19**	**02.65**
2	$S_1N_0C_0W_0I_0$		✓	✓		✓		✓		✓		00	00
3	$S_0N_1C_0W_0I_0$	✓			✓	✓		✓		✓		00	00
4	$S_0N_0C_1W_0I_0$	✓		✓			✓	✓		✓		00	00
5	$S_0N_0C_0W_1I_0$	✓		✓		✓		✓	✓			00	00
6	$S_0N_0C_0W_0I_1$	✓		✓		✓		✓			✓	00	00

7	$S_1N_1C_0W_0I_0$		✓		✓	✓		✓		✓		00	00
8	**$S_1N_0C_1W_0I_0$**		✓	✓			✓	✓		✓		**14**	**01.95**
9	$S_1N_0C_0W_1I_0$		✓	✓		✓			✓	✓		00	00
10	$S_1N_0C_0W_0I_1$		✓	✓		✓		✓			✓	00	00
11	**$S_0N_1C_1W_0I_0$**	✓			✓		✓	✓		✓		**14**	**01.95**
12	$S_0N_1C_0W_1I_0$	✓			✓	✓		✓	✓			00	00
13	$S_0N_1C_0W_0I_1$	✓			✓	✓		✓			✓	00	00
14	**$S_0N_0C_1W_1I_0$**	✓		✓			✓		✓	✓		**04**	**00.56**
15	**$S_0N_0C_1W_0I_1$**	✓		✓			✓	✓			✓	**31**	**04.33**
16	$S_0N_0C_0W_1I_1$	✓		✓		✓			✓		✓	00	00
17	**$S_1N_1C_1W_0I_0$**		✓		✓		✓	✓		✓		**128**	**17.88**
18	$S_1N_1C_0W_1I_0$		✓		✓	✓			✓	✓		00	00
19	$S_1N_1C_0W_0I_1$		✓		✓	✓		✓			✓	00	00
20	$S_1N_0C_1W_1I_0$		✓	✓			✓		✓	✓		00	00
21	$S_1N_0C_1W_0I_1$		✓	✓			✓	✓			✓	00	00
22	$S_1N_0C_0W_1I_1$		✓	✓		✓			✓		✓	00	00
23	$S_0N_1C_1W_1I_0$	✓			✓		✓		✓	✓		00	00
24	**$S_0N_1C_1W_0I_1$**	✓			✓		✓	✓			✓	**35**	**04.88**
25	$S_0N_1C_0W_1I_1$	✓			✓	✓			✓		✓	00	00
26	$S_0N_0C_1W_1I_1$	✓		✓			✓		✓		✓	00	00
27	**$S_1N_1C_1W_1I_0$**		✓		✓		✓		✓	✓		**59**	**08.24**
28	**$S_1N_1C_1W_0I_1$**		✓		✓		✓	✓			✓	**379**	**52.93**
29	$S_1N_1C_0W_1I_1$		✓		✓	✓			✓		✓	00	00
30	$S_1N_0C_1W_1I_1$		✓	✓			✓		✓		✓	00	00
31	$S_0N_1C_1W_1I_1$	✓			✓		✓		✓		✓	00	00
32	**$S_1N_1C_1W_1I_1$**		✓		✓		✓		✓		✓	**33**	**04.60**
Total												716	100

Source: Author

Chapter 3 Assessing the impact of fertilizer subsidy policies on the sustainability of production activities in the Republic of Benin

Abstract

Chemical fertilizers serve as essential nutrient inputs that significantly enhance crop productivity, making them vital components of food security policies in developing countries. However, the potential greenhouse gas (GHG) emission of mineral fertilizers coupled with the widespread implementation of chemical fertilizer subsidy policies across many African nations raises critical concerns regarding the sustainability of agricultural practices. This research investigates the impact of fertilizer subsidy policies on the sustainability of production activities in the Republic of Benin. Utilizing a bio-economic modeling framework, the research analyzes data from a survey of 705 farmers across six municipalities within three agricultural development zones. The findings reveal that the Eco-Inefficiency index is increasing, suggesting that achieving marginal profits now requires greater GHG emissions, indicative of unsustainable fertilizer overuse. Sensitivity analyses confirm the robustness of these results across different labor costs and GHG factor variations. The research underscores the need for targeted subsidy policies that promote sustainable agricultural practices while balancing economic and environmental objectives.

Keywords: Fertilizer Subsidy Policy, Agricultural Income, Greenhouse Gas Emissions, Sustainability, Eco-Inefficiency Index, Bio-Economic Modeling, Republic of Benin.

Résumé

Les engrais chimiques constituent des intrants nutritionnels essentiels qui améliorent significativement la productivité agricole, ce qui en fait des éléments clés des politiques de sécurité alimentaire dans les pays en développement. Cependant, le potentiel d’émissions de gaz à effet de serre (GES) lié aux engrais minéraux, combiné à la généralisation des politiques de subvention des engrais chimiques dans de nombreux pays africains, soulève des préoccupations majeures quant à la durabilité des pratiques agricoles. Cette recherche examine l’impact des politiques de subvention des engrais sur la durabilité des activités de production en République du Bénin. En mobilisant un cadre de modélisation bio-économique, l’étude analyse les données issues d’une enquête menée auprès de 705 exploitants agricoles répartis dans six communes appartenant à trois zones de développement agricole. Les résultats révèlent une augmentation de l’indice d’éco-inefficience, indiquant que la réalisation de profits marginaux nécessite désormais davantage d’émissions de GES — un signe de surexploitation non durable des engrais. Des analyses de sensibilité confirment la robustesse de ces résultats face à différentes hypothèses sur les coûts de la main-d’œuvre et les facteurs d’émission de GES. La recherche souligne la nécessité de politiques de subvention ciblées, favorisant des pratiques agricoles durables tout en conciliant objectifs économiques et environnementaux.

Mots-clés : Politique de subvention des engrais, Revenu agricole, Émissions de gaz à effet de serre, Durabilité, Indice d’éco-inefficience, Modélisation bio-économique, République du Bénin.

3.1 Introduction

The renewed interest in chemical fertilizer subsidies in Africa's agricultural development underscores the trade-offs between farmers' welfare and environmental conservation. The dual crises of COVID-19 and the Russian-Ukrainian conflict have driven up the prices of fertilizers, such as Urea and NPK, exacerbating the risks of climate-induced food insecurity (FAO, 2022; Kinkpe et al., 2023). In response, many African countries, like Ghana, Niger, Togo, Senegal, Burkina Faso, and Benin have adopted or enhanced fertilizer subsidy policies to mitigate food insecurity and poverty risks in rural areas (future, 2018, 2020). While these chemical fertilizer subsidies can positively impact production and welfare, their influence on climate change raises concerns about the sustainability of production systems under these policies (Ricker-Gilbert and Jayne, 2017). There is limited knowledge of the sustainability of production systems under chemical fertilizer subsidies in African countries, particularly given the greenhouse gas (GHG) emissions associated with chemical fertilizer use (Kahandage, Rupasinghe, Ariyawansha, and Piyathissa, 2023).

The environmental effects of chemical fertilizer use include soil degradation, biodiversity loss, water pollution, and GHG emissions, alongside economic and human health implications (Honfoga, 2018; Jote, 2023). Notably, chemical fertilizer use's impact on GHG emissions is critical due to its direct contribution to climate change. Nitrogen-based fertilizers significantly contribute to nitrous oxide (N2O) emissions, a potent GHG with a global warming potential approximately 300 times that of carbon dioxide (CO2) (Kanter, 2018). Studies indicate that agricultural practices, particularly chemical fertilizer use, are responsible for a substantial portion of global GHG emissions. For instance, in China, the intensive use of nitrogen fertilizers has significantly increased N2O emissions, contributing to the country’s overall GHG output (Li, Xiong, Huang, Xu, and Huang, 2020). Overuse of chemical fertilizers, often driven by subsidy policies, is a major exacerbating factor and a long-term threat to food security (Gazzani, 2021; Van Wesenbeeck, Keyzer, Van Veen, & Qiu, 2021).

Fertilizer subsidy policies are grounded in addressing the financial constraints smallholder farmers face (future, 2018). High input costs limit farmers' ability to purchase essential fertilizers for improving soil fertility and crop yields. In African countries, particularly in sub-Saharan Africa, fertilizer subsidies are implemented in various ways and target the most consumed and cash crops, with the primary objective of boosting yields to ensure food security. For example, while Ghana's fertilizer subsidy program subsidizes fertilizers directly for small maize and rice producers, Niger's program enhances the productivity of staple crops such as millet and sorghum through government distribution channels and private agro-dealers (future, 2018). Despite their positive effects on food security, local market development, and poverty reduction, chemical fertilizer subsidies also present shortcomings including the financial sustainability of subsidy programs, market distortions, leakages and corruption, dependency and reduced innovation, and environmental impacts, particularly through GHG emissions (Alabi, 2020; Fujimoto & Suzuki, 2024; future, 2018).

According to the substitution effect principle in agricultural economics theory, changes in input prices prompt farmers to substitute more expensive inputs with cheaper alternatives (Penson, Capps, Rosson, & Woodward, 2014). For example, if chemical fertilizer prices rise, farmers might turn to organic inputs or crop rotations to maintain soil fertility and output levels, and consequently reduce the use of chemical fertilizers (Colman & Young, 1989). Conversely, a subsidy that lowers the price of chemical fertilizers can lead to their increased use over organic inputs. In many developing countries, including those in Africa, high labor and capital costs due to rural exodus and imperfect financial and insurance markets make extensive use of chemical fertilizers a preferable option for farmers (future, 2018). Therefore, it is likely that farmers overuse chemical fertilizers due to subsidy policies.

A significant issue arising from subsidy-induced farmer behavior is the potential overuse of chemical fertilizer (Alta, Setiawan, & Fauzi, 2021; Van Wesenbeeck et al., 2021). Overuse implies inefficient resource utilization, which is not a sustainable agricultural practice. Some studies highlight the sustainability impacts of fertilizer subsidies, showing a modest impact on crop output and no significant long-term effects on production, indicating limited sustainability benefits (Ricker-Gilbert & Jayne, 2017). In African countries, there is limited understanding of the sustainability impacts of fertilizer subsidies. Therefore, it is essential to investigate the sustainability of production systems within the context of fertilizer subsidy policies in African countries, particularly the Republic of Benin.

The primary research question of this research is: Do fertilizer subsidy policies in African countries induce sustainable practices among farmers? Using the Republic of Benin as a case research, this research aims to assess the sustainability of production systems within the fertilizer subsidy policy. The research employs a linear programming model to evaluate sustainability, developing an eco-inefficiency index to express the GHG emissions corresponding to a marginal profit or net income for production activity.

As human activities are the main cause of climate change, there is a need for mitigation policies to reduce GHG emissions. Agriculture is a significant source of climate change, and without appropriate subsidy policies controlling the extent of chemical fertilizer use, the resulting emissions could continuously harm the environment. This might lead to the unsustainability of production systems, increasing the vulnerability of smallholder farmers and trapping them in poverty in the long term. By assessing the sustainability of production systems within the fertilizer subsidy context, this research intends to fill the gap in scientific research on fertilizer subsidy sustainability and motivate policymakers to develop effective green subsidy policies.

The results of the research demonstrate that increasing fertilizer subsidy rates significantly enhances farmers' revenues with different threshold increases across various regions. The results also highlight a concerning rise in greenhouse gas (GHG) emissions associated with increased nitrogen content from fertilizer use. The Eco-Inefficiency index indicates a troubling trend where achieving marginal profits necessitates greater GHG emissions, underscoring the unsustainability of current practices driven by policy-induced fertilizer overuse.

The research offers significant contributions. Firstly, it provides empirical evidence on the effects of the fertilizer subsidy policies on the sustainability of farming practices. Secondly, the research reveals the trade-offs between profit generation and environmental health using the Eco-Inefficiency index, an innovative approach. Furthermore, the findings inform about the need for balanced agricultural policies that optimize economic benefits while addressing environmental sustainability. Lastly, the research enriches the academic literature on agricultural economics and environmental studies by exploring the intersections of economic policy, agricultural practices, and environmental impacts.

The research is structured as follows: Sections 2 and 3 present the background and the literature review. Sections 4 and 5 present the materials and methods and Results and discussions, respectively, while Sections 6 and 7 present the hypothesis validation and policy implications. Section 8 concludes.

3.2 Background

Hunger is exacerbating in most African countries with 20% of the population undernourished showing the importance of increasing agricultural productivity with soil fertility and sufficient nutrient supply as a step (UNDP, 2021). Agriculture is a vital sector of Benin's economy, contributing 28% to the national GDP, employing about 50% of the population, representing 77% of export earnings and 15% of government revenue (MAEP, 2020).

The decreasing trend of the global productivity of factors in agriculture leads to the development of optimal agricultural strategies including the fertilizer subsidy policy throughout the seven Agricultural Development Zones (Pôles de Développement Agricoles, or ADZs), each tailored to specific agroecological conditions and land potentials (Benin, 2017). The northern regions, covering ADZs 1 to 3 and parts of ADZ 4, focus primarily on cereal production—particularly rice and millet—as well as extensive livestock farming, both well-suited to the semi-arid climate. In central Benin, particularly ADZ 4, maize and yam dominate the agricultural landscape, with certain areas also emphasizing cotton cultivation alongside maize and beans. Southern Benin, comprising ADZs 5, 6, and 7, benefits from the humid coastal climate and fertile soils, supporting the production of palm oil, vegetables, maize, cassava, and cotton (Benin, 2017).

Similar to other West African nations, Benin has recently revised its fertilizer subsidy policy in response to inflationary pressures, targeting the most widely consumed and cultivated crops, such as maize and cotton—both key staple and cash crops. This subsidy program is designed to enhance fertilizer affordability for farmers, primarily focusing on Urea and NPK fertilizers (Hounnou et al., 2023). Between 2022 and 2024, the total value of the subsidy reached approximately $181.5 million, leading to a 9.40% and 26.80% increase in imported chemical fertilizer volumes in 2022 and 2023, respectively, compared to 20213 levels (Benin, 2022b, 2024).

However, concerns over sustainability arise as agriculture currently contributes 28% of Benin's total greenhouse gas (GHG) emissions, which stand at 16.94 Mt CO2 equivalent (Benin, 2021). Without intervention, projections indicate that emissions could increase by 71% between 2018 and 2030, despite a slight projected decrease in agriculture's share of total emissions. Given Benin's commitment to reducing overall GHG emissions by 20.15% during the 2021–2030 period, it is essential to assess whether the fertilizer subsidy policy promotes sustainable farming practices, particularly concerning the environmental impact of chemical fertilizers (Benin, 2021).

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[3] https://africafertilizer.org/#/en/vizualizations-by-topic/trade-statistics/

Understanding the effects of this policy on farmers' behavior and its implications for GHG emissions is critical for determining the sustainability of the country's agricultural systems.

3.3 Literature review

Fertilizer subsidy policies in Africa are particularly essential in sub-Saharan Africa, where a significant proportion of the population relies on agriculture for their livelihoods, and the use of chemical fertilizers remains below global averages due to high costs and limited access. However, despite their significant benefits in terms of increased agricultural productivity, food security, and poverty alleviation, the sustainability impact of these policies has gotten less attention among researchers.

3.3.1 Fertilizer Subsidy Policies in Africa

The rationale behind fertilizer subsidy policies is grounded in the recognition of financial constraints faced by smallholder farmers (future, 2018). High input costs limit farmers' ability to purchase necessary and crucial fertilizers for improving soil fertility and crop yields. By subsidizing fertilizers, governments aim to make these inputs more affordable, encouraging their use and boosting agricultural output. Fertilizer subsidy policies have taken various forms, targeted different crop productions, and aimed at boosting production. For example, while the fertilizer subsidy program involves subsidizing directly the cost of fertilizers to make them affordable for small maize and rice producers in Ghana, it is implemented through government distribution channels and private agro-dealers to enhance the productivity of staple crops such as millet and sorghum in Niger (future, 2018). In Malawi, the subsidy program provides vouchers for fertilizers and improved seeds to smallholder farmers, aiming to boost maize production (future, 2018). The fertilizer subsidy programs have been subject to numerous evaluations to assess their effectiveness and impacts.

Subsidy programs have been successful in increasing the use of fertilizers, leading to higher crop yields and overall agricultural productivity (Hounnou et al., 2023; Yovo & Ganiyou, 2023). In addition, by increasing the availability and affordability of fertilizers, these programs help enhance food production, thereby improving food security (Alabi, 2020). On the other hand, subsidies reduce the cost burden on farmers, enabling them to invest more in their agricultural activities, which increases their income and lifts them out of poverty (Hounnou et al., 2023). In other countries, subsidies have incentivized the development of the fertilizer market due to the increase in fertilizer demand (Fujimoto & Suzuki, 2024). However, despite their significant effectiveness, the negative impact of chemical fertilizer use on the environment raises the issue of production sustainability (Morgan, Mason, Levine, & Zulu-Mbata, 2019).

3.3.2 Impacts on Sustainability of Crop Production

The impact of chemical fertilizer subsidy policies on the sustainability of production activity starts from the impact of its usage on the environment. As we already know, fertilizer use aims at improving crop yield and ensuring food security, however, the two types of fertilizer, chemical (inorganic) or organic fertilizers, show distinct environmental impacts, and consequently on the sustainability of crop production activity. Compared to chemical fertilizers, organic fertilizers which are derived from natural sources such as plant residues, animal manure, and compost, release nutrients more slowly, improve soil health and structure, and increase microbial activity (Jote, 2023; Kahandage, Rupasinghe, Ariyawansha, & Piyathissa, 2023). Especially, organic fertilizers result in lower overall emissions despite their methane (CH4) and nitrous oxide (NO2) production (Kahandage et al., 2023). Its impact on soil health improvement is derived from the organic content. The more organic matter content increases, the more the soil's ability to retain water and nutrients is improved, which promotes healthy microbial activity and reduces soil erosion (Jote, 2023; Kahandage et al., 2023). As a result, organic fertilizers are less prone to leaching and runoff reducing the risk of nutrient pollution in water bodies.

On the contrary, chemical fertilizers are synthesized from industrial processes and primarily contain high nutrients such as nitrogen, phosphorus, and potassium which are drivers of boosting crop yields. However, their production and application as fertilizers release an important volume of NO2 which is a high content of greenhouse gas (GHG). For example, Urea production and application are major sources of CO2 and N2O emissions, contributing significantly to climate change (Jote, 2023; Kahandage et al., 2023). Moreover, the continuous use of chemical fertilizers leads to soil degradation over time, while excessive can cause water pollution and induce significant health concerns for humans (Jote, 2023; Kahandage et al., 2023). Based on the substantial negative impacts on the environment, emerging studies began raising the issue of the sustainability of agricultural systems after chemical fertilizer use. (Bah, Ren, Wang, Tang, & Zhu, 2020) highlight that chemical fertilizer use has led to higher GHG emissions with decreasing yield-scaled global warming potential showing a potential inefficiency use of chemical fertilizer in wheat-maize cropping systems.

Although chemical fertilizer subsidy policies have been widely implemented in various African countries to boost agricultural productivity and ensure food security, they also pose significant challenges, including fiscal sustainability, market distortions, inefficiencies, and environmental impacts (Bah et al., 2020; Honfoga, 2018). According to (Honfoga, 2018), the high costs associated with purchasing and distributing fertilizers at subsidized rates can strain public finances, diverting resources from other essential sectors such as health and education. This issue is particularly acute in countries with limited financial resources, where sustaining long-term subsidy programs can be challenging. Subsidies can distort local fertilizer markets by discouraging private sector investment and also induce inefficiencies and leakages through black markets crowding out real beneficial farmers in favor of wealthier farmers who do not need subsidies (Honfoga, 2018).

On the other hand, the resulting increase use of chemical fertilizers, from the easy accessibility and availability spurred by subsidies, can lead to environmental degradation through soil acidification, water pollution, and increased greenhouse gas emissions (Bah et al., 2020). In addition, continuous reliance on fertilizer subsidies can create dependency among farmers, reducing their incentive to adopt innovative and sustainable farming practices. Farmers may become accustomed to receiving subsidized inputs and may not invest in alternative soil fertility management practices, such as organic farming or integrated nutrient management. This dependency can hinder the development of resilient and sustainable agricultural systems (Bah et al., 2020).

From the above-brief literature, we can notice that the sustainability issues induced by chemical fertilizer are not investigated enough. The present research aims to fill this gap by assessing the sustainability of crop production within the context of the fertilizer subsidy policy in the Republic of Benin.

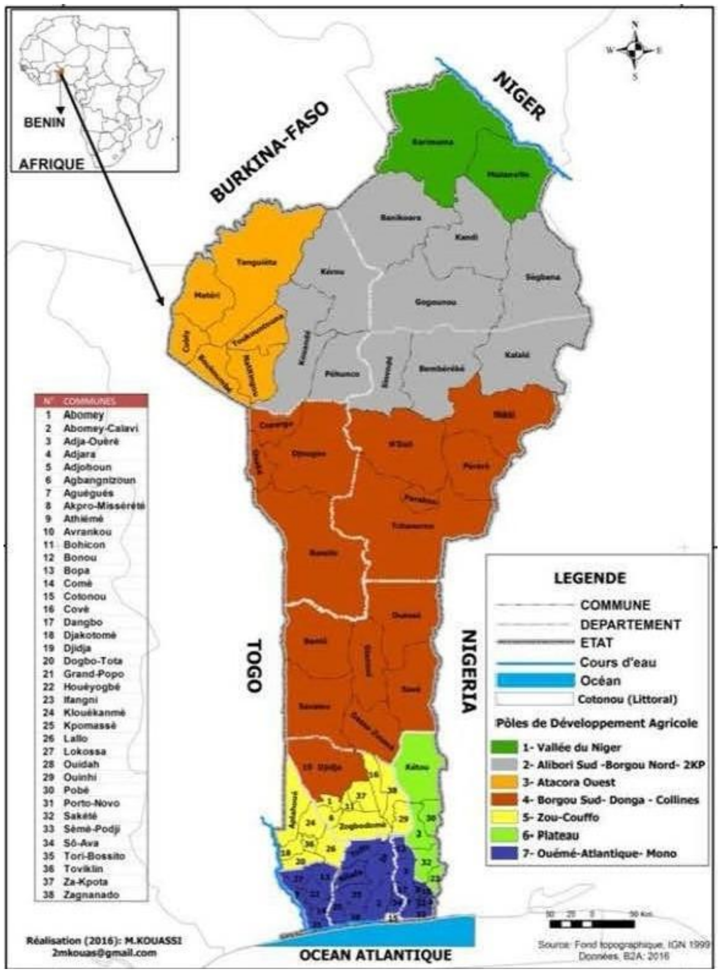
3.4 Materials and Methods

3.4.1 Research Area

The research was conducted in the Republic of Benin. This West African country stretches between latitudes 6°30' N and 12°30' N and longitudes 1° E and 3°40' E, bordered by Niger to the north, Burkina Faso to the northwest, Togo to the west, Nigeria to the east, and the Atlantic Ocean to the south. The country is divided into 12 departments, including Alibori, Atakora, Borgou, Collines, Donga, Couffo, Mono, Atlantique, Littoral, Ouémé, Plateau, and Zou. Its landscape varies from coastal plains in the south to more elevated plateaus and hills in the northern regions (World Bank, 2013).

Benin experiences a tropical climate, with significant variation between the northern and southern regions. The south has a sub-equatorial climate with two rainy seasons (April to July and September to November) and two dry seasons (December to March and August). Rainfall ranges from 900 mm to 1,400 mm annually. The north, on the other hand, has a tropical climate with one rainy season from June to September and a prolonged dry season from October to May. Rainfall here is more variable, ranging from 700 mm to 1,200 mm annually, with average temperatures throughout the country fluctuating between 25°C and 31°C (INSAE, 2015).

Figure 7: Research Area



Source : Ministère de l'Agriculture, de l'Elevage et de la Pêche (MAEP)

3.4.2 Theoretical framework

This research involves several theories that are connected to a specific aspect of the analysis. The research assesses the impact of fertilizer subsidy policies on the sustainability of production activities in the Republic of Benin. In this regard, environmental economics provides a foundation for understanding the unintended consequences of fertilizer subsidies, particularly their role in exacerbating negative externalities such as greenhouse gas (GHG) emissions. According to (Pigou, 1920), market failures arise when private costs do not reflect social costs, leading to environmental degradation. In the case of fertilizer subsidies, lower input costs incentivize excessive nitrogen application, which in turn increases nitrous oxide (N_2O) emissions—a potent GHG with a global warming potential significantly higher than CO_2 (Kanter, 2018). This research applies this perspective to evaluate whether the current subsidy structure in Benin contributes to an environmentally unsustainable trajectory by promoting fertilizer overuse, thus exacerbating agricultural emissions.

The impact of fertilizer subsidies on crop production is best analyzed through agricultural production theory, which describes how input levels affect output and efficiency. The Cobb-Douglas production function (Cobb & Douglas, 1928) and the law of diminishing returns suggests that while fertilizers enhance yields up to a certain point, excessive application leads to diminishing marginal productivity and environmental inefficiencies. This research employs Mitscherlich's yield response function, which mathematically represents the diminishing yield increases from additional nitrogen application. By integrating this function into a bio-economic model, the research assesses how subsidy-induced fertilizer use influences crop productivity, farm profitability, and sustainability.

Subsidies alter farmers' cost structures, thereby influencing their input demand behavior. According to subsidy and market distortion theories (Becker, 1983), government interventions such as subsidies can create inefficient resource allocation by artificially lowering the cost of inputs, leading to overuse. The substitution effect (Penson et al., 2014) suggests that when fertilizers become more affordable due to subsidies, farmers increase their reliance on chemical inputs rather than adopting alternative, more sustainable soil fertility management practices. This research examines the extent to which subsidy policies in Benin encourage nitrogen overuse, using an optimization framework to model farmers' decision-making regarding fertilizer application and land allocation.

Lastly, the eco-inefficiency framework evaluates the trade-off between economic profitability and environmental sustainability. While eco-efficiency emphasizes maximizing output with minimal environmental impact (Porter & Linde, 1995), this research instead employs eco-inefficiency, which measures the GHG emissions per unit of profit. A rising Eco-Inefficiency Index indicates that achieving marginal profits requires greater GHG emissions, highlighting an unsustainable pattern in fertilizer use.

This theoretical framework leads to an integrated bioeconomic modeling that models aspects from each key economic theory.

3.4.2.1 Hypothesis

This research hypothesizes that "*The current fertilizer subsidy policy promotes the overuse of fertilizers, contributing to increased GHG emissions in Benin*". This implies that while the subsidy policy aims to boost agricultural productivity, it may unintentionally encourage excessive fertilizer use beyond agronomic recommendations.

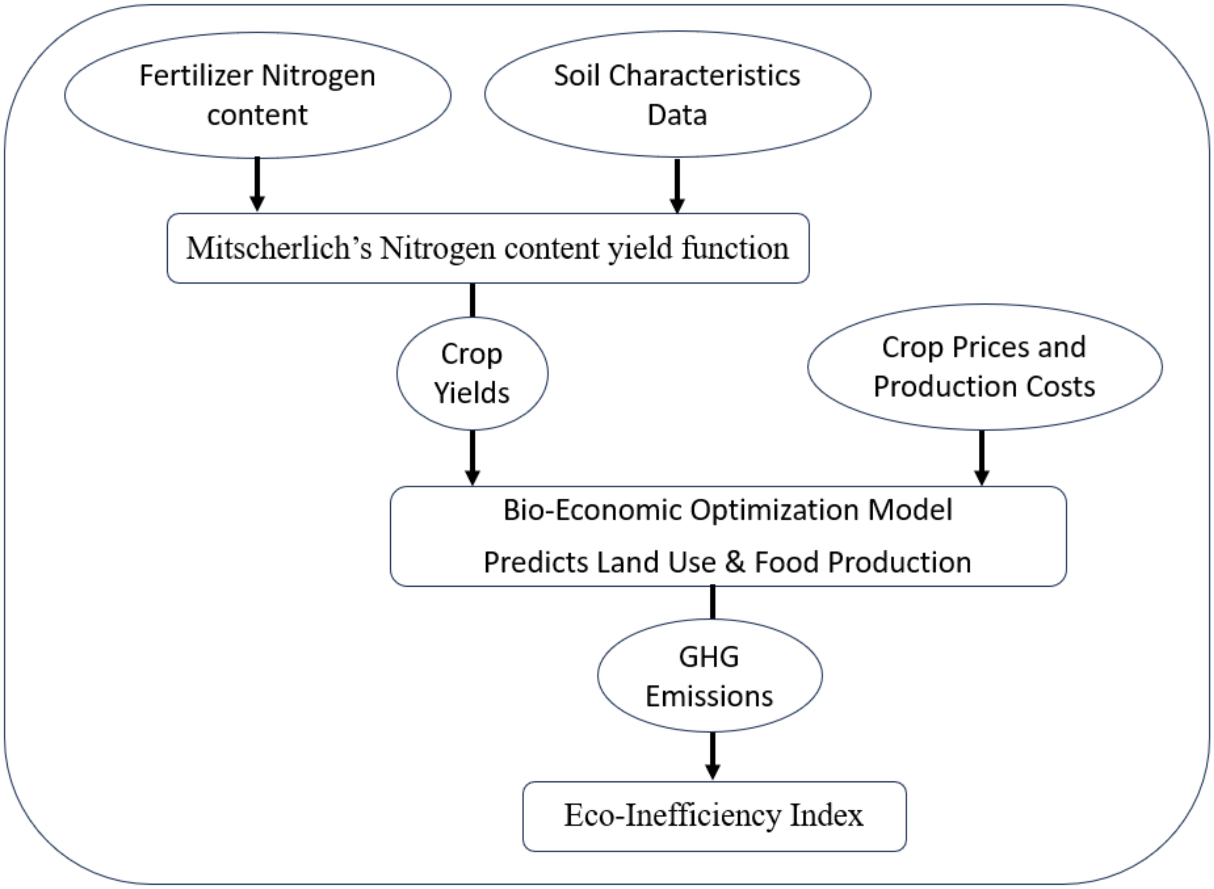
3.4.3 The structure of the bioeconomic model

The bioeconomic model is based on a representative risk-neutral, profit-maximizing agent within an integrated assessment framework. It combines biophysical and farm-level economic data in a mathematical programming model, drawing on previous regional bioeconomic models (Adji, Egbendewe, & Lokonon, 2022; Lokonon, Egbendewe, Coulibaly, & Atewamba, 2019). This approach has been successfully applied to analyze the effects of nitrogen fertilizer and optimal plant population on maize profitability in Tanzania (Kadigi et al., 2020).

In this research, the model treats several variables as exogenous, including nitrogen content in Urea and/or NPK fertilizers, soil fertility, Agro-Climatic Zones (ACZs), and input-output prices. The decision-making within the model focuses on endogenous variables such as land allocation and the quantity of nitrogen applied through fertilizers across different cropping systems.

The yield component of the model is determined using Mitscherlich's yield response function, which links crop yield to nitrogen content in chemical fertilizers (Schneeberger, 2009; Sileshi, 2022). The economic component is an optimization model that maximizes net outcomes subject to resource constraints, using the exogenous parameters to allocate land and fertilizer nitrogen content among cropping systems. The general structure of the bio-economic model is summarized as follows:

Figure 8: The structure of the Bio-Economic Model



Source: Inspired by (Lokonon et al., 2019)

3.4.3.1 Crop yield model

Crop yields are simulated using Mitscherlich's yield response function, which models the relationship between crop yield and nitrogen (N) content in chemical fertilizers (Schneeberger, 2009; Sileshi, 2022). Mitscherlich's formula describes crop yield as an exponential growth process with a horizontal asymptote, determined by the quantity of Nitrogen from both plant-available nitrogen in the soil and external chemical fertilizers. The formula is expressed as:

$$yield = a\left(1 - e^{-b(N+N_0)}\right) \qquad (1)$$

Where $yield$ is the crop yield in kg/ha, a represents the maximum possible yield under ideal conditions without over-fertilization, and b is the exponential factor that controls how sharply yield responds to increasing nitrogen levels. N is the nitrogen content from the applied chemical fertilizer, whereas N_0 is the plant-available nitrogen already present in the soil.

This is a modified version of the standard Mitscherlich function, which assumes no plant-available nitrogen ($N_0 = 0$). The modified version is more appropriate for analyzing yield response to a single nutrient like nitrogen (Sileshi, 2022). It also offers insights into nutrient deficiencies and expected yields under no-input conditions.

The choice of the Mitscherlich function is justified by its theoretical and empirical relevance in modeling diminishing returns to nutrient inputs—an essential feature of agricultural production. Unlike linear or quadratic models, which may misrepresent yield behavior at higher input levels, the Mitscherlich function captures the biological reality that crop yields increase at a decreasing rate and approach a maximum limit. Additionally, the incorporation of plant-available nitrogen (N_0) in the soil improves the model's realism, particularly for low-input farming systems where soil fertility plays a critical role. The function's widespread application in agronomic and economic studies (e.g., Sileshi, 2022) and its ease of interpretation also support its appropriateness for this research context.

The quantity of nitrogen applied through fertilizers (N) is calculated by multiplying the nitrogen content rate in 1 kg of fertilizer (Nlevel[4]) by the total quantity of nitrogen fertilizer used:

$$N = Nlevel \times N\_Fertilizer \qquad (2)$$

Plant-available nitrogen (N_0) is calculated using standard agronomy formulas, which take into account soil characteristics:

$$N_0 = SV \times SBD \times \frac{N\_percentage}{100} \qquad (3)$$

where SV is the soil volume in m³/ha, SBD is the soil bulk density in kg/ha, and N-percentage is the nitrogen content percentage in the soil, typically ranging from 0.02% to 0.05%.

In summary, the parameter values for Mitscherlich's yield response function are derived from survey data on crop yields and nitrogen content based on soil characteristics specific to each region.

3.4.3.2 Economic mathematical programming model

The farming system in the research area comprises 27 distinct cropping systems, including food and cash crops. Food crops are categorized into: Cereals: maize, sorghum, millet, and rice; Roots and tubers: Cassava, potatoes, sweet potatoes, and yams; Legumes: Cowpeas, soybeans, pigeon peas, voandzou, Sesame, Dohi, and groundnuts; Vegetables: Lettuce, Gboman, and cabbage; Fruits: Watermelon and Carrots; and Market gardening crops: Tomatoes, Chilli pepper, okra, and onion). The major cash crops are cashews and cotton.

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[4] Nlevel is a weighted average of N rate in 1 kg of Urea (0.46) and NPK (0.15) fertilizer.

The model assumes that farmers allocate labor, land, and inputs—primarily chemical fertilizers—to select a portfolio of cropping systems that maximize the discounted sum of farm net income. This approach accounts for short- and long-term profitability, balancing input costs and expected returns across different cropping systems.

$$\max_{X_{cr},N_{cr},H_r} Z = \sum_{c}\sum_{r}\left[P_cY_{cr}X_{cr} - \left(C_f(1-\tau)N_{cr} + \varphi_rX_{cr}\right)\right] + \sum_{r} W_rH_r \quad (2)$$

$$subject\ to: \begin{cases} \sum_{c} X_{cr} \leq \theta_r, \quad \forall r \quad (3) \\ \sum_{c} \delta_cX_{cr} \leq L_r + H_r, \quad \forall r \quad (4) \\ \sum_{c} N_{cr} \leq N_r, \quad \forall r \quad (5) \\ X_{cr}, H_{cr} \geq 0 \end{cases}$$

In the objective function (2), four key components are identified. The first expression represents the total discounted crop revenue ($\sum_c \sum_r P_cY_{cr}X_{cr}$). The second term ($\sum_c \sum_r C_f(1-\tau)N_{cr}$) indicates the total discounted fertilizer cost converted into Nitrogen content value, while the third term ($\sum_c \sum_r \varphi_rX_{cr}$) expresses the total land cost. The total hired labor cost is expressed in the fourth term ($\sum_r W_rH_r$). Input constraints are expressed through equations (3) to (5). Equations (3) and (4) express land and labor constraints, respectively, while equation (5) accounts for fertilizer or nitrogen content constraints.

By solving this optimization model, the analysis captures the optimal allocation of land, hired labor, and nitrogen content from fertilizers. This framework assesses the sustainability and economic viability of crop production activities across the research area.

3.4.3.3 Eco-Inefficiency (EIF)

This research proposed the concept of Eco-inefficiency (EIF) to assess the inefficiency of production systems within the context of chemical fertilizer subsidy. Unlike Eco-efficiency (EF), EIF brings out the negative perspective of the relationship between agricultural systems and the environment.

A. Concept

Eco-efficiency (EF) analysis is a widely applied tool to evaluate the efficiency of economic activities while increasingly considering their environmental and social impacts (Suzigan, Peña, & Guarnieri, 2020). It is also an instrument for sustainability analysis, indicating an empirical relationship in economic activities between environmental cost or value and environmental impact

(Zhang, Bi, Fan, Yuan, & Ge, 2008). In the literature, EF expresses the environmental performance of economic activities relative to their economic output. Specifically, it provides how efficiently production input or environmental resources (raw materials, energy, land, water, etc.) are being used to produce economic output (income, high-quality goods, and services, jobs, GDP, etc.) while minimizing environmental output (GHG effect, biodiversity loss, acidification, ozone depletion, waste, etc.) (Suzigan et al., 2020).

From this perspective, EF considers efficiency as a performance of economic activity, potentially obscuring the extent to which economic activity harms the environment. Using EF to assess the sustainability of agricultural systems in this research might not be appropriate, given the suspected increase in GHG emissions from production systems due to fertilizer overuse. Therefore, the EIF concept is employed to evaluate the inefficiency of agricultural systems concerning the environment.

B. EIF Index: Implementation Strategy, Measurement, and Indicators

Various approaches are used for EF analysis, including Life-Cycle Assessment (LCA), Cost-Benefit Analysis (CBA), contingent valuation (CV), and Data Envelopment Analysis (DEA), the latter being the most recent and widely used (Suzigan et al., 2020). While DEA is a comprehensive approach addressing the holistic challenges of EF, other methods tend to focus on specific issues, ignoring other key challenges (Suzigan et al., 2020). This research analyzes the EIF of production systems from a limited perspective by focusing solely on their GHG emissions impact. Consequently, other environmental impacts, such as soil degradation, biodiversity loss, and water pollution, are not included (Jote, 2023). Therefore, the research applied the CBA approach to analyze the EIF of production systems within the fertilizer subsidy policy.

Formally, EIF is the inverse of EF and is measured as the ratio between the (added) environmental impacts of the product or service (GHG emissions) and the (added) value of what has been produced (net income) (Zhang et al., 2008).

$$EIF\ index = \frac{GHG\ emissions\ (\mathrm{kgCO_{2eq}})}{Net\ income\ (CFA)}$$

An increase in the EIF index indicates an improvement in inefficiency, suggesting potential overuse and unsustainable practices. This implies that generating marginal net income or profit requires an increase in GHG emissions. From the EF perspective, it means the economic activity generates less economic value per unit of environmental impact.

Similar to the EF analysis framework, EIF also uses three indicators or variables to calculate the EIF index. These indicators include net income (economic output), chemical fertilizers such as Urea and NPK (production input), and GHG emissions (environmental output) (Suzigan et al., 2020). The GHG emissions value is computed by multiplying the chemical fertilizer volume (kg) by the GHG emission factor (kg CO2 eq/kg). The parameters and variables used in the model are defined in Table 1.

Table 14: List of sets, parameters, and variables definition for the model

Sets, Parameters, and Variables	Description
	Sets
c	27 Crop systems
r	Six regions : Malanville, Banikoara, Pehunco, Sinendé, Glazoué, Bassila
	Parameters
P_c	Crop sold price (CFA/kg)
C_f	Fertilizer (Urea and NPK) price (CFA/kg)
τ	Subsidy rate (%)
ρ	GHG emission factor (kgCO2eq\kg)
θ_r	Total land area available (ha) in region r
φ_r	Land cost (CFA/ha) in region r
N_r	Nitrogen-content availability (Kg) in region r
Y_{cr}	Yield for crop c (kg/ha) in region r
δ_c	Labor requirement (man-days/ha) for crop c
W_r	Hired labor wage (CFA/man-days) in region r
L_r	Total family labor available (man-days) in region r
	Variables
Z	Total discounted Net income (CFA)
X_{cr}	Land allocated for crop c in region r (ha)
N_{cr}	Nitrogen content for crop c in region r (Kg)
H_r	Additional labor hired in region r (man-days)

Source : Author

3.4.4 Data sources and parametrization of the model

The model is parametrized using data obtained from a survey conducted across 705 farmers randomly selected from six municipalities. These municipalities were chosen from three of the seven Agricultural Development Zones (ADZs), specifically Malanville (ADZ1), Banikoara, Pehunco, Sinendé (ADZ2), Glazoué, and Bassila (ADZ4). The selection of municipalities reflects the significance of each ADZ, based on the number of municipalities it covers. Table 15 and Table 16 provide the distribution of land, fertilizer, and farmers across these regions.

The majority of the parameter data used in the optimization model were obtained from the survey, including variables such as cropland, crop yields, crop prices, hired labor wages, family labor, and land costs. Specific yield response parameters—such as the maximum yield value (a) and the exponential factor (b)—were also derived from the survey data.

For other critical parameters, data were drawn from previous studies. These include working capital requirements, base fertilizer costs, subsidy rates, greenhouse gas (GHG) emission factors, nitrogen content rates in fertilizers (Urea and NPK), average soil depth, soil bulk density, plant-available nitrogen (N), and nitrogen content percentages in the soil. Sources for these parameters include studies by (Bruno, 2015; Hounkpatin, Bossa, Yira, Igue, & Sinsin, 2022; Hounnou et al., 2023; Lokonon et al., 2019).

Table 15: Land distribution by crop across regions

Crop systems		**Land (ha)**					
		Malanville	Banikoara	Pehunco	Sinendé	Glazoué	Bassila
Cash crop	Cashew	2	0	0	1.83	4.286	2.81
	Cotton	2.08	3.37	2.04	3.31	4	3.5
Cereal	Maize	1.54	2.28	2.53	2.71	1.7	2.081
	Millet	1.02	0.94	0.625	0.5	2	0.8875
	Rice	1.47	2.08	0.64	0.625	1.85	1.62
	Sorghum	1.86	1.35	0.83	2.25	0	1.125
Fruit	Carrots	0.073	0	0.16	0	0	0.036
	Watermelon	0	0	0	0	0	2
Legumes	Cowpea	1.42	0.96	0.3	0.583	0.9	1.15
	Dohi	0	0	0	0	0	0.5

	Groundnuts	1.1	0.71	0.6	0.5	1.06	1.4
	Pigeon pea	0	0	0	0	0.75	1.5
	Sesame	1.45	0.3	0.75	0	0.625	0.75
	Soybean	1.25	2.24	2.86	2.93	2.13	2.377
	Voandzou	0	0.67	0	0	0.75	0.5
Root and Tuber	Cassava	0	0	0.44	0.43	1	1.34
	Potato	0.5	0	0.75	0	0	0
	Sweet potato	0	0.54	0	0	0	0.5
	Yam	0	3.7	0.78	1.14	0.57	0.96
Vegetable	Bissap	0.145	0	0	0	0	0
	Cabbage	0.33	0	0.185	0	0	0
	Gboman	0.08	0	0	0	0.001	0
	Lettuce	0.106	0.25	0	0	0	0
	Okra	0.875	0.4	0.12	0	0.001	0.35
	Onion	0.25	0	0.375	0	0.024	0
	Pepper	0.5	0.61	0.25	0.145	0.0192	0.43
	Tomato	0.375	0.375	0	0	0.5	1.1
Total number of farmers		**80**	**113**	**116**	**114**	**131**	**151**

Source : Author

Table 16: *Fertilizer (Urea + NPK) distribution by crop across regions*

Crop systems		**Fertilizer (kg)**					
		Malanville	Banikoara	Pehunco	Sinendé	Glazoué	Bassila
Cash crop	Cashew	0	0	0	0	0	0
	Cotton	385.6	226.7	600	283.3	230.6	481.3
Cereal	Maize	124.1	181.1	450	188.3	121.7	329.7
	Millet	50	0	0	0	0	0
	Rice	355.1	229.6	50	0	114.1	0
	Sorghum	0	100	0	0	0	0
Fruit	Carrots	0	0	1	0	0	0

	Watermelon	0	0	0	0	0	0
Legumes	Cowpea	0	137.5	0	0	0	0
	Dohi	0	0	0	0	0	0
	Groundnuts	57.5	225	0	50	0	0
	Pigeon pea	0	0	0	0	0	0
	Sesame	175	50	0	0	0	0
	Soybean	0	178.2	75	516.7	98.5	218.8
	Voandzou	0	0	0	0	0	0
Root and Tuber	Cassava	0	0	0	0	0	0
	Potato	50	0	400	0	0	0
	Sweet potato	0	0	0	0	0	0
	Yam	0	75	0	0	0	0
Vegetable	Bissap	0	0	0	0	0	0
	Cabbage	10	0	3.5	0	0	0
	Gboman	8	0	0	0	0	0
	Lettuce	0	50	0	0	0	0
	Okra	475	200	2	0	0	87.5
	Onion	0	0	8.5	0	0	0
	Pepper	125	150	0	0	0	0
	Tomato	400	106.3	0	0	0	500
Total number of farmers		**80**	**113**	**116**	**114**	**131**	**151**

Source: Author

3.4.5 Calibration of the model and policy simulations

The calibration of the model focuses on reproducing observed data for 2022, which serves as the baseline for observed land use. The Positive Mathematical Programming (PMP) method was employed for this purpose. The strength of PMP lies in its ability to provide a model solution that closely approximates the observed data, aligning well with both empirical evidence and microeconomic theory (Howitt, 1995; Louhichi et al., 2010). Furthermore, the PMP approach leverages farmers' land use data from the baseline to generate self-calibrating models of agricultural production and resource use, accommodating the heterogeneous quality of land.

The PMP calibration process consists of three main steps:

1. **Step 1:** A constrained linear programming (LP) model is first used to generate dual land-use values, reflecting the opportunity cost of land-use decisions.
2. **Step 2:** The dual values, in combination with data-derived average yield functions, are then used to determine the parameters of the calibrating yield functions.
3. **Step 3:** The derived yield function parameters are applied to the base-year data, resulting in a PMP model calibrated as a nonlinear quadratic optimization model.

Through this calibration process, the model can predict land use and yield response to nitrogen application with an average percentage absolute deviation of 10.71% for land use. These deviations are within the acceptable range (7-14%) for models that simulate farmer behavior (Howitt, 1995). Following calibration, the model simulates various chemical fertilizer subsidy policy scenarios. These simulations explore different fertilizer subsidy rates and examine how changes in subsidy levels affect farmers' use of chemical fertilizers. Specifically, the model assumes that current fertilizer subsidies encourage the overuse of fertilizers, leading to increased greenhouse gas (GHG) emissions. The simulations aim to evaluate the sustainability of agricultural production, measured using the Environmental Impact Factor (EIF) index.

The simulation process includes the following scenarios:

- **Baseline Scenario:** Current fertilizer subsidy level, 44% in 2022 taking the price from 500 to XOF 280 kg per ha (Hounnou et al., 2023).
- **Subsidy Scenario:** Increase subsidy level from 44% to 100%.

Table 17: Land use and yield in 2022

Crop systems		Land use (ha)						Yield (kg)					
		Malanville	Banikoara	Pehunco	Sinendé	Glazoué	Bassila	Malanville	Banikoara	Pehunco	Sinendé	Glazoué	Bassila
Cash crop	**Cashew**	2			1.83	4.286	▨	399.99			1015.394	811.094	316.197
	Cotton	2.08	3.37	▨	3.31	4	3.5	1707.77	1688.48	840.11	1256.827	1171.961	1947.352
Cereal	**Maize**	1.54	2.28	2.53	2.71	1.7	2.08	1417.48	1875.36	1203.50	1604.42	837.228	850.806
	Millet	1.02	0.94	0.63	0.5	2	0.89	1012.96	762.79	1004.99	699.99	1249.99	725.296
	Rice	1.47	2.08	0.64	0.63	1.85	1.62	2035.32	1923.86	2001.86	1933.291	1266.082	1125.50
	Sorghum	1.86	1.35	0.83	▨		1.13	1093,00	762.64	632.10	853.10		374.994
Fruit	**Carrots**	0.073		▨			0.04	2291.69		93.79			833.29
	Watermelon						2						849.99
Legumes	**Cowpea**	1.42	0.96	▨	▨	▨	▨	1244.39	1210.06	416.69	283.29	173,00	386.40
	Dohi						0.5						599.99
	Groundnuts	1.1	0.71	0.6	▨	1.06	1.4	1568.01	1362.93	979.99	415.77	419.10	936.60
	Pigeon pea					▨	1.5					249.99	449.99
	Sesame	1.45	0.3	0.75		0.625	0.75	1068.20	1054.185	633.29		624.99	824.99
	Soybean	1.25	2.24	2.86	2.93	2.13	2.38	772.20	1742.035	801.20	976.13	756.59	606.06
	Voandzou		0.67			0.75	▨		899.994			537.50	549.99
Root and Tuber	**Cassava**			0.44	▨	▨	▨			2467.40	1257.10	1174.10	62.00
	Potato	0.5		0.75				1948.30		2033.28			
	Sweet potato		▨				0.5		1572.195				799.99
	Yam		3.7	0.78	1.14	0.57	0.96		1348.90	2190.60	1446.095	1575.695	1617.60
Vegetable	**Bissap**	0.145						1449.99					
	Cabbage	0.33		▨				1799.23		6.09			
	Gboman	0.08				0.001		1474.56				1500.00	
	Lettuce	0.11	0.25					1114.50	1632.01				
	Okra	0.88	0.4	▨		▨	0.35	1644.00	1852.03	1250.00		2000.00	2610.5
	Onion	0.25		0.38		0.02		3600.00		2298.99		1041.69	
	Pepper	0.5	0.61	0.25	0.145	0.02	0.43	1692.30	1147.221	1099.99	993.09	449.094	1419.0
	Tomato	0.375	0.375			0.5	1.1	2004.72	2340.308			1799.99	1732.85

Note: Grey color cells are land areas for which data failed the calibration process

Source: Author

3.5 Results and Discussions

In this section, the sustainability assessment of crop systems production within fertilizer subsidy policies is presented.

3.5.1 The Baseline: Cropland Allocation and Yield Response to Nitrogen

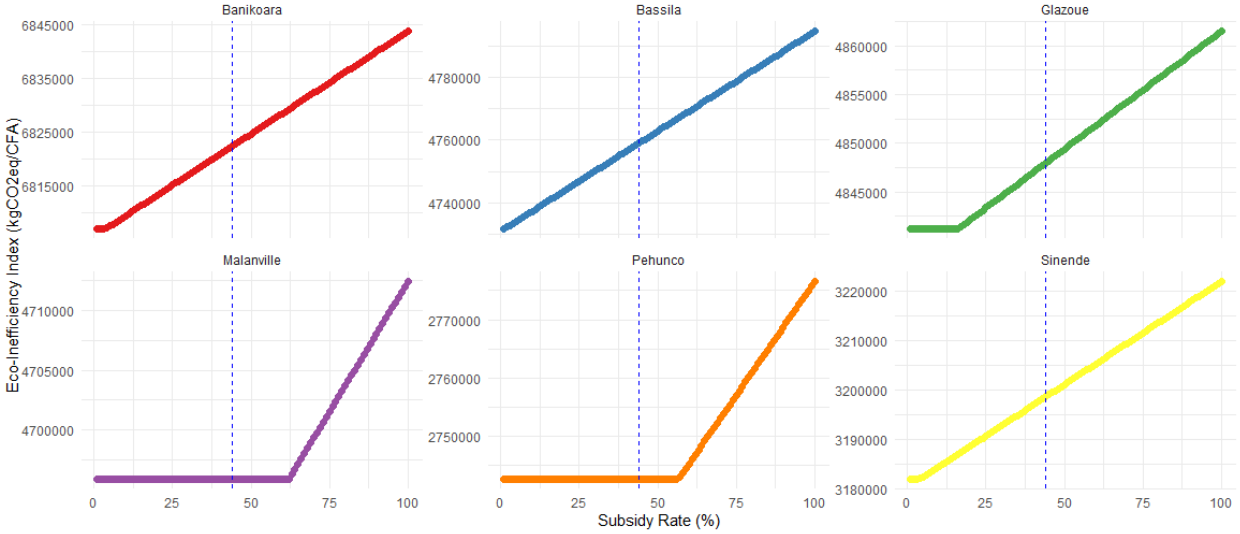
The calibration of the model using the PMP approach was able to predict land use for the year 2022. The predicted land use and yield response to Nitrogen are reported in Table 4 and constitute the baseline (the model without chemical fertilizer subsidy policies). Cash crops, including cashews and cotton, exhibit significant variations in land allocation and yield across the regions. Cereals such as maize, millet, rice, and sorghum also display substantial yields, with rice achieving particularly high values in Malanville and Banikoara. In the legume category, soybean appears to be the most widely cultivated crop, with notable land use and yield, particularly in Banikoara and Sinendé. Root and tuber crops, such as yam and cassava, are also highlighted, with yam demonstrating high yields in Banikoara and Glazoué. Among vegetables, okra, onion, and tomato are prevalent, showing significant yields, particularly in Banikoara, Pehunco, and Bassila. Overall, the table illustrates the diversity of crops grown across the regions, with variations in land use and yield based on location and crop type. This underlines the disparities in agricultural practices and agroecological and climatic conditions across regions.

3.5.2 Impact of fertilizer subsidy policy on the income

The simulation results indicate that increasing fertilizer subsidy rates enhances the affordability of fertilizer for farmers, leading to a corresponding increase in their revenue. However, the threshold at which revenue begins to rise varies significantly across regions (Figure 9). In Banikoara, Bassila, and Sinendé, farmers observe an increase in revenue starting from a subsidy rate of just 3%. In contrast, in Glazoué, Pehunco, and Malanville, the thresholds for revenue increases are higher, beginning at subsidy rates of 17%, 56%, and 62%, respectively (Figure 9).

These disparities highlight that certain regions cultivate crops with a greater reliance on fertilizer compared to others. Overall, the findings underscore the positive impact of the fertilizer subsidy policy on farmers' revenues across all regions. The results are consistent with predictions from previous studies, particularly after increasing the subsidy from the current level (blue dashed line in Figure 9) (Hounnou et al., 2023).

Figure 9: Change in Net Income across regions



Note: The blue dashed line captures the current subsidy level, 44%

Source: Author

3.5.3 Impact of fertilizer subsidy policy on GHG emission

The impact of the fertilizer subsidy policy on greenhouse gas (GHG) emissions was assessed by analyzing trends in nitrogen content resulting from farmers' use of chemical fertilizers. The simulation results reveal that as subsidy rates increase, farmers tend to prioritize certain crops over others, influenced by both the economic incentives provided by the subsidies and the constraints associated with fertilizer application (Figure 10).

Notably, there is a marked increase in nitrogen content for cotton in Bassila, Glazoué, and Sinendé, while maize and soybean in Pehunco, as well as rice in Banikoara and Malanville, also experience significant nitrogen increases. This trend can be attributed to the agricultural significance of these crops: maize, rice, and soybean are staple foods widely consumed and sold in local markets, whereas cotton serves as a major cash crop primarily for export in the Republic of Benin.

The thresholds at which nitrogen content begins to increase significantly, and those at which it stabilizes, vary across regions and crops (Figure 10). For cotton in Bassila, nitrogen content rises immediately at the smallest subsidy rate and stabilizes quickly, indicating an immediate response to the economic incentives. In Glazoué and Sinendé, however, both the increase and stabilization thresholds for cotton nitrogen content occur within a subsidy range of 0–25%, with stabilization observed at the higher end of this range.

In Banikoara, rice nitrogen content begins to rise at lower subsidy rates, stabilizing within the 12–25% range. This reflects the relatively high dependency of rice on nitrogen for optimal productivity in this region. Conversely, in Pehunco and Malanville, nitrogen content shows a delayed response for maize, soybean, and rice. The increased thresholds for these crops exceed a 50% subsidy rate, with stabilization observed only beyond this level (Figure 10). This delay suggests that farmers in these regions face additional constraints, such as the need to allocate resources among multiple crops.

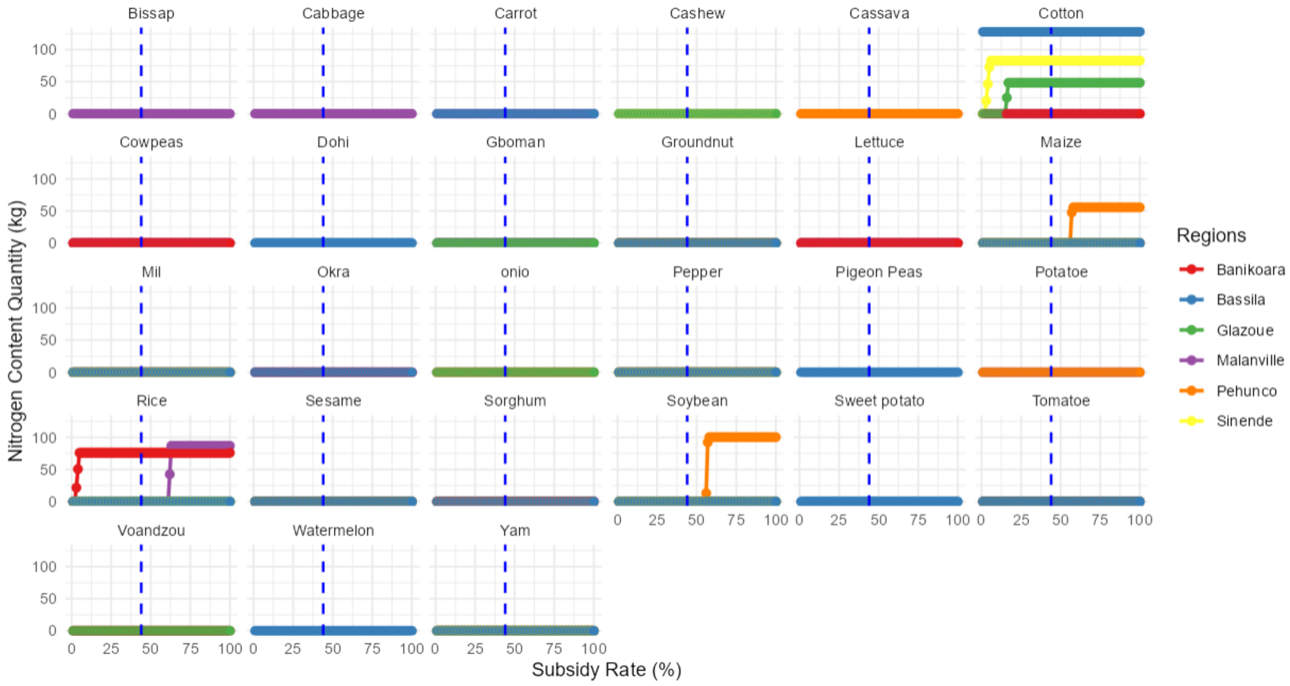
Comparison analysis shows that at the current subsidy rate of 44%, the observed GHG emissions result primarily from increased nitrogen application for cotton and rice in Bassila, Glazoué, Sinendé, and Banikoara. In contrast, for rice in Malanville and maize and soybean in Pehunco, the nitrogen content continues to rise beyond this subsidy rate, as these crops have not yet reached stabilization thresholds. This indicates that while certain crops and regions may have already maximized their nitrogen application, others remain on an upward trajectory, contributing to escalating GHG emissions.

The increase in nitrogen content correlates directly with higher GHG emissions, as nitrous oxide—a byproduct of nitrogen application—is a potent greenhouse gas. These findings underscore the environmental risks associated with the fertilizer subsidy policy, particularly in regions where nitrogen application has not yet reached stabilization. The results also align with microeconomic theory, which posits that demand for inputs like fertilizer is highly sensitive to price changes. Farmers, responding to economic incentives, adjust their practices in ways that can unintentionally exacerbate environmental impacts.

Furthermore, these findings corroborate existing studies on the environmental implications of nitrogen use in agriculture, emphasizing its contribution to GHG emissions (Colman & Young, 1989; Jote, 2023; Kahandage et al., 2023).

In summary, while the fertilizer subsidy policy supports agricultural productivity and income generation, it also raises significant environmental concerns. The variation in nitrogen content thresholds across regions and crops reflects differences in crop dependency on nitrogen, agroecological conditions, and farmers' resource allocation strategies.

Figure 10: Nitrogen Content trend under the Fertilizer subsidy policy



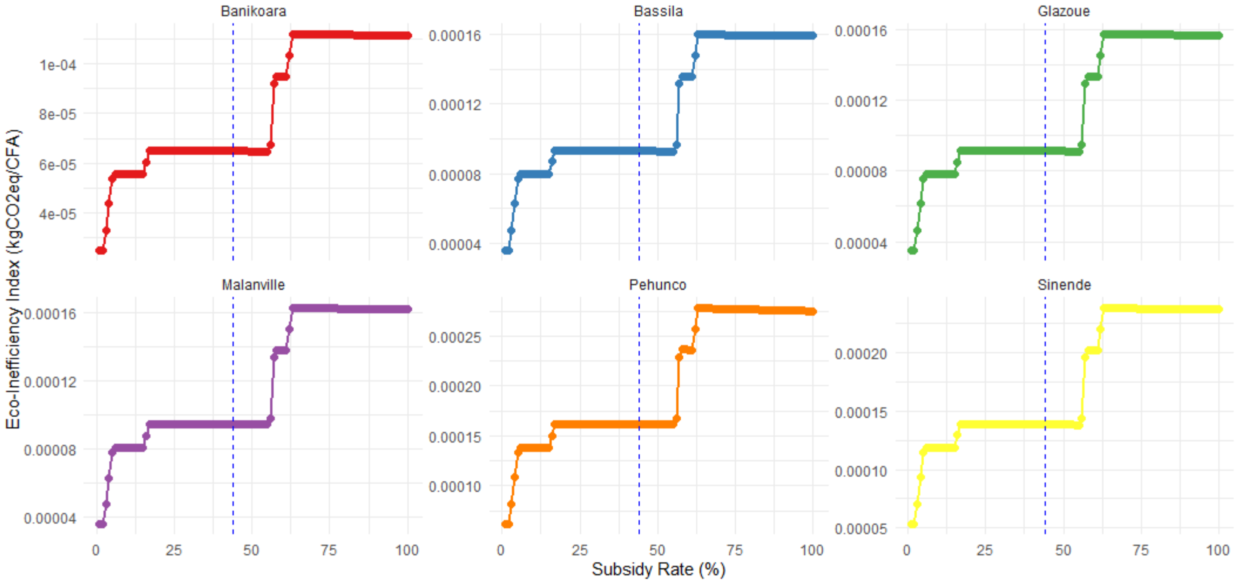
Source: Author

3.5.4 Impact of fertilizer subsidy policy on the sustainability of crop production

The Eco-Inefficiency Index (EIF) serves as a critical measure for assessing the sustainability of production activities by evaluating the greenhouse gas (GHG) emissions associated with marginal profits. The analysis of the fertilizer subsidy policy's influence on the EIF trend reveals significant insights into the sustainability of agricultural practices across various regions. As illustrated in Figure 11, there is a noticeable upward trend in the EIF index, indicating that generating marginal net income from agricultural production increasingly necessitates higher GHG emissions. This trend suggests that the overuse of chemical fertilizers is prevalent, marking a move towards unsustainable agricultural practices. Overall, the findings indicate that the fertilizer subsidy policy contributes to the unsustainability of crop production systems, primarily due to the heightened GHG emissions stemming from policy-induced adjustments in fertilizer application. These results affirm our hypothesis regarding the overuse of chemical fertilizers driven by subsidy policies, aligning with existing literature that raises concerns about the sustainability of agricultural systems following extensive chemical fertilizer use (Bah et al., 2020).

In summary, while the fertilizer subsidy policy may enhance short-term agricultural productivity, it poses long-term sustainability challenges due to its adverse environmental impacts, underscoring the need for more balanced agricultural policies that prioritize both economic viability and ecological health.

Figure 11: Eco-Inefficiency trend under fertilizer subsidy policy



Source: Author

3.5.5 Sensitivity Analysis on Eco-Inefficiency Index

To assess the robustness of our findings regarding the Eco-Inefficiency Index (EIF), we conducted a sensitivity analysis by simulating various levels of variation for labor costs and the GHG emission factor. The specific variations analyzed included -20%, -10%, 10%, and 20%. These factors were chosen due to their potential influence on the results of the EIF index, with labor cost being particularly significant. It is the primary factor affecting fertilizer application decisions, which in turn impacts the net income—the numerator in the EIF index formula.

The results of the sensitivity analysis, detailed in the Appendix, reveal that the overall impact of the chemical fertilizer subsidy policy remains consistent across all sensitivity variation levels for both labor costs and the GHG factor. This consistency underscores the robustness of our conclusions regarding the fertilizer subsidy policy's effect on the sustainability of crop production systems in the Republic of Benin.

In conclusion, the findings from the sensitivity analysis reinforce the reliability of our initial results, indicating that the implications of the fertilizer subsidy policy on the Eco-Inefficiency Index are resilient to changes in key economic factors.

3.5.6 Hypothesis Validation

The hypothesis of this research posited that *"The current fertilizer subsidy policy promotes the overuse of fertilizers, contributing to increased greenhouse gas (GHG) emissions in Benin."* The empirical findings provide substantial support for this hypothesis.

First, the analysis reveals that increased fertilizer subsidy rates lead to notable gains in farmers' revenues, albeit with regional variation in the magnitude of benefit. However, this economic gain is accompanied by a significant rise in GHG emissions, primarily driven by elevated nitrogen input levels. The increase in emissions confirms that higher subsidy-induced fertilizer use has direct environmental consequences. Furthermore, the Eco-Inefficiency index highlights a critical trade-off between profitability and environmental sustainability. As fertilizer use intensifies under the subsidy regime, marginal profit gains are increasingly tied to disproportionately higher emissions. This inefficiency underscores the unsustainable nature of current agricultural practices shaped by the subsidy policy.

Together, these results validate the hypothesis by demonstrating a clear causal link between the fertilizer subsidy policy and increased environmental externalities—particularly GHG emissions—thus calling into question the long-term viability of such an approach in the context of climate-smart agriculture and sustainable development.

3.6 Conclusion and Policy implication

The research investigated the impacts of fertilizer subsidy policy on the sustainability of agricultural production in the Republic of Benin. The research employed an integrated bioeconomy optimization modeling to assess the sustainability of crop production activities through an Eco-Inefficiency Index (EIF) concept. The findings show that increased fertilizer subsidies lead to higher EIF index suggesting that while the fertilizer subsidies increase revenues for farmers, it results in higher increase in GHG emissions. The resulting overuse of chemical fertilizers, driven by financial incentives, threatens the sustainability of agricultural practices, raising important questions about long-term environmental viability. The increase in the Eco-Inefficiency index further underscores the urgent need to balance economic gains with ecological considerations.

In light of these findings, it is imperative for policymakers to adopt a more nuanced approach to fertilizer subsidies. This includes mainly promoting sustainable agricultural practices, investing in education and research, engaging collaboration with stakeholders particularly farmers' networks for any policy measures. By doing so, the government can help ensure that the agricultural sector not only thrives economically but also contributes to environmental sustainability and food security. More specifically, the following policy implications can be derived:

1. **Promotion of Sustainable Practices**: The findings indicate that increased fertilizer application due to subsidies can lead to unsustainable practices and heightened GHG emissions. Rather than calling for the complete removal of fertilizer subsidies, this research recommends a reform of current subsidy policies to align them better with sustainability objectives. Specifically, subsidies should be redesigned to encourage the adoption of sustainable nutrient management strategies, such as integrated nutrient management, agroecological approaches, and the use of organic fertilizers. By linking financial support to the uptake of environmentally friendly practices, policymakers can mitigate the negative environmental impacts of fertilizer use while still supporting farmers' productivity and food security.

2. **Education and Training**: To optimize fertilizer use and minimize GHG emissions, educational programs for farmers should be implemented. Training should focus on the effective application of fertilizers, understanding soil nutrient dynamics, and adopting practices that enhance soil health. This could involve workshops, demonstrations, and collaborations with agricultural extension services.

3. **Monitoring and Evaluation**: Establishing robust monitoring and evaluation frameworks is essential to assess the long-term impact of fertilizer subsidies. By tracking both economic and environmental indicators, policymakers can adjust subsidy programs as necessary, ensuring they remain effective and aligned with sustainability goals.

4. **Diversification of Crops**: Encouraging farmers to diversify their cropping systems can enhance resilience against price fluctuations and improve soil health. Policies promoting crop

rotation and intercropping can reduce dependency on chemical fertilizers, thereby minimizing GHG emissions and improving the sustainability of agricultural practices.

5. **Research and Development**: Continued investment in research to develop low-input, high-output crop varieties and innovative agricultural technologies is critical. These advancements can help improve productivity without excessive reliance on chemical fertilizers, thereby supporting both farmer income and environmental sustainability.

6. **Incentives for Low-Emission Practices**: Policymakers could consider providing financial incentives or grants for farmers who adopt practices that lead to lower GHG emissions. These could include measures such as cover cropping, reduced tillage, and precision agriculture technologies.

7. **Collaboration with Stakeholders**: Engaging various stakeholders, including farmers, agribusinesses, NGOs, and researchers, is vital for the successful implementation of any policy measures. Collaborative efforts can lead to the development of comprehensive strategies that address both economic viability and environmental sustainability in agriculture.

By incorporating these policy implications, the fertilizer subsidy policy can be more effectively aligned with the goals of enhancing farmer income while promoting sustainable agricultural practices and reducing environmental impacts.

Ultimately, this research contributes to the ongoing discourse on agricultural policy in Benin, providing valuable insights that can guide future interventions aimed at optimizing the benefits of fertilizer use while mitigating its environmental impact. Through careful consideration of both economic and ecological factors, policymakers can foster a more sustainable agricultural landscape that supports the livelihoods of farmers and protects the environment for future generations. While this research provides valuable insights into the environmental and economic impacts of fertilizer subsidy policies in the Republic of Benin, several limitations should be acknowledged.

First, the bio-economic modeling relies on specific assumptions and average values for greenhouse gas (GHG) emission factors and labor costs, which may not capture the full variability of real-world farming practices across different agroecological zones. Second, the use of cross-sectional survey data limits the ability to capture long-term dynamics and temporal changes in input use and emission trends. Third, although the sample includes a diverse set of farmers across six municipalities, the findings may not be generalizable to the entire country or other sub-Saharan African contexts with differing institutional and agro-climatic conditions. Lastly, the focus on chemical fertilizers excludes potential interactions with other inputs or management practices (e.g., organic fertilization, agroecological techniques) that could influence sustainability outcomes. These limitations point to the need for further research using longitudinal data and more comprehensive models to deepen understanding of the long-term trade-offs between productivity and environmental sustainability in fertilizer subsidy policy design.

3.7 Appendix

3.7.1 Sensitivity analysis on Eco-Inefficiency Index

3.7.1.1 Sensitivity to GHG factor

Figure 12: Sensitivity to -20%

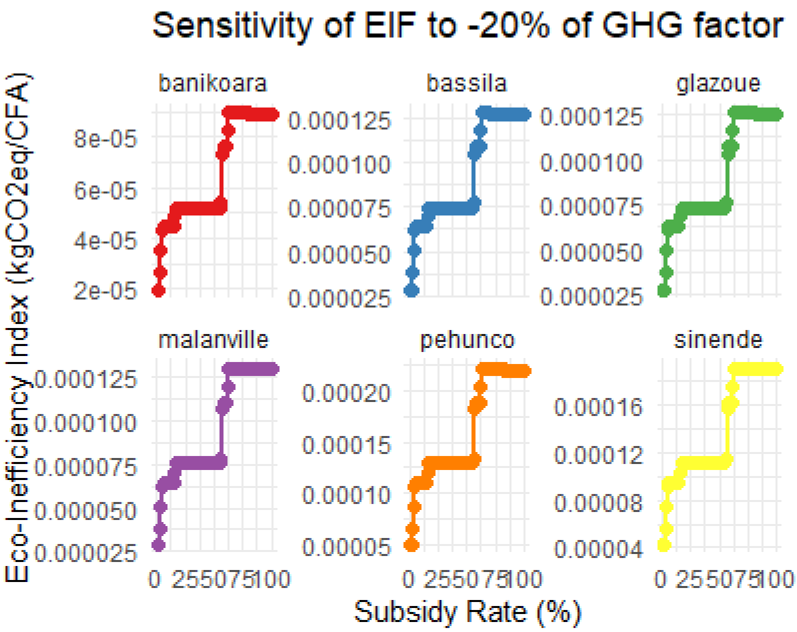


Figure 13: Sensitivity to -10%

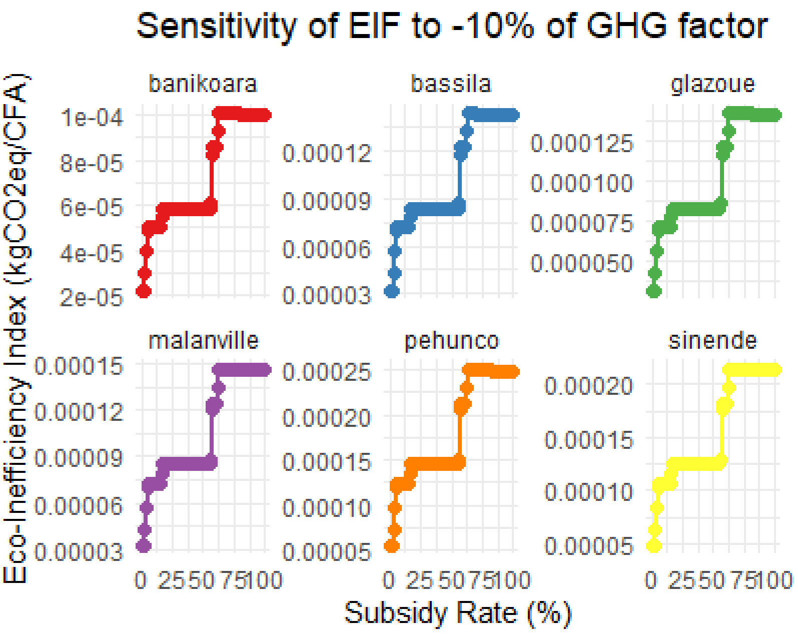


Figure 14: Sensitivity to +10%

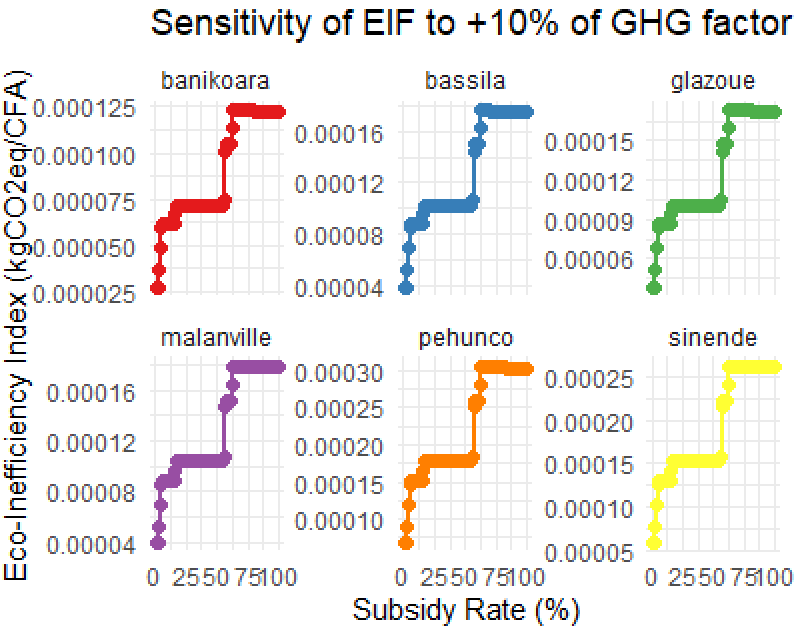
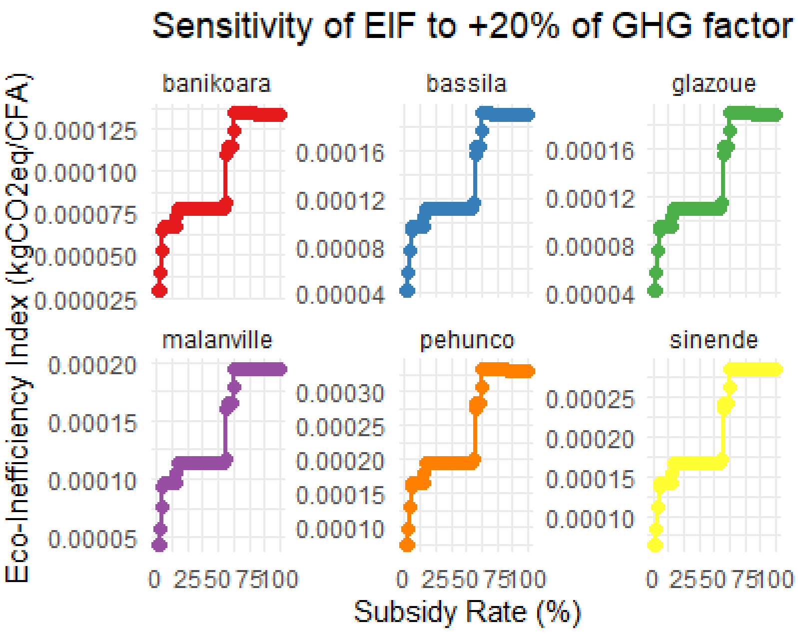


Figure 15: Sensitivity to +20%



3.7.1.2 Sensitivity to labor cost

Figure 16: Sensitivity to -20%

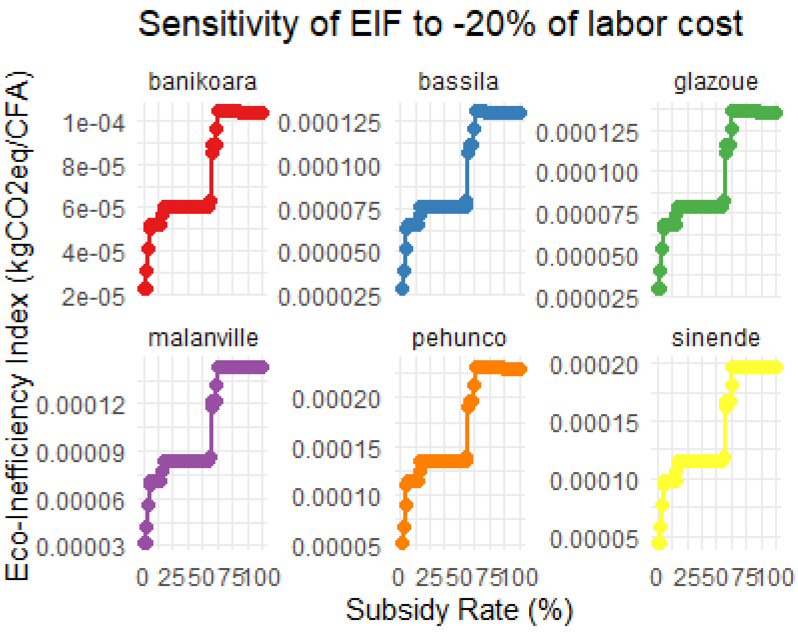


Figure 17: Sensitivity to -10%

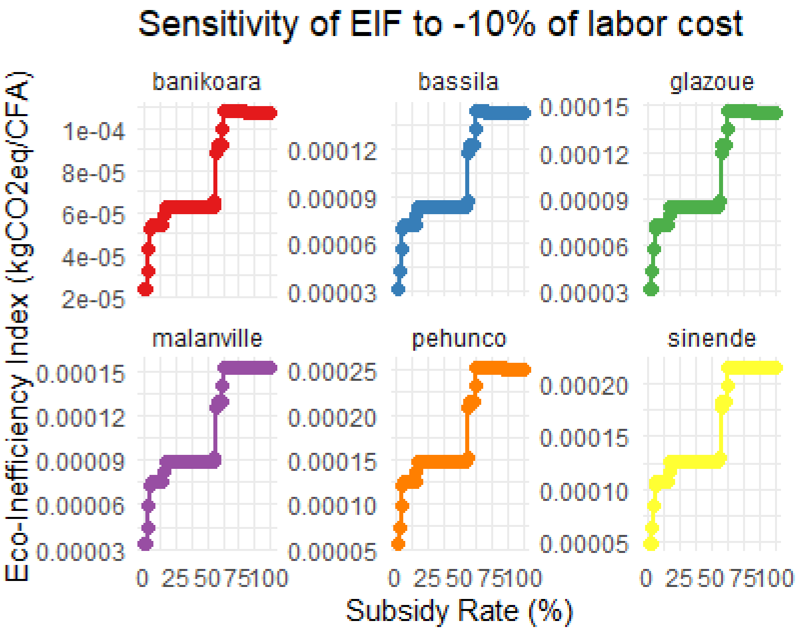


Figure 18: Sensitivity to +10%

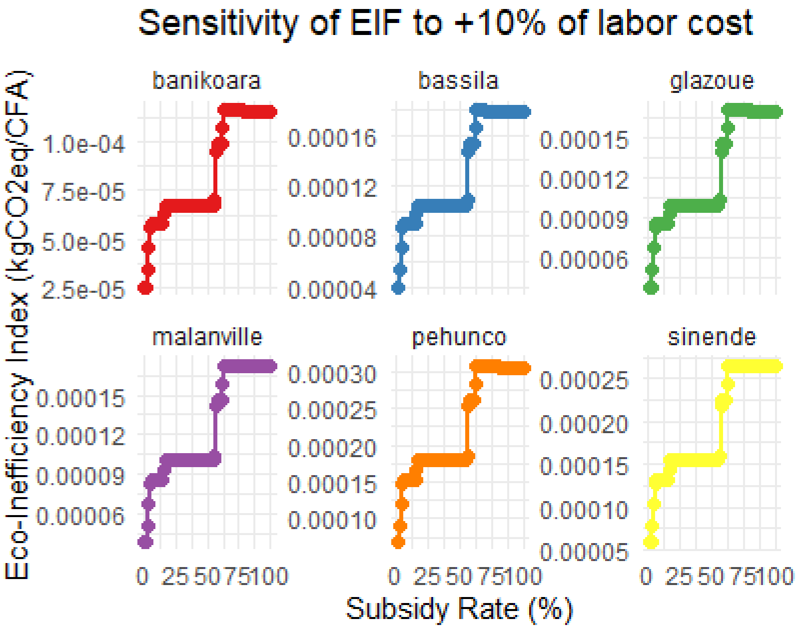
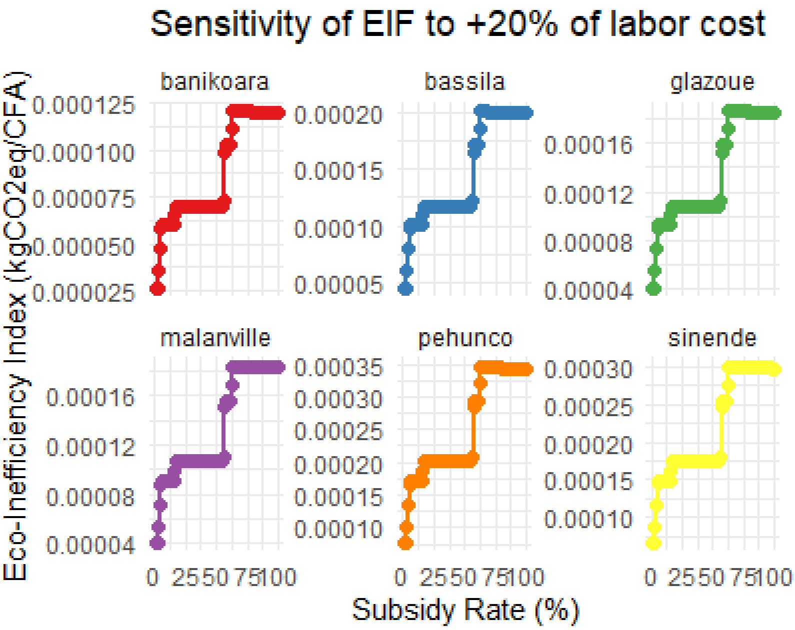


Figure 19: Sensitivity to +20%



General Conclusion

This thesis set out to explore the critical role of policy synergies and stakeholder cooperation in promoting the adoption of CSA practices, with a particular focus on balancing adaptation and mitigation objectives. Through the analysis of policy frameworks, economic decision-making by farmers, and the environmental sustainability of current agricultural policies, the research contributes to a deeper understanding of the factors that enable or hinder CSA adoption.

The findings across the three chapters consistently highlight the complexity of adopting CSA at scale. **Chapter 1** revealed the importance of an integrated policy framework that fosters stakeholder cooperation. Policies that are fragmented or poorly coordinated lead to inefficiencies and missed opportunities for synergies between adaptation and mitigation. It becomes evident that strong institutional frameworks and aligned stakeholder efforts are essential in creating enabling environments where farmers feel supported to adopt CSA practices.

Chapter 2 demonstrated that while institutional support is important, farmers' decision-making processes are fundamentally shaped by economic considerations. In an environment of uncertainty, farmers weigh the trade-offs between short-term gains and long-term sustainability. The use of expected utility theory in this chapter showed that adoption decisions are influenced by the perceived risks and benefits of CSA, underlining the need for policies that mitigate risks and provide clear incentives for adopting climate-smart practices.

Chapter 3 extended the analysis to the environmental sustainability of current agricultural policies, with a particular focus on fertilizer subsidies. The chapter highlighted that while such policies may enhance productivity in the short term, they can contribute to long-term environmental degradation, particularly through increased greenhouse gas (GHG) emissions. This finding underscores the need for policy reforms that not only promote productivity but also ensure environmental sustainability by aligning short-term objectives with long-term climate goals.

Together, these chapters provide a holistic understanding of the multi-dimensional factors influencing CSA adoption. The overarching conclusion is that the adoption of CSA cannot be fully realized through isolated interventions. A coordinated approach is necessary—one that involves the alignment of policies, stakeholder cooperation, and farmer incentives to ensure that both adaptation and mitigation objectives are met. The trade-offs between short-term productivity and long-term sustainability must be carefully managed, and policies must be designed with this balance in mind.

1. **Policy Integration and Coordination**: National and regional governments should prioritize the harmonization of CSA-related policies across different sectors (e.g., agriculture, environment, and finance) to avoid fragmentation and create a more cohesive framework for farmers.
2. **Stakeholder Engagement**: Multi-stakeholder platforms should be strengthened to facilitate the alignment of objectives among policymakers, farmers, NGOs, and private sector actors, ensuring that all parties contribute to a supportive environment for CSA adoption.
3. **Incentivizing Sustainable Farming Practices**: Economic incentives, such as subsidies or insurance schemes, should be designed to lower the perceived risks associated with CSA adoption, especially in the context of uncertain climate conditions. These incentives should also promote long-term environmental sustainability.
4. **Sustainable Policy Reforms**: Re-evaluating policies, such as fertilizer subsidies, to ensure they promote environmentally sound practices while maintaining productivity is crucial. Subsidies could be restructured to encourage the use of organic fertilizers or integrated soil management practices that reduce GHG emissions.

Concluding Remarks:

The research presented in this thesis underscores the necessity of a balanced approach to CSA adoption that simultaneously addresses both adaptation and mitigation challenges. The pursuit of sustainable agricultural systems that are climate-smart will require not only technical innovations but also institutional and policy reforms that foster cooperation, reduce risks, and align incentives. Ultimately, achieving these objectives is critical for ensuring the long-term resilience of agricultural systems in the face of climate change, while also contributing to global efforts to mitigate its impacts.

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