RESEARCH ARTICLE

A Dynamic Agricultural Production Model Under Climate-Induced Uncertainty and Investment in Adaptive Capacity

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Received: 13 June, 2025, Accepted: 15 August, 2025, Published: 26 September, 2025

Abstract

Climate change poses an increasing threat to global agriculture, especially in developing economies where smallholder farmers experience repeated climate shocks due to their lack of sufficient adaptive capacity. This paper develops a novel dynamic theoretical framework which examines how risk-averse farmers decide between productive capital investments and resilience-building measures when faced with unpredictable climatic events. The model shows how adaptation investments reduce output volatility which results from climate shocks when adaptive capacity is treated as resilience capital. The framework reveals essential trade-offs between short-term productivity and long-term climate resilience while demonstrating how adaptation functions as an intertemporal investment decision. The model shows that adaptation benefits decrease as investments exceed certain points, producing important insights for creating specific climate risk insurance programs. The paper presents future research directions that include behavioral biases and credit constraints, along with spatial externalities and compound environmental stressors. The study provides a forward-looking perspective on agricultural choices under climate uncertainty which connects resilience theory to practical adaptation strategies, thus making it a relevant addition to climate change economics and food security research.

Keywords: climate smart agriculture; climate change adaptation; adaptive capacity; climate resilience; smallholder farmers; climate change

Introduction

Agriculture is among the most climate sensitive sectors of the global economy, which makes it highly vulnerable to its intensifying effects (Clapp, Newell and Brent, 2018). Global agricultural production systems experience changes due to temperature variations and precipitation patterns along with rising frequency and severity of droughts, floods and heatwaves (Handmer et al., 2012). The changes in weather patterns threaten food security, rural livelihoods, and the economic stability of countries that depend on agriculture (IPCC, 2022). Estimates suggest that a 1°C rise in global temperature may reduce yields of major crops, such as maize, soybeans, and cotton by approximately 7% (Lobell, Schlenker, and Costa-Roberts, 2011). Major food-producing regions now face increasing chances of simultaneous climate shocks which heighten systemic vulnerabilities in global food supply chains (Kornhuber et al., 2023).

In this context, adaptation has become a central pillar of agricultural resilience strategies. Farmers, particularly in vulnerable areas, are increasingly engaging in practices aimed at mitigating climate-related threats. These include investments in drought-resistant crop varieties, improved irrigation systems, implementation of climate-based planting schedules and soil conservation techniques (Ignaciuk and Mason-D'Croz, 2014). However, the economic incentives, costs, and long-term benefits associated with these investments are unclear. A farmer's risk assessment along with their financial situation and predicted climate conditions determine their investment decisions toward adaptation measures (Eitzinger, Binder, and Meyer, 2018).

Several empirical studies have analyzed the impact of climate change on agriculture and adaptation techniques (Eka Suranny, Gravitiani and Rahardjo, 2022; Pathak, Aggarwal and Singh, 2012). However, there is a relative scarcity of formal theoretical models that capture the dynamic nature of farmers' decision-making under climate uncertainty. Traditional production models present climate risk as an exogenous factor without showing how farmers can reduce their exposure through direct investments into risk reduction measures (Finger and Schmid, 2007). Furthermore, adaptive capacity models in the literature represent static conditions rather than agents' time-dependent choices regarding adaptation capacity (Allison et al., 2023).

This study addresses these gaps by developing a dynamic stochastic model, which represents farmers' decisions regarding their agricultural production and adaptive capacity investments across time periods. The model introduces a climate-sensitivity function which shows diminishing sensitivity as adaptive investment levels rise. Adaptive capacity is treated as a stock variable that depreciates over time and requires periodic investments to maintain or enhance resilience. The model incorporates climatic uncertainty through stochastic climate shocks which directly impact production while demonstrating the connection between environmental unpredictability and adaptive choices.

The primary contribution of this paper consists of integrating adaptive investment into a dynamic optimization framework. It highlights the trade-off between short-term agricultural output and long-term resilience, depicting how forward-looking farmers may choose to allocate resources between consumption and adaptation under uncertainty. The model provides theoretical insights about how changes in climate volatility and risk preferences along with adaptation costs shape optimal behavior. The proposed framework serves as a foundation to understand when and how policy instruments such as subsidies, insurance mechanisms and public investments in adaptation infrastructure influence private investment decisions.

The structure of the paper is as follows. Introduction is followed by a summary of the current literature about the impact of climate change on agriculture, adaptation strategies and theoretical modeling frameworks. The next section explains the design of the dynamic stochastic model while showing how the farmer makes their optimal choices. It is followed by the uses, comparative statics and theoretical analysis to examine the model's outcomes. The next section discusses the policy relevance of the findings. The final section provides the conclusion of this study along with proposed research directions for future studies.

Literature Review

The intersection of agricultural economics and climate change has increasingly gained attention in literature, driven by mounting evidence of the vulnerability of food systems to environmental stressors. This literature review discusses the theoretical and conceptual frameworks that inform our understanding of climate impacts on agriculture and the role of adaptive investments, highlighting existing gaps that motivate the model developed in this study.

Climate Change and Agricultural Production

Multiple studies demonstrate how climate change causes negative effects on agricultural yields and farm income. Lobell and Field (2007) show that rising temperatures result in yield reductions across multiple staple crops, particularly in tropical and subtropical climates. U.S. crop yields strongly respond to temperature extremes and yield reductions. These effects become more severe beyond certain heat thresholds (Schlenker and Roberts, 2009). These studies highlight the importance of considering both gradual climate changes and acute weather shocks in agricultural planning and policy development.

However, most of the early research failed to examine farmer behaviour in response to rising risk because it treated climatic variables as exogenous and static (Agba et al., 2017; Moore, Baldos, and Hertel, 2017; Xiang et al., 2022; Baris-Tuzemen and Lyhagen, 2024). This limitation led to calls for more dynamic and micro-funded approaches that may endogenize the role of decision-making under uncertainty (Barrett et al., 2007; Choquette-Levy et al., 2024).

Modeling Adaptation to Climate Change

Agricultural adaptation consists of both reactive and proactive strategies directed at reducing vulnerability to climate-related changes. These adaptation approaches include adopting new technology such as drought-resistant seeds and infrastructure investments in irrigation systems and institutional strategies with insurance mechanisms. Various theoretical models have approached adaptation employing various frameworks.

Mendelsohn et al. (1994) introduce the Ricardian framework, which evaluates land value as a function of climate while controlling for adaptation implicitly. This method captures long-term equilibrium impacts, but it does not explicitly demonstrate adaptation processes. DiFalco and Perrings (2005) employ Real Options Theory, which allows them to analyze the timing of adaptive investment under uncertain conditions because such choices capture irreversibility alongside path-dependent characteristics.

Moreover, dynamic programming models serve to analyze the process of sequential choice in situations where outcomes remain uncertain. Antle and Capalbo (2010) recommend a risk-based approach which helps evaluate farm-level decisions by taking into account weather uncertainty and soil variations. These models, however, often lack a mechanism in resilience as a capital stock that evolves over time.

Adaptive Capacity as a Dynamic Stock Variable

Existing research focuses on representing adaptive capacity as both a static outcome and a dynamic stock that is augmentable and subject to depreciation. A system's ability to withstand shocks grows with adaptation capital including knowledge, infrastructure, and physical assets but demands continued investment for sustainability (Fankhauser and Burton, 2011).

However, few theoretical models integrate adaptation capital into farmers' decision problems. Exceptions include the work of Cai et al. (2011), who presents a model for water infrastructure investments under climate risk as a notable exception in this regard. Similarly, Robert, Bergez and Thomas (2018), develop a stochastic dynamic model to analyze farmers' decision concerning irrigation investments, water application rates, and crop choices. Moreover, Kalthof et al. (2025) suggest an agent-based model, the Geographic, Environmental and Behavioral (GEB) model, coupled with a hydrological model to examine farmers' adaptive behaviors under long spells of droughts. These models, however, do not apply to wider agricultural adaptation cases and rarely provide mechanisms for stochastic climate changes that trigger endogenous responses.

Gaps in the Literature and Contributions of this Paper

The existing literature lacks a generalizable dynamic framework to depict how farmers simultaneously make production and investment decisions in the face of climate-induced uncertainty. Furthermore, most existing models either assume perfect foresight or treat adaptation as an exogenous variable instead of a strategic choice. This paper contributes to the literature by developing a dynamic stochastic optimization model that explicitly integrates resource allocation decisions between productive agricultural activities and the accumulation of adaptive capacity. Climate shocks are modeled as a stochastic process, influencing output through a climate sensitivity function that captures the non-linear effects of environmental variability. Adaptive capacity is treated as a stock variable that enhances resilience to climate shocks but is subject to depreciation over time, necessitating sustained investment to maintain its protective benefits.
This framework integrates risk, investment dynamics and endogenous adaptation, which provides new theoretical insights for climate-resilient agricultural decision-making.

Model Formulation

Overview

The section introduces a dynamic stochastic model in which a representative farmer allocates resources between agricultural production and investments in adaptive capacity. The model captures the intertemporal trade-offs farmers face under climate uncertainty and shows how investments in adaptation serve as a buffer against climate-induced output losses. Adaptive capacity is modeled as a dynamic stock which enhances resilience but depreciates over time. Climate shocks are introduced as stochastic disturbances that influence agricultural output.

Economic Environment

The model considers a risk-averse representative farmer, operating over an infinite time horizon, denoted as $t = 0, 1, 2, \ldots\ldots$. At each period, the farmer receives revenue from agricultural production and decides the portion of the available income to allocate toward consumption, reinvestment in agricultural inputs, and adaptive investment.
Let:

- Y_t be the agricultural output at time t
- A_t denote the stock of adaptive capacity
- θ_t be the stochastic climate shock at time t
- I_t^a denote investment in adaptive capacity
- I_t^p denote investment in productive capital
- C_t denotes consumption

The farmer maximizes expected lifetime utility.

$$E_0 \sum_{t=0}^{\infty} \beta^t U(C_t)$$

subject to

Budget Constraint

$$Y_t = F\ (K_t, A_t, \theta_t) = \ \phi\ (A_t, \theta_t)\ .\ f\ (K_t)$$
$$Y_t = \ C_t, I_t^a, I_t^p$$

2. Adaptive Capital Accumulation

$$A_{t+1} = (1 - \delta_a)A_t + \ I_t^a$$

3. Productive Capital Accumulation

$$K_{t+1} = \left(1 - \delta_p\right)K_t + \ I_t^p$$

where:
$\beta\ \in (0, 1)$ is the discount factor,
$U\ (C_t)$ is a CRRA utility function, $U\ (C) = \frac{C^{1-\sigma}}{1-\sigma}\ , \sigma > 0$
δ_a and δ_p are depreciation rates of adaptive and productive capital respectively,
$f(K_t)$ is a neoclassical production function,
$\phi\ (A_t, \theta_t)$ is the climate resilience function,
$\theta_t \sim\ i.i.d\ \Theta$ is the stochastic climate shock

The Climate Resilience Function

A novel element of this model is the climate resilience function $\phi\ (A_t, \theta_t)$, which determines the impact of climate shocks on agricultural output, conditional on adaptive capacity. The model proposes:
$\phi\ (A_t, \theta_t)$ = exp $(-\gamma\theta t\ e^{-\eta A_t})$
where:
$\gamma > 0$ is a shock sensitivity parameter,
$\eta > 0$ is the effectiveness of adaptive capital

This function ensures that in the absence of adaptation ($A_t = 0$), climate shocks significantly reduce agricultural output. As A_t increases, the effect of θ_t on output is mitigated. The exponential form ensures diminishing marginal returns to adaptation, a property consistent with empirical findings by Fankhauser and Burton (2011).

The Farmer's Optimization Problem

Substituting into the budget and dynamic constraints, the farmer solves:

$$E_0 \sum_{t=0}^{\infty} \beta^t U \frac{C_t^{1-\sigma}}{1-\sigma}$$

subject to:
$C_t + \ I_t^a + \ I_t^p\ =$ exp $(-\gamma\theta t\ e^{-\eta A_t})\ .\ f\ (K_t)$

$$A_{t+1} = (1 - \delta_a)A_t + \ I_t^a$$
$$K_{t+1} = \left(1 - \delta_p\right)K_t + \ I_t^p$$

This dynamic problem can be solved using value function iteration or other numerical techniques. However, in this study, the focus is on theoretical properties and implications of the model rather than explicit numerical solutions.

Comparative Statics and Theoretical Implications

The comparative statics analysis examines how changes in key parameters like the variance of climate shocks, the depreciation rate of adaptive capital, and the functional curvature of the climate sensitivity function affect optimal investment behavior and long-term resilience.

The model yields several testable implications.

1. Increased climate variability increases adaptive investments

An increase in the variance of θt elevates the marginal value of adaptation capital A_t, thereby inducing higher optimal adaptation investment I_t^a.

2. Trade-off between resilience and short-term output

Greater allocation of current income to I_t^a reduces productive investment and output in the short run but enhances resilience and expected future output.

3. Depreciation of adaptive capacity necessitates sustained investment

Given $\delta_a > 0,$ resilience can only be maintained through continuous reinvestment; absent this, the system gradually becomes more vulnerable over time.

4. Diminishing marginal returns to adaptation

The function form of ϕ implies that beyond a certain level of A_t, additional adaptation investment yields minimal incremental protection, indicating the existence of an optimal adaptive capital stock.

Theoretical Analysis and Policy Implications

Optimal Adaptive Investment and the Role of Climate Risk

In the theoretical model, farmers face a dynamic trade-off between agricultural production in the short run and long-term resilience to climate shocks. The model shows that optimal investment in adaptive capacity (I_t^a) increases in both the perceived severity and variability of climate risk. As climate shocks (θt) become more intense, the marginal benefit of adaptation increases due to its role in mitigating output volatility. This aligns with theoretical expectations from risk management literature, suggesting that risk-averse agents will increase precautionary investments upon exposure to higher uncertainty (Barrett et al., 2017).

A key insight from the model is that the climate resilience function $\phi\ (A_t, \theta_t)$ transforms the nature of risk exposure. Specifically, adaptive capacity acts as a form of resilience capital that flattens the marginal damage curve of climate shocks. The exponential decay function $\exp\ (-\gamma\theta t\ e^{-\eta A_t})$ implies that investments in A_t can considerably reduce output losses at lower levels of adaptation. However, diminishing marginal returns imply that further investment becomes less effective. This creates a critical policy window for identifying the optimal range of adaptation investment, beyond which public subsidies or joint adaptation strategies may be needed to avoid inefficient over-investment.

Temporal Trade-offs: Short Term Costs and Long-Term Gains

Another vital implication is the intertemporal trade-off embedded in the farmer's decision-making. Increased investment in adaptive capacity in the current period (I_t^a) reduces the resources available for immediate consumption or productive capital investment (I_t^p), potentially resulting in a reduction of short-term output. However, by increasing future resilience, such investments reduce the expected damage from future shocks and smooth income over time. This supports the idea that adaptation policy needs to focus on long-term welfare maximization rather than short-term output maximization, a principal highlighted in sustainable development frameworks (Hallegatte et al., 2011).

Policy Implications for Agricultural Adaptation Under Climate Change
Based on the model, several important policy implications can be drawn:

Targeted Adaptation Incentives

When policymakers assess diminishing marginal returns in adaptation efforts, they need to identify specific threshold levels of adaptive capacity beyond which additional investment yields limited output stabilization. Investments in adaptation infrastructure require specific subsidies and grants to maintain economic justification below this established threshold.

Dynamic Investment Strategies

Since adaptive capacity depreciates over time, therefore one-time investments are insufficient. policymakers need to encourage continuous and dynamic investment strategies. This may involve multi-year budgeting for adaptation or institutional arrangements that mandate recurrent evaluations and top-ups of adaptation stock.

Integration with Risk-Transfer Mechanisms

The model confirms that adaptation and insurance work together as mutual components rather than as alternative solutions. The implementation of adaptive investments decreases probable losses yet preserves some level of risk exposure. When adaptation policies unite with weather-indexed insurance and disaster risk financing mechanisms, it results in better welfare outcomes (Carter et al., 2014).

Equity and Distributional Considerations

Since adaptive capacity tends to be higher in capital-rich contexts, inequalities in resilience may emerge between regions and/or farmers. The model demonstrates that market mechanisms may reinforce vulnerability of smallholder farmers unless corrective redistribution measures are implemented. This support calls for international climate finance mechanisms along with domestic redistributive policies to reduce adaptation gaps (IPCC, 2022).

Broader Theoretical Implications

From a theoretical perspective, this model contributes to the literature by embedding a dynamic resilience framework directly into agricultural production under conditions of uncertainty. Traditional production functions under risk conditions typically depend on exogenous shocks which static effects (Rosenzweig and Binswanger, 1993). The model provides a new approach to climate adaptation behavior analysis by including an endogenous resilience mechanism. Thus, opening the door for richer models' development for climate adaptation behavior that can be extended to encompass behavioral biases, credit constraints and multi-agent interactions.
The model demonstrates that adaptation operates as an economic choice which optimizes itself rather than functioning as a mere policy instrument. This insight provides the potential to merge different adaptation research

streams through a unified microeconomic framework, which may offer new opportunities for better empirical model calibration and simulation-based policy design.

Extensions and Future Research Directions

Incorporating Behavioral Dimensions into Adaptation Decisions

The model presents a rational, forward-looking farmer who optimizes over time under climate risk but real-world decisions are often affected by cognitive biases along with limited foresight and imperfect information. Behavioral economics suggests that farmers may underinvest in adaptive capacity on account of present bias, ambiguity aversion and/or risk misperception (Duflo, Kremer, and Robinson, 2011; Tversky and Kahneman, 1992). A vital extension of this model may involve incorporating behavioral parameters, including hyperbolic discounting and subjective probability weighting, into the farmer's utility function. Such an analysis would help explain observed adaptation inertia among farmers despite rising climate risks and provide policy recommendations about behavioral modifications through framing techniques, default options and capacity-building interventions.

Furthermore, the model could be extended to account for social learning and peer effects in adaptation investment decisions. Research shows that farmers generally adapt new technologies based on what they observe or through local social networks (Conley and Udry, 2010). Incorporating such dynamics into the model through agent-based simulations or network-based optimization frameworks would help identify tipping points in adaptation uptake and highlight collective resilience limits at the community level.\

Introducing Market Imperfections and Credit Constraints

A crucial area for future work is to introduce market imperfections, particularly insurance market failures and credit constraints. Developing regions have smallholder farmers who may be unable to invest in adaptive capital due to liquidity constraints (Dercon and Christiaensen, 2011). The current model assumes full access to intertemporal budget smoothing; relaxing this assumption by borrowing restrictions or high interest rates may result in a more realistic approach for climate adaptation policy design.

This extension could also enable researchers to study the effects of public adaptation subsidies on private investment behavior. For instance, the provision of subsidies to farmers who need credit allows them to reach optimal investment levels which then attracts additional private investment. Alternatively, poorly designed subsidies may displace private initiative, resulting in overreliance on government support.

Integrating Multiple Climatic and Environmental Stressors

The current model identifies climate shocks as the primary environmental risk factor. However, farmers may face compound risks, encompassing soil degradation together, pest outbreaks and market volatility. Future extensions could model multi-dimensional environmental shocks that impact adaptive capacity in different ways. For instance, resilience to drought may not translate to pest infestation resilience, and investments in one form of adaptive capacity may have trade-offs or synergies with another.

This line of research may benefit from a multi-shock framework to model adaptive capacity through specific stressor-oriented asset portfolios. Through this approach policymakers and researchers can develop optimal diversification strategies for resilience-building while creating a theoretical basis for climate-agriculture-environmental planning integration.

Spatial Dynamics and Regional Spillovers

A promising direction involves spatializing the model to account for regional heterogeneity and spillover effects. Adaptive investments generate public benefits in local areas because they involve projects such as watershed management, community irrigation systems and cooperative pest control. Extending the model with spatial externalities would enable researchers to examine coordination issues and the design of cooperative adaptation strategies.

Furthermore, spatial modeling may also integrate climate migration dynamics. Failure of adaptation efforts in particular areas due to extreme climate conditions may force people to move as a coping mechanism The incorporation of adaptation decisions into a spatial general equilibrium model would reveal how agricultural labor markets, regional development and land use patterns change through climate adaptation and migration processes (Feng, Krueger and Oppenheimer, 2010).

Empirical Calibration and Simulation-Based Policy Testing

Future work could involve empirical calibration of the model using data from reliable sources like the World Bank Climate Change Knowledge Portal combined, FAOSTAT and LSMS (Living Standards Measurement Study) datasets. By assigning real-world parameter values, the model would enable the simulation of policy interventions such as adaptation subsidies, climate insurance schemes and resilience-indexed credit to evaluate their welfare effects across various farmer profiles and climatic zones.

The use of simulation-based methods would enable researchers to conduct counterfactual analysis and sensitivity testing, which may help merge theoretical models with practical policy applications. These calibrated models can serve as policy laboratories that examine the evolution of adaptive behaviors under various climate scenarios and institutional constraints.

Conclusion

Agricultural lies at the nexus of food security and climate vulnerability, making it one of the most critical sectors for proactive climate adaptation. This paper introduced a dynamic theoretical framework which integrates endogenous investment in adaptive capacity into the decision-making process of a risk-averse farmer under stochastic climate shocks. The framework differs from traditional exogenous resilience models by showing adaptation as an intertemporal process which enables us to study farmers' decisions between productive capital and resilience-building investments under conditions of uncertainty.

The model yields several crucial insights. Firstly, the model demonstrates that adaptive capacity acts as resilience capital which reduces negative effects of climate variability on agricultural output. The demonstrates the importance of adaptation not only as a reactive strategy but also as a forward-looking investment decision. Secondly, the marginal returns from adaptation investment decrease after reaching specific levels which indicates important investment barriers that lead to substantial welfare benefits below the thresholds and potentially inefficient investment above them. The finding has direct implications for the design of targeted adaptation subsidies and the prioritization of policy interventions.

The model also shows how investment decisions regarding resilience between current periods create long-term benefits while reducing short-term output and consumption levels. The trade-off between adaptation costs and long-term benefits demonstrates the necessity of patient capital along with long-term planning in adaptation financing. It provides a strong rationale for public intervention when private actors face liquidity constraints or behavioral biases that result in insufficient investment for resilience.

The paper provides a roadmap for future research. Multiple promising model extensions are proposed, which involve behavioral aspects together with imperfect credit markets, spatial relationships and combined climate risk factors. Extending the model allows both theoretical depth enhancement and practical model application improvement for real-world policy assessments. Simulation-based testing alongside empirical calibration of the model would help link theoretical findings to practical applications thus creating a useful tool for climate policy assessment.
The study contributes to a growing body of literature emphasizing the importance of adaptive capacity as a vital component in agricultural systems. As climate change intensifies and climate shocks become more frequent and severe, the resilience of agricultural livelihoods will increasingly depend on the ability of farmers and supporting institutions to predict, absorb and recover from environmental stressors. The theoretical framework developed in this paper provides a foundation for understanding this adaptive behavior and offers a conceptual guide for designing efficient and equitable climate adaptation policies.

Declaration

Acknowledgment: N/A

Funding: N/A

Conflict of interest: The author declares that there is no conflict of interest.

Ethics approval/declaration: N/A

Consent to participate: N/A

Consent for publication: N/A

Data availability: This study develops a theoretical model. No empirical data were generated or used; all relevant arguments and formulations are contained within the article.

Authors contribution: The author was solely involved in all aspects of this work, including the study's conceptualization and design, and the preparation of the manuscript.

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