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MODELLING ADAPTATION TO CLIMATE CHANGE IN AGRICULTURAL SYSTEMS: AGENT-BASED APPROACH[1]

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Abstract

In recent years, there has been increased interest in using agent-based modeling to simulate climate change's effects on agricultural output. Agent-based modeling allows for a more detailed and nuanced understanding of how individual agents, such as farmers, make decisions in response to changing environmental conditions. We can better anticipate how different adaptation strategies may impact agricultural productivity by simulating interactions between these agents and their environment. This approach also enables exploring various scenarios and their potential outcomes, providing valuable insights for policymakers and stakeholders. Agent-based models offer the advantage of simulating individual entities' decision-making processes and interactions, integrating social dynamics and non-financial factors into decision-making, and establishing dynamic connections between social and environmental processes. In this paper, we review the agent-based climate change adaptation models that have been developed around the questions of (a) who or what adapts, (b) adaptation to what, (c) how adaptation occurs, and (d) what good is the adaptation. From there, we aim to show how these models simplify perceiving the world by approximating reality. While at the same time recognizing the constraints of the model itself and the uncertainties, we also discuss whether they can be overcome.

Keywords ***:*** *Agent-based Model, Climate Change, Social Learning, Decision-making*

JEL Classification ***:*** *Q54, R14*

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TARIMSAL SİSTEMLERDE İKLİM DEĞİŞİKLİĞİNE UYUMUN MODELLENMESİ: AJAN TEMELLİ YAKLAŞIM

Öz

Son yıllarda, iklim değişikliğinin tarımsal üretim üzerindeki etkilerini simüle etmek için ajan temelli modellerin kullanımı oldukça yaygınlaşmıştır. Ajan temelli modelleme, çiftçiler gibi bireysel ajanların, değişen çevresel koşullara karşı verdikleri karar süreçlerinin, daha ayrıntılı ve incelikli bir şekilde anlaşılmasını sağlar. Bu modeller aracılığıyla, ajanlar ve çevreleri arasındaki etkileşimleri simüle ederek, iklim değişikliğine karşı farklı adaptasyon stratejilerinin tarımsal verimliliği nasıl etkileyebileceğini daha iyi tahmin edebiliriz. Bu yaklaşım aynı zamanda çeşitli senaryoların ve bunların potansiyel sonuçlarının araştırılmasına olanak tanıyarak politika yapıcılar ve paydaşlar için de değerli bilgiler sağlar. Ajan temelli modeller, bireysel ajanların karar verme sürecini ve etkileşimlerini simüle etme, sosyal dinamikleri ve finansal olmayan faktörleri karar verme sürecine entegre etme ve sosyal ve çevresel süreçler arasında dinamik bağlantılar kurma avantajı sunar. Bu makalede, (a) kimin adapte olduğu, (b) kimin neye adapte olduğu, (c) adaptasyonun nasıl gerçekleştiği ve (d) adaptasyonu iyi yapan özellikler nelerdir soruları etrafında geliştirilen ajan temelli, iklim değişikliğine uyum modellerini gözden geçiriyoruz. Buradan hareketle, bu modellerin gerçekliğe yaklaşarak dünyayı algılama sürecini nasıl basitleştirdiğini göstermeyi amaçlıyoruz. Aynı zamanda modelin kendi kısıtlamalarını ve belirsizliklerini kabul ederken, bunların üstesinden gelinip gelinemeyeceğini de tartışıyoruz.

Anahtar Kelimeler ***:*** *İklim Değişikliği, Ajan Temelli Model, Karar Verme*

JEL Sınıflandırılması ***:*** *Q54, R14*

INTRODUCTION

Climate change is one of the most extensively researched and debated global phenomena. While natural climatic variability has historically shaped the Earth's climate, sustained warming coincides directly with the Industrial Revolution and the associated increase in greenhouse gas emissions (Block et al., 2004). The observed warming over the last 160 years has significantly exceeded similar warming periods in previous millennia (0.6°- 0.9°C compared to less than approximately ±0.2°C for any other century) (P. D. Jones & Mann, 2004).

Increasing greenhouse gas emissions is an environmental problem and a multidimensional issue that threatens agricultural production, food security, and rural development (Carozzi et al., 2022; Howden et al., 2007). Climate Change impacts on agricultural systems are complex and far-reaching, necessitating the development of comprehensive strategies to build resilience and adapt to changing conditions.

Two main strategies have emerged to address the impacts of climate change on agricultural systems: mitigation and adaptation. According to the Intergovernmental Panel on Climate Change (IPCC), mitigation involves human interventions to minimize pressure on Earth's climate systems - strategies include reducing greenhouse gas emissions from industrial activities and improving natural carbon sinks. Adaptation requires developing systems and infrastructure to withstand climate-induced stressors such as rising sea levels, intensifying weather events, and long-term ecosystem changes In response to this challenge, international organizations have developed comprehensive strategies to increase agricultural systems' resilience by aligning sustainable development goals (SDG) with climate change. Of the 17 targets of the Sustainable Development Goals, some targets are directly related to climate change and include agricultural systems, such as ensuring food security (SDG 2, Zero Hunger), water management (SDG 6; Clean Water and Sanitation), and promoting rural development (SDG 15, Life on Land) (UN, 2020).

Aligning the Sustainable Development Goals with climate change adaptation and mitigation efforts in agriculture underscores the need for an integrated approach considering multiple sustainability dimensions. However, it is important to examine how adaptation and mitigation are conceptualized and operationalized in different agricultural systems and regions to develop target- and context-specific interventions. The IPCC's approach to adaptation and mitigation emphasizes human emphasis on mitigation to anthropogenically-caused climate change, while adaptation emphasizes an externality decoupled from anthropogenic factors. This conceptualization creates a dichotomy in the mitigation and adaptation process. For instance, reducing greenhouse gas emissions from agriculture may require changes in land use and management practices, affecting the system's adaptive capacity to respond to climate change impacts. In other words, the production system that causes emissions also determines the ability of regions to adapt to changing conditions.

The conceptualization of climate change responses has significantly influenced modeling approaches through Integrated Assessment Models (IAMs) and Computable General Equilibrium (CGE) models, offering broad perspectives on climate change impacts and policy responses (Fujimori et al., 2014; Hasegawa et al., 2014; Nelson et al., 2014; Popp et al., 2014; Thepkhun et al., 2013). Prominent examples such as GCAM, IMAGE, and REMIND-MAgPIE have contributed to our understanding of how agricultural practices affect GHG emissions and how they can be optimized under various climate scenarios. These integrated models aim to predict climate change impacts by linking economic, environmental, and social factors (Hertel et al., 2010; Van Meijl et al., 2006).

While useful, these models often ignore critical societal changes and emerging technologies that can significantly affect outcomes (Hertel et al., 2010; Popp et al., 2014; Van Meijl et al., 2006). So, these top-down approaches face significant limitations in representing agricultural adaptation processes. The fundamental assumption of rational economic actors responding predictably to price signals and policy incentives fails to capture the complexity of farmer decision-making (Howden et al., 2007; Simutowe et al., 2024; Van Asseldonk et al., 2023). Empirical evidence consistently shows that risk aversion, cultural traditions, and resource constraints significantly influence farmers' adoption of new practices, even when economic incentives exist (Williamson et al., 2018). As Kahneman (2003) emphasizes, the rationality assumption of traditional economic models often differs significantly from real-world scenarios. Real-world problems are complex because they result from the behavior and interaction of multiple entities, such as people, markets, and the natural environment (Macal & North, 2010). Models are used to understand this complexity better. While valuable for macro-level analysis, the top-down approach of CGE models often fails to capture the nuanced complexity of farmer behavior in agricultural systems, suggesting the need to fundamentally reconsider the climate change modeling approach. This reconsideration involves shifting from a mitigation/adaptation framework to an adaptation/mitigation perspective that better reflects the realities of agricultural systems. The transition from top-down to bottom-up modeling approaches represents a paradigm shift in understanding and analyzing complex agricultural systems under climate change.

Agent-based models (ABMs) emerge as a powerful methodological bridge between these approaches, the ability to capture both micro-level behavioral dynamics and macro-level system outcomes (de Vries, 2010; Delli Gatti et al., 2011). Unlike traditional economic models that assume rational behavior, ABMs acknowledge the heterogeneity of decision-making processes and allow for the emergence of complex system behaviors from relatively simple individual interactions. ABMs are valuable because they depict individual elements within a system and their behavior (Railsback & Grimm, 2019, p. 10). Agent-based models create an artificial environment of various agents through simulations, allowing for the study of the interactions between these agents and how interactions between agents and additional elements, such as time and space, contribute to the emergence of observed patterns (Hamill & Gilbert, 2016).

This modeling approach becomes particularly valuable when examining climate change adaptation strategies because it can capture the bottom-up nature of adaptation decisions while providing insights relevant to top-down policymaking. By simulating how individual farmers respond to climate pressures and policy interventions, ABMs can help identify potential barriers to adaptation and evaluate the effectiveness of different policy instruments. This makes them especially useful for developing targeted interventions considering local contexts and individual circumstances rather than assuming a one-size-fits-all approach.

I. FROM THE TOP-DOWN APPROACH TO THE BOTTOM-UP APPROACH: A SYSTEMATIC REVIEW OF AGENT-BASED MODELS IN AGRICULTURAL CLIMATE CHANGE ADAPTATION

The impacts of climate change on agricultural systems have traditionally been assessed through crop yield decline, as this provides a quantifiable metric with established measurement protocols, historical data sets and clear economic significance. However, from a regional perspective, impacts are much more complex and interconnected than yield measurements alone can capture. These complexities include farmer decision-making processes, social learning dynamics, resource allocation patterns, and the interaction between environmental and socio-economic factors.

Agent-based models have emerged as valuable tools for capturing these complex dynamics, offering new insights into how agricultural systems adapt to climate change. This section presents a systematic review of ABM applications in agricultural climate change adaptation to understand how different studies conceptualize and model these adaptation processes.

I.I. Review Methodology

This paper presents a systematic review of Agent-Based Models (ABMs) in agricultural climate change adaptation. A comprehensive search of peer-reviewed literature published between 2005 and 2023 was conducted using SCOPUS, focusing on papers that combine agent-based modeling with climate change adaptation in agriculture. Search is confined to papers written in English and published in peer-reviewed journals between 2005 and 2023 and either in title, abstract or keywords include one or more of “agent-based”, “agent based”, “abm”, “multi-agent” or “multi agent” and any word beginning from “climate” and in title any word beginning from “adap”, “miti”, or “agri”. This is equivalent to the following SCOPUS search command:

(TITLE-ABS-KEY ("agent-based" OR "agent based" OR "abm" OR "multi-agent" OR "multi agent") AND TITLE-ABS-KEY ("climate change") AND TITLE-ABS-KEY (climate*) OR KEY (adap*) AND TITLE-ABS-KEY (agri*)) AND PUBYEAR > 1999 AND PUBYEAR < 2025 AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (LANGUAGE , "English"))

From an initial pool of 139 papers, first, papers that merely mentioned but did not use agent-based models were removed, followed by those unrelated to climate change adaptation and mitigation. After removing papers that did not examine climate change adaptation in the agricultural sector specifically, 59 papers that focused on agricultural adaptation and mitigation mechanisms remained—finally excluded articles that did not include individual farmers or farms as main actors and those without specific study areas, resulting in 21 empirically based and individual farm-related articles. These studies are shown in Table 1.

Table 1. List of Reviewed Papers

Author(s)	Year	Title	Source Title	Short Name
Bharwani S, Bithell M, Downing TE, New M, Washington R, Ziervogel G.	2005	Multi-agent modelling of climate outlooks and food security on a community garden scheme in Limpopo, South Africa	Philosophical Transactions of the Royal Society B	Bharwani et al. 2005
Happe K., Hutchings N.J., Dalgaard T., Kellerman K.	2011	Modelling the interactions between regional farming structure, nitrogen losses and environmental regulation	Agricultural Systems	Happe et al. 2011
Alexander, P., Moran, D., Rounsevell, M., & Smith, P.	2013	Modelling the perennial energy crop market: the role of spatial diffusion	Journal of the Royal Society	Alexander et al. 2013
Arnold, R. T., C. Troost, and Berger, T.	2014	Quantifying the economic importance of irrigation water reuse in a Chilean watershed using an integrated agent-based model	Water Resources Research	Arnold et al. 2015

Wossen, T., Berger, T., Swamikannu, N., & Ramilan, T.	2014	Climate variability, consumption risk and poverty in semi-arid Northern Ghana: Adaptation options for poor farm households	Environmental Development	Wossen et al. 2014
Reidsma, P., Bakker, M. M., Kanellopoulos, A., Alam, S. J., Paas, W., Kros, J., & De Vries, W.	2015	Sustainable agricultural development in a rural area in the Netherlands? Assessing impacts of climate and socio-economic change at farm and landscape level	Agricultural Systems	Reidsma et al. 2015
Brown, C., Bakam, I., Smith, P., & Matthews, R.	2016	An agent-based modelling approach to evaluate factors influencing bioenergy crop adoption in north-east Scotland	GCB Bioenergy	Brown et al. 2016
Berger, T., Troost, C., Wossen, T., Latynskiy, E., Tesfaye, K., & Gbegbelegbe, S.	2017	Can smallholder farmers adapt to climate variability, and how effective are policy interventions? Agent-based simulation results for Ethiopia	Agricultural Economics	Berger et al. 2017
Amadou, M. L., Villamor, G. B., & Kyei-Baffour, N.	2018	Simulating agricultural land-use adaptation decisions to climate change: An empirical agent-based modelling in northern Ghana	Agricultural Systems	Amadou et al. 2018
Hailegiorgis, A., Crooks, A. and Cioffi-Revilla, C.	2018	An Agent-Based Model of Rural Households' Adaptation to Climate Change	Journal of Artificial Societies and Social Simulation	Hailegiorgis et al. 2018
Baeza, A., Janssen, M.A.	2019	Modeling the decline of labor-sharing in the semi-desert region of Chile	Regional Environmental Change	Baeza and Janssen 2018
Yang, Y. E., Son, K., Hung, F., & Tidwell, V.	2020	Impact of climate change on adaptive management decisions in the face of water scarcity	Journal of Hydrology	Yang et al. 2020
Williams, T., Guikema, S., Brown, D., & Agrawal, A.	2020	Resilience and equity: Quantifying the distributional effects of resilience-enhancing strategies in a smallholder agricultural system	Agricultural Systems	Williams et al. 2020
Mirzaei, A., Zibaei, M.	2021	Water Conflict Management between Agriculture and Wetland under Climate Change: Application of Economic-Hydrological-Behavioral Modelling	Water Resources Management	Mirzaei and Zibaei 2021
Musayev, S., Mellor, J., Walsh, T., & Anagnostou, E.	2021	Development of an Agent-Based Model for Weather Forecast Information Exchange in Rural Area of Bahir Dar, Ethiopia	Sustainability	Musayev et al. 2021
Bazzana, D., Foltz, J., & Zhang, Y.	2022	Impact of climate smart agriculture on food security: An agent-based analysis	Food Policy	Bazzana et al. 2022
Marvuglia, A., Bayram, A., Baustert, P., Gutiérrez, T. N., & Igos, E.	2022	Agent-based modelling to simulate farmers' sustainable decisions: Farmers' interaction and resulting green consciousness evolution	Journal of Cleaner Production	Marvuglia et al. 2022
Wens, M. L. K., van Loon, A. F., Veldkamp, T. I. E., and Aerts, J. C. J. H.	2022	Education, financial aid, and awareness can reduce smallholder farmers' vulnerability to drought under climate change	Natural Hazards and Earth System Sciences	Wens et al. 2022
Babaeian, F., Delavar, M., Morid, S., & Jamshidi, S.	2023	Designing climate change dynamic adaptive policy pathways for agricultural water management using a socio-hydrological modeling approach	Journal of Hydrology	Babaeian et al. 2023
Harik, G., Alameddine, I., Zurayk, R., & El-Fadel, M.	2023	An integrated socio-economic agent-based modeling framework towards assessing farmers' decision making under water scarcity and varying utility functions	Journal of Environmental Management	Harik et al. 2023
Huber, R., Kreft, C., Späti, K., & Finger, R.	2024	Quantifying the importance of farmers' behavioral factors in ex-ante assessments of policies supporting sustainable farming practices	Ecological Economics	Huber et al. 2024

I.II. Research Questions

The research questions were defined by considering conceptualization in the studies. Conceptualization forms the foundation of effective climate change modeling by providing the framework through which complex real-world systems are translated into analyzable components. In agent-based models (ABMs), conceptualization refers to identifying the underlying components, interactions, and rules that govern agents' behavior and the environment in which they operate. It transforms real-world phenomena into a simplified, abstract representation suitable for modeling and simulation. The conceptualization phase in ABMs starts with the identification of *agents*. After the identification of agents, the *rules of behavior* of these agents should be determined. The third conceptualization stage defines the system the agents represent, i.e., the *environment*. *Interactions* between agents and environments are the final stage of conceptualization.

Following the selection of studies, the analysis proceeded through established research questions. In agent-based models, conceptualization means identifying the basic components, interactions and rules that govern the behavior of agents and the environment in which they operate. Climate change adaptation modeling represents complex processes of agent behavior. These stages of ABM conceptualization align naturally with four fundamental questions that climate change adaptation modeling must address, as identified by Smit et al. (2000):

1. Who or what adapts?
2. Adaptation to What?
3. How Does Adaptation Occur?
4. How Good is the Adaptation?

This alignment provides a structured framework for analyzing climate adaptation studies through the lens of ABM conceptualization. The question “Who or what adapts?” identifies the key agents in the climate change adaptation system and determines the decision-making units. The question “Adaptation to what?” corresponds to the definition of the environment and context in which agents operate. It specifies climate-related stressors, spatial and temporal constraints. “How Does Adaptation Occur?” allows us to understand the mechanisms for determining decision-making rules and behavioral mechanisms. It describes how agents perceive and process information and make adaptive choices, and includes strategies, constraints and response patterns. The question “How Good is the Adaptation?” is concerned with modeling the interactions between agents and the environment. It evaluates the effectiveness of adaptive strategies. It captures system-level responses and adaptation outcomes.

This framework illustrates how conceptual questions are intrinsically linked to the ABM conceptualization process and provides a structured approach to modeling adaptation to climate change.

a. Who adapts?

The analysis starts with the question "Who adapts?" because this question corresponds directly to the first and most fundamental stage of ABM conceptualization: identifying agents. In agricultural ABMs, this process involves defining not just basic units but also their key characteristics (such as farm size or resource access) and decision-making capacities (including awareness levels and learning abilities). Farmers are the primary adaptive agents in the reviewed literature, though their challenges and constraints vary by context.

The reviewed studies reveal three distinct categories of agricultural adaptation challenges: food security, water scarcity, and greenhouse gas emissions. Table 2 provides a comprehensive overview of how these challenges shape agent types and their constraints across different contexts.

Table 2. Agents, Constraints, and Problem Contexts in Agricultural Climate Adaptation ABMs

Food security		
Who adapts	**Main constraint**	**Author(s)**
Smallholder farmers	Limited access to credit	Bharwani et al. 2005; Amadou et al. 2018; Wens et al. 2022
	Lack of Trust in Weather Forecast Information	Musayev et al. 2021
Farm households	Limited access to credit	Wossen et al. 2014; Berger et al. 2017
Rural households	Limited access to public climate prediction information	Hailegiorgis et al. 2018
Farmers	Limited of access to credit	Bazzana et al. 2022
Smallholder households	Uncertainty in market conditions	Williams et al. 2020
GHG		
Who adapts	**Main constraint**	**Author(s)**
Farmers and agricultural policy makers	Sunk costs	Happe et al. 2011
Farmers and biomass power plant investors	Lack of a well-developed market for perennial energy crops	Alexander et al. 2013
Farmers and rural communities	Price dynamics	Reidsma et al. 2015
Farmers	Establishment costs	Brown et al. 2016
Farmers	Uncertainty in Market Prices	Marvuglia et al. 2022
Farmers		Huber et al. 2024
Water Scarcity		
Who adapts	**Main constraint**	**Author(s)**
Farms	Dependence on Surplus Water	Arnold et al. 2015
Agricultural households	Lack of Access to Surface Water for Irrigation	Baeza et al. 2019
Farmers	Inequality of water access	Yang et al. 2020
Farmers	Limited capital availability	Mirzaei and Zibaei 2021
Farmers	Penalty Costs for inefficient water use	Babaeian et al. 2023
Farmers	Production costs	Harik et al. 2023

Table 2 reveals distinct patterns in agent representation and constraints.

In food security studies, agents are predominantly smallholder farmers and farm households, with their adaptation capacity primarily constrained by limited access to credit, information, and forecasting services. These constraints mainly affect regions where agricultural production depends heavily on weather conditions.

In water scarcity studies, the agents range from individual farmers to agricultural households, facing constraints related to water access inequality, capital limitations, and water overuse penalties.

In GHG emission studies, the agent types expand beyond individual farmers to include policymakers and investors, with constraints centered on market uncertainties and capital requirements.

This analysis demonstrates how the identification of adapting agents and their constraints varies significantly based on the specific climate-related challenges being addressed.

b. Adaptation to what?

Understanding what agents adapt to requires defining their environment, which in the ABM conceptualization represents the system in which agents operate. In ABMs, the environment encompasses the external conditions and resources available to agents, including biophysical factors (climate and soil conditions) and socio-economic factors (market prices and policy incentives). The environment can change dynamically depending on agents' actions (land use change) and external events (climate and market price dynamics), allowing the model to simulate the effects of different adaptation strategies under various scenarios (Marvuglia et al., 2022). Agents in ABMs exhibit complex adaptive behaviors by interacting with each other and their environment (Savin et al., 2023).

The review reveals regional differences in how ABMs address adaptation to climate change. For example, modeling studies often focus on emission reduction strategies in regions with industrialized agriculture, particularly in Europe. These studies emphasize bioenergy adoption and efficiency improvements. In contrast, in parts of Africa, where economic activity is heavily dependent on the agricultural sector and agricultural production is mainly dependent on rain-fed agriculture, drought caused by climate change threatens food security. In irrigated agricultural regions, drought due to climate change poses different challenges, primarily focused on water resources management. Studies in the Americas and Asia focus on modeling how farmers adapt water use practices in response to increase scarcity.

Table 3 provides a comprehensive overview of how these adaptation challenges unfold in different regions, highlighting the specific climate contexts that shape adaptation needs.

Table 3. Regional Distribution of Climate Change Adaptation Challenges and Economic Contexts

Food security		
Adaptation to what	**Region**	**Author(s)**
Drought	South Africa	Bharwani et al. 2005
	Ethiopia	Berger et al. 2017; Hailegiorgis et al. 2018; Williams et al. 2020; Musayev et al. 2021; Bazzana et al. 2022
	Ghana	Wossen et al. 2014; Amadou et al. 2018
	Kenya	Wens et al. 2022
GHG		
Adaptation to what	**Region**	**Author(s)**
GHG	Denmark	Happe et al. 2011
	UK	Alexander et al. 2013
	Netherlands	Reidsma et al. 2015
	Scotland	Brown et al. 2016
	Luxembourg	Marvuglia et al. 2022
	Switzerland	Huber et al. 2024
Water Scarcity		
Adaptation to what	**Region**	**Author(s)**
Drought	Chile	Arnold et al. 2015; Baeza et al. 2019
	Colorado	Yang et al. 2020
	Iran	Mirzaei and Zibaei 2021; Babaeian et al. 2023
	Lebanon	Harik et al. 2023

Table 3 reveals clear regional patterns in adaptation challenges. These regional challenges illustrate how ABMs must adapt to local contexts while maintaining consistent modeling principles.

c. How does adaptation occur?

Understanding how adaptation occurs requires defining the behavioral rules that guide agents' decision-making processes. Some studies use farmer typologies to construct rules. These typologies can be based on farmers' willingness and abilities (Brown et al., 2016; Valbuena et al., 2010), or they can represent differences in farmers' implementation of the existing system (Li et al., 2018). Some studies also identify agents' rules of behavior through their farming style. Farming styles may be defined in terms of farmers' perceptions of risk (Egger et al., 2023) or ownership of the means and modes of production (orphan, entrepreneurial, agroecology) (Lloyd & Chalabi, 2021). How many styles of farming there are, the degree to which they explain variance, and the extent to which they are linked to structural differences in agricultural development patterns, are questions which a priori are not easily answered (van der Ploeg, 2008, p. 12). The diversity in farming styles and agent typologies leads to different adaptation pathways.

Adaptation to climate change in agricultural systems emerges from the complex interplay between agents' behavioral rules and adaptation options. Agents' rationality is bounded in their decision-making processes; their adaptation choices follow certain patterns shaped by regional contexts and challenges.

ABMs typically represent a system of a large number of heterogeneous agents, each with bounded rationality, i.e., making decisions based on limited information and cognitive constraints (Castro et al., 2020; Findlater et al., 2019; Gerst et al., 2013; Savin et al., 2023). The heterogeneity of agents is an important feature of ABMs: each agent can differ from each other in countless ways: wealth, preferences, memories, decision rules, social networks, locations, genetics, culture and so on, some or all of which may endogenously adapt or change over time (Epstein, 2006, p. 51). Farmers' choices of adaptation strategies are shaped by their limited information, cognitive constraints, and individual characteristics that define their decision-making rules. For instance, a farmer's decision to adopt precision agriculture techniques may depend on their technological capacity and risk perception. At the same time, their previous experiences and social network information might influence the choice of drought-resistant crops. Some farmers might quickly adopt new technologies due to their entrepreneurial farming style, while others might stick to traditional practices based on their risk-averse decision rules. The interactions between individual decision-making characteristics and available adaptation options demonstrate that adaptation is not a uniform process but rather a dynamic one that reflects both the Heterogeneity of agents and the specificity of their environmental challenges. Climate change adaptation strategies are developed by combining technological, policy, and sustainable practices or by applying them individually.

The review identified five main categories of adaptation strategies, each representing different approaches to climate change adaptation, as shown in Table 4.

TABLE 4. Classification of Agent-Based Models by Climate Change Adaptation Purposes and Options

How does adaptation occur?	**Author(s)**
Precision Agriculture	(Bharwani et al., 2005; Musayev et al., 2021; Wens et al., 2022; Williams et al., 2020; Wossen et al., 2014)
Use of adapted crops and varieties	(Alexander et al., 2013; Berger et al., 2017; Brown et al., 2016; Harik et al., 2023; Wossen et al., 2014)
Conservation agriculture	(Amadou et al., 2018; Bazzana et al., 2022; Hailegiorgis et al., 2018; Happe et al., 2011; Huber et al., 2024; Marvuglia et al., 2022; Reidsma et al., 2015)
Water restrictions and water rationing	(Arnold et al., 2015; Babaeian et al., 2023; Baeza et al., 2019; Yang et al., 2020)

Table 4 categorizes the main adaptation strategies identified in the reviewed studies. Each of these strategies represents different approaches to climate adaptation, varying in their implementation requirements, scope, and effectiveness. The following sections examine each strategy in detail, exploring how they are implemented in different regional contexts and their role in addressing specific climate challenges.

Precision Agriculture**:** Precision agriculture refers to a process in which farmers' self-directed decisions are supported by technological advances, such as changing planting dates, using weather information systems, and developing early warning systems. By shifting planting dates, farmers can better align their crop production with the changing patterns of rainfall (Bharwani et al. 2005; Williams et al. 2020; Wossen et al. 2014). This adjustment helps mitigate the risk of crop failure due to irregular rainfall during critical growth stages, thereby stabilizing food production and enhancing food security. By adopting weather forecasts, farmers can better prepare for and respond to climate variability such as droughts or floods, helping to minimize crop losses and stabilize food production (Musayev et al. 2021). For instance, improved early warning systems in Kenya contribute to an average reduction of 4.5% in food insecurity (Wens et al., 2022).

Use of adapted crops and varieties**:** The use of adapted crops and varieties helps to reduce the negative impacts of climate change on agricultural systems while ensuring stable agricultural production. The new crop varieties reduce the risk of food shortages and improve the overall resilience of farm households to environmental changes, providing more stable and higher yields (Berger et al., 2017). For example, adopting early maturing crop varieties can complete their growth cycle before the onset of adverse weather conditions, thereby reducing the risk of crop failure and ensuring a more reliable food supply (Wossen et al., 2014).

Beyond food security benefits, some adapted varieties serve multiple purposes; for instance, drought-tolerant crops with low water demand help mitigate the effects of reduced water availability (Harik et al., 2023), or by replacing fossil fuels with biomass from bioenergy crops, farmers can help reduce greenhouse gas (GHG) emissions (Alexander et al., 2013; Brown et al., 2016).

***Conservation agriculture*:** Conservation agriculture practices include several key practices that increase climate resilience in agricultural systems. These practices include crop rotation, contour plowing, terracing and cover crops, soil conservation practices that prevent soil erosion and increase water holding capacity, crop diversification, and CSA. These practices serve multiple adaptation purposes.

Crop rotations help farmers to prevent the depletion of soil nutrients and reduce the need for synthetic fertilizers, which are significant sources of GHG emissions (Marvuglia et al., 2022). Soil conservation practices reduce nitrogen surplus and contribute to GHG emissions reduction. For example, in Denmark, ammonia emissions, a component of greenhouse gases, are reduced from 19 kg ha-^{1} to 10 kg ha-^{1} per year with nutrient use efficiency and reduction in the accumulation of nitrogen in the soil (70%) (Happe et al., 2011), or in Switzerland, nitrogen applications can reduce GHG emissions by 20-70% (Huber et al., 2024)

Crop diversification strategies help mitigate the risks associated with unpredictable rainfall and droughts, thereby enhancing food security by ensuring a more stable food supply (Hailegiorgis et al., 2018); diversifying crops can also lead to economic benefits, as some of the diversified crops have higher market value, and this economic gain can improve household income, allowing farmers to purchase food and other necessities, thus enhancing food security (Amadou et al., 2018).

CSA offers a comprehensive approach to climate adaptation by fundamentally transforming production technology and agricultural practices. These practices can help solve multiple problems simultaneously. CSA increases crop yields by improving soil health and increasing the soil's capacity to hold water, thereby increasing food security (Bazzana et al., 2022), or reducing emissions from agricultural activities by reducing carbon sequestration in the soil (Reidsma et al., 2015).

***Water restrictions and water rationing*:** Agricultural regions can better manage increasingly scarce water resources by combining water rights arrangements, market mechanisms, rationing schemes, pricing structures, and use restrictions. These strategies make adapting to changing climatic conditions possible while promoting more sustainable and efficient water use in agriculture. The choice and implementation of specific water management strategies depends on local institutional, environmental, and socioeconomic contexts. However, all aim to increase resilience and productivity due to climate variability and water scarcity.

Different regions have developed varied approaches. In Chile, where water rights are separate from land ownership, farmers often "stack" or accumulate water rights over typical irrigation needs per hectare as a risk management strategy for drought periods (Arnold et al., 2015), or adaptation happens through labor-sharing agreements that help manage costs and increase productivity (Baeza et al., 2019). In Colorado, during droughts, water management authorities can impose cuts in water deliveries to farmers and implement water scarcity-sharing schemes to distribute limited resources more equitably, sharing agreements are triggered under drier conditions (Yang et al., 2020). In Iran, the government combines penalties for excessive water use with subsidies for modern irrigation techniques, simultaneously discouraging overuse and promoting efficiency (Babaeian et al., 2023; Mirzaei & Zibaei, 2021).

The review reveals that most studies implement strategies that simultaneously address multiple aspects of climate change adaptation. This multi-purpose approach is evident in how adaptation strategies are modeled and implemented across different contexts.

d. How good is the adaptation?

The effectiveness of adaptation emerges from interactions between agents in ABM conceptualization. These interactions reveal how agents respond to and cope with climate challenges through their relationships with both other agents and their environment. In reviewed studies, these interactions manifest in several ways, and the effectiveness of adaptation strategies varies by regional context and challenge.

Table 5 provides a comprehensive overview of adaptation effectiveness across different regional contexts.

Table 5. Evaluation of Adaptation Effectiveness Across Different Regional Contexts

Precision agriculture		
Adaptation strategy	**How good is the adaptation?**	**Author(s)**
Shifting planting dates	Adaptation is effective, but poor farmers remain vulnerable due to limited confidence in forecasts and resource constraints. The studies emphasize the need for targeted support to increase resilience.	Bharwani et al. 2005; Williams et al. 2020
Weather forecasts	Policies targeting social networks and prediction accuracy are essential to improve adaptation and adoption rates.	Musayev et al. 2021
Early warning systems	Adaptation is highly effective when policy interventions are combined.	Wens et al. 2022
Use of adapted crops and varieties		
Adaptation strategy	**How good is the adaptation?**	**Author(s)**
Bioenergy crops	Adaptation is limited, because farmers' climate change awareness is low, and diffusion is slow. Policy interventions can provide economic incentives, such as subsidies or grants, to make the adoption of bioenergy crops more attractive to farmers.	Alexander et al. 2013; Brown et al. 2016
Drought-tolerant crops	Adaptation strategies are effective. The need for policies that farmers' decisions are influenced by attitudes, beliefs, community norms, and traditions, requiring policies that address these complexities.	Harik et al. 2023
New crop varieties	While some households benefit from adaptation strategies, many poor and food insecure farmers remain vulnerable. The need for targeted, context-specific policies to address these inequalities.	Berger et al. 2017; Wossen et al. 2014
Conservation agriculture		
Adaptation strategy	**How good is the adaptation?**	**Author(s)**
Crop diversification	Adaptation is effective. Targeted policies are crucial for adaptation as they address the specific needs and vulnerabilities of different communities and ecosystems.	Amadou et al. 2018; Hailegiorgis et al. 2018
Crop rotations	Adaptation is effective, but green consciousness among farmers must be increased.	Marvuglia et al. 2022
Nutrient use efficiency	Adaptation is effective requiring integrated modeling approaches to fully understand and optimize their environmental and economic impacts.	Happe et al. 2011; Huber et al. 2024
CSA	The adoption of CSA is significantly influenced by farmer networks and stakeholder involvement. Policy makers can develop extension models that leverage these networks to spread information about CSA, enhancing adoption rates.	Bazzana et al., 2022; Reidsma et al., 2015
Water restrictions and water rationing		
Adaptation strategy	**How good is the adaptation?**	**Author(s)**
Labor-sharing agreements	Adaptation strategies are effective. Policies need to address the interplay between environmental variability, social dynamics and economic incentives to sustain these institutions.	Baeza et al. 2019
Water rights	Adaptation strategies are effective, but the need for equitable water management policies for farmers with low water rights.	Arnold et al. 2015
Water scarcity-sharing schemes	Adaptation strategies show mixed effectiveness the need for more comprehensive and realistic adaptive management actions.	Yang et al. 2020
Penalties for excessive water use with subsidies for modern irrigation techniques	Adaptation strategies are effective emphasizing the need for stakeholder engagement and education.	Babaeian et al., 2023; Mirzaei and Zibaei 2021

Analyzing these adaptation strategies across regions reveals how local contexts and challenges shape their effectiveness. While some strategies show consistent effectiveness across regions, their implementation requirements and success factors vary significantly based on regional characteristics and constraints. Food security is the main problem in Africa because of the drought. Precision agriculture, the use of adapted crops and varieties, and conservation agriculture are adaptation options for food security. GHG emissions are the main problem in industrialization areas, mainly Europe; adaptation options include using adapted crops and varieties and conservation agriculture. Water scarcity is the main problem of farmers who produce irrigation-based crops. These studies are concentrated in America and Asia. Adaptation options for water scarcity problems include adapting crops and varieties, water restrictions, and rationing.

Adapted crops and varieties are a cross-cutting adaptation option for the three problems. Enhancing new crop varieties strategy for food security is used. This variety needed some policy support because these crops are cash-crops, so their fertilizer and seed needs are different. These crops are a good option, but increasing inequalities between farmers in Africa for smallholders creates inequality. So, policy interventions are needed to strategy. Bioenergy crops reduce GHG emissions from agriculture. However, farmers' awareness is important in adopting this strategy. So, policy intervention is needed to enhance this awareness. For water scarcity, drought-tolerant crops are used. These crops' water needs are very low. Farmers' decisions to produce these crops are influenced by attitudes, beliefs, and community norms, so policy interventions are needed to change farmer's minds.

Conservation agriculture is used for food security and GHG emissions, and this option's success depends on enhancing policies again. However, while GHG emission studies show that increasing the adaptation rate requires policies emphasizing stakeholder involvement, food security needs policies that increase adaptation through social networks.

Precision agriculture only solves food security problems; water restrictions and rationing solve water scarcity problems.

The regional analysis of adaptation effectiveness reveals distinct patterns across geographical and problem contexts. These strategies' success heavily depends on policy design and economic incentives. These studies reveal that while technical solutions can be effective, their success is moderated by social dynamics, economic conditions, and the equitable distribution of resources. Across all regions, a common theme emerges: the effectiveness of adaptation strategies is not solely determined by their technical merits but is strongly influenced by social, economic, and institutional factors specific to each context.

II. THE GAP IN THE LITERATURE: FROM WHOM DO WE LEARN?

Our review of ABM studies shows that while climate change challenges may be similar, their adaptation strategies vary significantly across regional contexts.

For example, drought threatens food security in Africa while it creates water scarcity challenges in basin regions, particularly Asia and America. Both problems require policy intervention to improve farmers' adaptation capacity.

For food security problems, farmers change their crop calendar or use new crop varieties to adapt to climate change. Farmers need to access the climate forecast mechanism to change the crop calendar. This access is unequal between the farmers. So, policy support is important to access climate forecast mechanisms. Besides the policy support, the reliability of these forecasts allows farmers to change their crop calendars. This reliability is associated with the presence of farmers who update their crop calendars based on weather forecasts. In his study, Musayev et al. (2021), showed that adaptation is effective when forecast accuracy is at least 70% and farmers have strong networks and access to extension services. However, barriers such as low prediction accuracy and limited communication reduce adoption rates and highlight areas for improvement. Therefore, implementing this strategy requires the simultaneous existence of many factors, such as the farmer's access to information and the existence of farmers who produce using information. Developing and adopting new crop varieties often involves significant costs for smallholder farmers (Berger et al., 2017; Wossen et al., 2014). Policy support focuses on enhancing farmers' adaptive capacity through access to credit and subsidies. Specific to food security, the inequitable structure in these regions is the main constraint to adaptation. Policy support must focus primarily on reducing these inequalities.

In water-scarce regions, policy interventions are considered in a different context because of the drought. In Chile, like land ownership, water use is subject to ownership. However, this property relationship creates inequality in water use. For about 50% of farmers experiencing total gross margin losses in dry years, the loss of surplus water accounts for nearly all their income losses (Arnold et al., 2015). Therefore, policy interventions are needed for farmers with low water rights vulnerability and adaptive capacity. In Iran, penalties for the overuse of water and support mechanisms for adopting new irrigation techniques work together. In these studies, a reward-punishment mechanism is applied by supporting farmers who use modern irrigation techniques to prevent the unconscious use of water. However, although the subsidies and modern irrigation systems' benefits, e.g., increase farmers' gross margins by 34-46%, farmers in upstream units with readily available water resist adopting adaptive strategies (Mirzaei & Zibaei, 2021). The other study in Iran shows that subsidies for modern irrigation techniques (e.g., sprinkler or drip irrigation) were ineffective as farmers preferred free and easily accessible surface and groundwater resources, and encouraging cooperative behavior through training and cultural programs was more effective than subsidies or penalties (Babaeian et al., 2023). So, gradual education and awareness about future environmental conditions are necessary to change attitudes.

The policy response emerges as an adaptation strategy that cuts across all three main challenges. In Europe, adopting new energy crops is the adaptation strategy developed to meet GHG emission reduction targets. Farmers' awareness, shaped by social learning and spatial interactions, is important for adopting these crops. In Scotland, for example, 23% of farmers are willing to sacrifice income to reduce GHG emissions. However, adaptation depends on targeted policies that address different farmer typologies' specific needs and attitudes (Brown et al., 2016). Alexander's study also shows that adaptation through information dissemination alone and without policy interventions can create time lags of at least 20 years in meeting GHG emission targets (Alexander et al., 2013).

Ultimately, the effectiveness of adaptation varies significantly in different contexts; success depends on specific conditions such as policy support, climate change awareness, and social networks. However, studies also show that these factors are interlinked: policy interventions often work best when they support social networks, and awareness is most effective when backed by institutional support. Success requires the presence of all three elements, not just one factor.

While ABMs effectively model the importance of social networks in adaptation success, they reveal a critical limitation: they oversimplify how farmers acquire adaptation knowledge and practices through basic threshold-based rules. This oversimplification is evident in several prominent studies in literature. (Alexander et al., 2013)'s study reduces complex social interactions to an 'adoption threshold value' that determines whether farmers adopt energy crops based on neighbors' experiences. Similarly, (Wens et al., 2022) assume farmers without extension services only adopt measures implemented by neighbors, using a probability threshold for adoption decisions. (Marvuglia et al., 2022) analyzes farmers' green consciousness, which drives their adoption decisions. The farmer's green consciousness level is adjusted to approximate their neighbors' average green consciousness level to reflect social influence and peer pressure. While these approaches acknowledge social influence in decision-making, they fail to capture the nuanced reality of how farmers acquire and implement adaptation knowledge.

The social learning process in agricultural communities is far more complex than current ABMs suggest. However, the basic assumptions of ABMs align with fundamental observations in literature. Farmers often adjust their agricultural practices based on the successes they observe in their neighbors' practices. This phenomenon, known as social learning, suggests that farmers are influenced by the outcomes experienced by their peers, leading to adjustments in their farming inputs and techniques (Conley & Udry, 2010; Le et al., 2020; Wu et al., 2022). Social interactions within farming communities play an important role in how interacting with peers helps farmers develop practical knowledge and promotes the adoption of innovative farming practices (Llones & Suwanmaneepong, 2021). This learning mechanism is critical for climate change adaptation (Apetrei et al., 2024). However, some studies reveal that psychological factors such as risk perception, psychological distance, and trust are significant drivers of farmers' adaptation behaviors. Trust can predict adaptability and influence the choice of mitigation behaviors (Azadi et al., 2019; Han et al., 2022; Peng et al., 2022). Perceived social norms and behavioral control work together to drive farmers' intentions to adopt sustainable practices, as their decisions reflect both social pressure and their perceived ability to implement new methods. For example, farmers who strongly identify with environmentally conscious groups are more likely to adopt sustainable practices that align with these group norms (Valente & Rogers, 1995). Conversely, some farmers may insist on maintaining existing practices aligned with regional social norms, even when alternative production options, such as sustainable techniques, could yield higher profits (Harik et al., 2023). Intrinsic motivations and social norms influence farmers' willingness to share information (Chang et al., 2024). Some studies have found that farmers with higher levels of knowledge often hesitate to share their expertise voluntarily (Xiao et al., 2022). Therefore, understanding the effectiveness of learning mechanisms requires careful consideration of social dynamics and power structures within farming communities. These power structures are deeply rooted in the distribution of agricultural resources, as land distribution and resource access significantly impact social learning and adaptation capabilities.

Land distribution and resource access significantly impact social learning and adaptation capabilities. Small-scale farmers operating on limited land are often more vulnerable to climate impacts and have fewer resources to adapt than large landholders (Asrat & Simane, 2018; Idrisa et al., 2012). This vulnerability is compounded by limited access to information and extension services, crucial for improving environmental awareness and adaptation strategies (Idrisa et al., 2012). In contrast, larger farmers have better access to resources and information, enabling them to take more proactive measures against climate variability (Sulewski & Gołaś, 2019; Tshikororo et al., 2021). This disparity creates more than just economic differences: the resulting inequality in access to information and resources creates a self-reinforcing cycle of vulnerability for smallholder farmers, making them less likely to adopt innovative practices that could mitigate climate change impacts.

Land inequality creates social barriers that hinder knowledge sharing and cooperation between farmers, limiting the spread of productive agricultural innovations. In rural India, for example, dominant classes, often linked to specific castes, monopolize economic benefits, exacerbating existing inequalities and inhibiting collective action among marginalized groups (Levien, 2015). In northwest Ecuador, perceived economic differences led to trust being placed only in wealthier members, which initially facilitated cooperative development but later negatively impacted its success (E. C. Jones, 2004). This monopolization of resources undermines the social ties necessary for practical cooperation, hindering the diffusion of agricultural innovations.

Social learning emerges from the complex interplay of farmers' social identities and the agricultural structure in which they operate. However, existing ABMs often make a simplistic assumption: if one farmer successfully applies adaptation knowledge, neighboring farmers will follow suit. While this assumption might hold within social networks, it may not apply to all neighbor relationships. Learning from neighbors differs from learning within an established social network. The key distinction is that being neighbors does not automatically create the trust relationships that naturally develop within social networks.

This understanding has led to more nuanced approaches in modeling neighbor-based learning. For example, (Brown et al., 2016), developed a survey-based modeling approach that directly addressed trust and influence through specific questions such as 'Would you learn from your neighbor who is planting bioenergy crops?' and 'To what extent do neighboring farmers influence your decision to plant bioenergy crops?'. This approach helped create an agent typology that reflects the reality of farmers' learning processes. In the other study, (Ambrosius et al., 2022), examined learning mechanisms through social identity theory, considering how farmers' social networks, social position, and market relationships influence their learning preferences. These studies demonstrate how ABMs can evolve beyond simple profit maximization to capture the complex social factors that shape farmers' decision-making.

While ABMs offer powerful tools for understanding farmers' adaptation behaviors, current models often oversimplify the complex mechanisms of social learning, indicating the need for further investigation. These shortcomings in representing social learning mechanisms represent only one aspect of the broader challenges facing agent-based modeling approaches while highlighting important areas for improvement in ABMs.

CONCLUSION

This review has examined both the capabilities and limitations of agent-based models in representing agricultural adaptation to climate change. While these models have significantly advanced our understanding of adaptation processes, their limitations in data requirements, computational capacity, scale representation, and behavioral assumptions must be considered when applying them to policy development. This review demonstrates that while agent-based models have significantly advanced our understanding of agricultural adaptation to climate change, current approaches need enhancement to better capture the complex social dynamics that influence adaptation processes. The literature reveals a clear evolution from simple threshold-based adoption models to more sophisticated representations of farmer decision-making, yet significant gaps remain in modeling social learning mechanisms.

The analysis highlights three key findings. First, effective climate change adaptation in agriculture depends not just on the availability of adaptation strategies but on the social contexts that enable their adoption. Second, land distribution patterns fundamentally shape both adaptation capacity and knowledge diffusion networks, suggesting that structural inequalities cannot be separated from adaptation outcomes. Third, the success of adaptation strategies is intimately linked to social learning mechanisms that operate through trust networks and community relationships.

These findings have important implications for both modeling approaches and policy development. For modeling, they suggest the need to:

- Incorporate more sophisticated representations of social networks and trust relationships
- Account for the influence of land ownership patterns on knowledge diffusion
- Consider power dynamics and social hierarchies in adoption processes
- Develop methods to represent the quality and reliability of social connections, not just their existence

For policy, the implications include:

- Recognition that adaptation strategies must account for existing social structures and inequalities
- Understanding that technical solutions alone may be insufficient without addressing social barriers to adoption
- Acknowledgment that land reform and social equity issues may be integral to successful adaptation
- Appreciation that building community trust networks may be as important as developing technical solutions

Future research should focus on developing more sophisticated methods for modeling social learning processes, particularly how trust relationships and power dynamics influence adaptation pathways. Additionally, more attention should be paid to how structural inequalities in agricultural systems affect the diffusion of adaptation strategies.

This enhanced understanding of social learning mechanisms in agricultural adaptation is crucial as climate change continues to pose increasing challenges to global food security. Success in addressing these challenges will require models that can better represent the complex social dynamics that determine adaptation outcomes.

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